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DISCUSSION PAPER

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The Interplay Between Product Innovation, Publishing, Patenting and Developing Standards

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The Interplay between Product Innovation, Publishing, Patenting and Developing Standards

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Abstract

Firms use a variety of practices to disclose the knowledge generated by their R&D activities, including, but not limited to, publishing findings in scientific journals, patenting new technologies, and contributing to developing standards. While the individual effects of engaging in the listed practices on firm innovation are well-understood, the existing literature has not considered their interrelation. Therefore, our study examines if the three practices are complements, substitutes, or unrelated in terms of firms' performance with product innovations new to the market. Our analysis builds on a sample of innovation-active firms from the German Community Innovation Survey, which includes information on the development of standards, enhanced with information on firms' engagement in patenting and publishing. We find that 26% of innovation-active firms engage in at least one of the three practices, and 22% of engaging firms combine them. Using supermodularity tests, we show that publishing and patenting as well as patenting and developing standards are substitutes. Publishing and developing standards are not significantly linked. Based on our findings, we derive implications for innovation management and policy.

Keywords: Standardization, patents, scientific publications, product innovation

JEL Classification: O31, O32, O34

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1. Introduction

Firms use and combine different practices to disclose their knowledge. The most prominent formal practice is the patenting of new technologies, which allows firms to appropriate the returns from their innovations through time-restricted exclusive rights. However, patent applications require the disclosure of relevant knowledge that convincingly shows the novelty of the invention, the needed inventive steps, and its capability of industrial application. Moreover, the disclosure needs to be "*sufficiently clear and complete to enable it to be replicated by a person with an ordinary level of skill in the relevant technical field*" (WIPO 2022). Thus, patenting is considered a form of selective knowledge disclosure (Alexy et al. 2013). A long tradition of studies considers the impact of patenting on innovations and commercial success. Seminal contributions by Griliches (1981), Mansfield (1986), and Cohen et al. (2000) focused on firms' involvement in patenting and studies about the influence of patent portfolios on firm market valuation, such as Belezon and Patacconi (2013), Hall et al. (2005), and Neuhäusler et al. (2016), followed them.

In addition to patenting, firms use other practices to improve their technological and market conditions through selective knowledge disclosure (Alexy et al. 2013). For instance, firms add the results of their R&D activities to the public domain by publishing them in scientific journals or by contributing to the development of standards. Scientific publishing requires significant original contributions to theory, methodology, or empirical evidence, whereas standards consist of technical specifications or other precise criteria designed as guidelines for best practices. These alternative forms of knowledge disclosure practices do not grant exclusive rights to the disclosed knowledge. On the contrary, the knowledge disclosed in scientific publications and standard documents is not restricted by intellectual property rights and is freely available. Scientific publications are easily accessible from scientific journals - as open access publication or for a fee. Similarly, standard-setting bodies claim the copyright of standard documents but do not restrict the access to their content. However, they might, like scientific publishing houses, ask for a fee.[1] Thus, both practices can enable competitors to utilize the disclosed firm knowledge.

Compared to the literature on patenting, research on firms' involvement in scientific publishing and the development of standards is still premature. As for patenting, early studies on scientific publishing explained firms' involvement in publishing (Hicks 1995, Godin 1996, Simeth and Raffo 2013, Simeth

[1] An exception of the free access to the content of standard documents is the case of standard-essential patents. Patents can be claimed essential for a standard, and firms aiming at implementing the standard are forced to negotiate the licensing conditions with the patent owner (e.g. Lerner and Tirole 2015). However, the declaration of standard-essential patents is concentrated to a few mainly large firms. Among the 25 firms with the highest number of declarations related to standards released by the European Telecommunications Standards Institute is Siemens the only German firm (Bekkers et al. 2020a).

and Lhuillery 2015, Stephan 1996). Recent studies analyzed its impact on innovation performance (Cockburn and Henderson 2003, Jong and Slavova 2014, Li et al. 2015), firm valuation (Arora et al. 2018, Pellens and Della Malva 2017, Simeth and Cincera 2016), and economic competitors (Della Malva and Hussinger 2012). The same is the case for the development of standards. Early literature studied the engagement of firms in developing standards (Blind 2006, Blind et al. 2021, Blind and Mangelsdorf 2013, Blind and Thumm 2004, Wakke et al. 2015, Zhang et al. 2020a). Then, studies started to analyze its impact on innovation (Wen et al. 2020, Zhang et al. 2020b) and commercial performance (Wakke et al. 2016).

These streams of literature built our understanding of the separate impacts of publishing, patenting, and developing standards as different knowledge disclosure practices, which might go back to the same idea or technology, but display it differently. However, firms combine different practices, for instance, by patenting and trademarking (Sandner and Block 2011, Brem et al. 2017) or by integrating intellectual property in open innovation strategies (Arora et al. 2016, Belderbos et al. 2014, Brem et al. 2017). Still, empirical research on the interrelation of different disclosure practices is rare and has focused on the tension between patenting and secrecy (e.g. Hall et al. 2014, Holgersson and Wallin 2017).

We add to the literature by analyzing the combination of different disclosure practices and their relationship with innovation performance. More precisely, we focus on how combinations of publishing, patenting, and the development of standards relate to firm's new to the market product innovation performance. We focus specifically on new to the market product innovation, as all three disclosure practices, in particular patenting, but also scientific publishing, relate to new technologies and are poorly suited to disclose imitations. Thus, our study enhances the understanding of the synergies between publishing, patenting, and developing standards, and extends our understanding of the dichotomous relationship between scientific publishing and patenting practices (e.g., Holgersson and Wallin 2017) by the development of standards.

The core of our empirical analysis builds a sample of innovation-active firms from the 2015 wave of the German Community Innovation Survey. The 2015 wave includes unique questions about firms' participation in the development of standards. We enhance it with information on firms' scientific publishing from Scopus and patenting from the German Patent Office. For our explorative analysis on the complementarity and substitutability between publishing, patenting, and standard development practices, we conduct supermodularity tests described by Carree et al. (2011).

Our results show that 26% of innovation-active firms in our sample engage in at least one of the examined three disclosure practices. Moreover, they demonstrate, that patenting and standard development are more common than publishing: 17% develop standards, 13% patent, and 2% publish. Also, the different disclosure practices are frequently combined. 22% of firms engaging in at least one of the three practices employ at least one additional practice. We further see that publishing, patenting, and the development of standards are primarily conducted by firms in high-tech and knowledge-intensive industries. In addition, firms that combine practices are on average larger and more internationally oriented than firms only pursuing one practice. The analysis on the complementary and substitutional relations between practices reveals that firms engaging in an individual practice have a higher revenue share of new to the market product innovations than firms engaging in no practices. However, the supermodularity tests also show that publishing and patenting are substitutes in new to the market product revenue shares, as are patenting and developing standards. Thus, combining these practices does not yield a positive premium on top of the two base effects of the individual practices, but, on the contrary, decreases their joint effect on innovation performance. These findings highlight that firm-level tensions between disclosure channels inhibit firms' abilities to benefit from potential synergies between channels.

2. Related literature

We first discuss commonalities and differences between publishing, patenting, and standard development from a knowledge disclosure perspective, and then discuss the literature on each practice. After that, we describe how the practices could interrelate. Alexy et al. (2013) categorize scientific publishing, patenting, and participation in standards development as selective revealing of technical solutions. However, there are differences between the three practices. Becoming a contributor to a standard document by actively participating in standardization committees and consortia can be perceived as a practice positioned between scientific publishing and patenting. Whereas scientific publications are mainly the result of basic research, participation in standardization aims to extend the path of existing technologies in the context of applied research. While scientific knowledge still needs to be further developed in order to be implemented in new products, standards are developed to be immediately implementable in practice. However, in both cases codified knowledge is publicly available and usable. Publishing and standards development can also be related to patenting. Standards are closer to patents than publications, as the former are typically nearer to marketable technologies than the latter. Concerning exclusivity, the content of standards and scientific publications can be implemented by all interested parties, whereas the use of patents requires the agreement of their owners. The exception are standards that include references to patents, so-called standard-essential patents (Lerner and Tirole 2015) that also require the consent of their owners. However, the relevance of standard-essential patents remains mainly limited to the generations of mobile communication technologies (Bekkers et al. 2020a).

2.1 Publishing

Contrary to the primary rationale of appropriating the knowledge outputs of their R&D (Ahuja et al. 2013), firms publish their results also in the scientific literature (Arora et al. 2018, Camerani et al. 2018, Larivière et al. 2018) . A large body of literature has investigated why firms publish their findings in such a non-proprietary fashion (see Camerani et al. 2018 for a review), concluding that publishing allows firms i) to connect to scientific communities to access knowledge, networks, and human resources, ii) to signal to financial markets, potential partners, and other stakeholders, and iii) to complement their intellectual property strategies.

Complementing other forms of intellectual property is particularly relevant in the context of this study. Publishing adds to the stock of prior art and prevents a firm's competitors, and itself from claiming the published results through patenting (e.g. Holgersson and Wallin 2017). This safeguards firms' freedom to operate, i.e. from being restricted by patents of competitors, without incurring cost of acquiring formal intellectual property measures (Barrett 2002, Gans et al. 2017, Hayter and Link 2018, Johnson 2014, Della Malva and Hussinger 2012, Pénin 2007). Publishing can also help to commercialize innovations, as they can signal the effectiveness of products to potential users (Azoulay 2002, Hicks 1995, Rafols et al. 2014), or encourage regulators to approve products (Penders and Nelis 2011).

Existing evidence shows a positive link between publishing and firm outcomes (Simeth and Cincera 2016). Publishing, however, requires specific capabilities that relatively few firms possess, such as an extensive knowledge base and scientifically educated R&D personnel (Simeth and Lhuillery 2015). Nevertheless, the scientific capabilities generated by publishing are considered key success factors in sectors such as the pharmaceutical industry (Cockburn and Henderson 2003) or the nanotechnology industry (Li et al. 2015). More generally, corporate publishing allows firms to develop science-based collaborations and absorptive capacity that can be leveraged to higher radical innovation success (Jong et al. 2014). Studies about the impact of publishing on firm success have mainly focused on valuation, and documented a positive relation in high-tech industries (Arora et al. 2018, Pellens and Della Malva 2018, Simeth and Cincera 2016). The effects are, however, heterogeneous even within high-tech industries. Simeth and Cincera (2016) find a positive impact of publishing on valuation in the biotechnology and pharmaceutical industries, in instrumentation, and in the chemicals industry, but not for information and communication technologies. In the semiconductor industry, Pellens and Della Malva (2016) reveal positive relations for design-based fabless firms, but a negative relation for integrated manufacturers. Arora et al. (2018) show that the relation between publishing and valuation has weakened over time, and document that firms are to a lesser degree publishing scientific results.

In summary, the literature reveals a positive influence of firms' publication activities on their innovation performance at least in the long run. In the short run, the knowledge spillovers generated by scientific publications might benefit the competitors and, therefore, limit the success of the own innovations at the market.

2.2 Patenting

Although patenting requires the disclosure of the invention to be protected, it is still the most common formal instrument for firms to appropriate the returns from investment in R&D. It is the primary means for appropriation according to Ahuja et al. (2013) and protects firms' technological know-how. Many studies have investigated the quality and value of patents (e.g. Gambardella et al. 2008). Following these analyses, numerous studies have examined the impact of patent portfolios and their quality on firm value (e.g. after the seminal contribution by Griliches 1981, Hall et al. 2005, Belezon and Patacconi 2013, and Neuhäusler et al. 2016). The majority of these studies have revealed a positive effect. Related to the direct link between patenting activities and innovation performance, e.g. the share of revenue with products new to the firm or to the market, there are fewer studies than expected. Many studies focus on patents as an indicator for innovation or on the role of the patent regime for innovation. Furthermore, the use of patents depends on the sectoral context, as they are heavily used in pharmaceuticals and biotechnology, but are deemed less effective in other industrial sectors (Cohen et al. 2000, Belezon and Patacconi 2013). However, several empirical studies reveal a positive relationship between patenting and innovation. For example, Hagedoorn and Cloodt (2003), but also Nerkar and Roberts (2004), report that the number of patents is correlated with the commercial success of new products. For incumbents in the software industry, Cockburn and MacGarvie (2009) provide evidence that patenting does not only spur product development but also buys time to commercialize their products, because of its entry-deterring effect. Despite the challenges of patenting for SMEs, Andries and Faems (2013) and Hall et al. (2013) find that it promotes the commercialization of their product innovations. Moreover, for both SMEs and large firms, the increased innovation performance, in turn, contributes to higher profit margins.

However, patents are more and more used for strategic reasons (Blind et al. 2006, Torrisi et al. 2016), like for blocking competitors, or signaling to the capital market. Therefore, the relationship between patenting and the innovation performance of firms might become blurred. However, Noel and Schankermann (2013) find no negative implications of strategic patenting, but still a positive patent premium for software firms.

Overall, patenting has a positive influence on firms' innovation performance. However, more strategic reasons to patent blur not only the link between firms' R&D activities and patenting but also between patenting and innovation performance. With these strategic patenting activities, firms try to improve their positions related to their competitors, but not necessarily their immediate returns from their innovation activities, which further complicates this link.

2.3 Standards development

Companies' decisions about their participation and eventually the disclosure of their knowledge within standardization processes depend on the expected economic impact of the standard to be developed. Following Swann (2000), three economic functions of standards can be distinguished, in addition to the disclosure and codification of knowledge. First, standards reduce the variety of technological alternatives, which allows companies to exploit economies of scale in mass production. Second, standardized interfaces of two or more components generate compatibility, which is the base for networks and network products (David and Greenstein 1990). Third, standards can help to define minimum levels of quality related to health, environmental, or safety aspects of products and processes. Consequently, market failures caused by information asymmetries can be reduced.

If we put these functions into the context of innovation, they are on the one hand drivers for innovation due to their cost-reducing impact, which can promote their market diffusion through price reduction. On the other hand, compatibility standards generate positive direct network externalities, which are crucial for the success of many communication products and services. They are also relevant for complex system innovations, like electromobility, which relies on positive indirect network externalities between electric cars and the infrastructure of charging systems (e.g. Wiegmann et al. 2017). Finally, quality standards can generate trust among consumers, thereby supporting the diffusion of innovative products, which are characterized by in general higher information asymmetries than already well-established products.

In addition to the cost of participation - mainly personnel costs and fees - and the lengthiness of standardization processes, about which participants from research organizations complain (e.g. Blind et al. 2018), the negative impacts of standards identified by Swann (2000) can also be put in the context of innovation (e.g. Blind 2016). First, the variety-reducing impact of standards might cause lock-in effects that restrict the development of alternative innovative technologies and products. Lock-in effects are even stronger in the context of compatibility standards, where they might hinder the transition into new standards based on radical innovations. Second, quality standards can be defined in such a challenging way by dominant market players that they restrict the market access by competitors, thereby reducing competitive pressure, and hence innovation. However, these negative implications of standards can be prevented by open and transparent standardization processes. Then, the positive impacts of standards and, therefore, also the participation in standardization should prevail.

Empirical studies about firms' active participation in standardization committees have been performed mainly since the new century and were always based on rather limited samples of companies, e.g. by Blind (2006), and Blind and Thumm (2004) followed by Blind and Mangelsdorf (2013) and recently by Zhang et al. (2020a) and Wiegmann et al. (2022). Only Wakke et al. (2015) connected the Dutch Community Innovation Survey with data about the involvement of the national standardization body. A positive relationship between the active involvement in standardization and innovation is revealed by Delcamp and Leiponen (2014), whereas Blind (2006), Blind and Mangelsdorf (2013), and Wakke et al. (2015) highlight an inverse U-shape between R&D, innovation, or patent intensity and firms' involvement in standardization. It is explained by the tension between absorptive capacity as a driver towards and the threat of uncontrolled knowledge spillovers away from participation. This is consistent with knowledge sourcing as the most important motive to participate in standardization identified by Blind and Mangelsdorf (2016), who further reveal that pursuing specific company interests, solving technical problems, influencing regulation, and facilitating market access act as further drivers. Expanding the only cross-sectional studies, Zhang et al. (2020b) show that involvement in standard-setting activities pushes corporate innovation in China based on patent data mainly through improving firms' R&D efficiency, reducing financial constraints, and inducing collaborative innovation. Finally, Wen et al. (2020) investigate the role of firms' position in standardization alliance networks for the speed and quality of their product innovations. In general, it is argued that the active involvement in developing standards creates a time advantage compared to those firms only implementing the standards after their release. In addition, the participants define standards according to their preferences, in particular related to their portfolio of technologies. Whereas these relative advantages for participants compared to non-participants are realized after the publication of standards, there are immediate benefits for the own innovative performance resulting from participating due to common knowledge creation and exchange with competitors, suppliers, customers, and other stakeholders representing societal interests in standards committees.

Complementary to the involvement in standardization, the implementation of standards within firms influences their innovation performance. Recently, Foucart and Li (2021) find that the use of technology standards fosters firms' incremental innovation while reducing their incentive to innovate more radically. Furthermore, the introduction of quality management schemes increases the likelihood to start innovation activities (Mangiarotti and Riillo 2014) and product innovation at least in the long run (Bourke and Roper 2017). Based on data generated by the declaration of patents to be essential for the implementation of standards, in particular in mobile telecommunication (Bekkers et al. 2002), many empirical studies harvest this growing accessible information on the combination of patents and standards. In general, they reveal a positive relationship with innovation for the owners of standard-essential patents (Rysman and Simcoe 2008).

The impact of firms' engagement in standardization on their commercial performance has not been broadly investigated. One exception is the study of Wakke et al. (2016), based on a sample of German companies. They highlight not only a positive impact of companies' general involvement but also that the intensity of engagement, i.e. the number of positions in technical committees in standardization, affects profits. The studies about the impact of standard-essential patents on firms' market values reveal mixed results (Hussinger and Schwiebacher 2015, Pohlmann et al. 2016).

So far, the literature about the impact of the involvement of firms in standardization committees on innovation performance is still limited also due to data restrictions. In summary, the majority of studies reveal a positive relationship, which seems to disappear for firms with very high R&D intensities.

2.4 Combining publishing, patenting, and standards development

After reviewing the studies on the innovation impact of publishing, patenting, and standardization, we discuss the potential relationship of their combinations with firms' innovation performance, for which little evidence is available. As a result of the nature of the different types of knowledge that is typically disclosed through these mechanisms, namely novel scientific findings and technological developments, we focus specifically on new to the market innovations in the following discussion.

Combining publishing and patenting can create conflicts related to a specific technology or invention, as the publication of specific scientific findings contributes to the existing stock of prior art making successful patent applications in the scope of the publication less likely (e.g. Holgersson and Wallin 2017). In addition, even after having successfully applied for patents, follow-up publications reduce the likelihood of consecutive patent applications. However, scientific publications represent firms' research results and relative basic knowledge (Arora et al. 2018). In contrast, patents are the output of applied research and technology development and show the industrial applicability of a firm’s knowledge. Since basic and applied research are complementary in the generation of commercial gains, their sophisticated combination can contribute in theory to firms' innovation performance. However, Arora et al. (2018) observe a declining investment of firms in basic research, which is potentially reflecting its limited impact on the commercialization of their innovations. Moreover, patents based on scientific knowledge tend to be more innovative (Sorenson and Fleming 2004). In that regard, Arora et al. (2018) show that, whereas firm publishing seems to be diminishing, the use of scientific input in inventions is increasing, especially among publishing firms. Still, disclosing potentially important knowledge for technology development can impede future patenting because of prior art, and might generate knowledge spillovers towards competitors. However, the legal protection of scientific knowledge by patents might stimulate its disclosure through subsequent publications. Hayter and Link (2021) show in that regard that a sizeable share of Phase II SBIR awardees, which represent small knowledge-intense firms, combine publishing and patenting in the commercialization of their technologies.

Tensions, in terms of the future appropriation of the generated technological know-how or inventions, should be less for firms that combine publishing and standards development because both - despite the rather different form of knowledge - contribute to the stock of prior art. They are even complementary in the sense that scientific publications are the results of more basic than applied research, whereas standards represent best practice in the commercial application of science and technology. Firms that combine both might thus achieve a wider coverage of their research and innovation outputs, than firms that exclusively publish or contribute to standards development. Additionally, doing both neither limits nor fosters the appropriation of returns from technology development due to their non-proprietary character. Publishing scientific findings does not prohibit them to be used in standardization, nor does using results in standardization processes prohibit their publication. However, similar to the declaration of patented technologies to be essential for standards, it is also possible to reference the own scientific publications in standard documents (Blind and Fenton 2022). This strategy is leveraging the diffusion of own contents in time and space as already shown by Sorenson and Fleming (2004), who analyze patents referencing scientific (peer-reviewed) or commercial (non-peer-reviewed) publications. This positive diffusion effect might even promote the firms' innovation performance, but only in the long run (see Ahuja et al. 2013).

Finally, firms combining patenting with the development of standards can experience conflicts in the short run, in particular concerning new to the market innovation. Since standardization not only involves disclosing information in standards documents but also during standardization processes itself (Bekkers et al. 2020b), it contributes - at least in the European Patent Office - to the stock of prior art in the patent examination process. After a technology enters prior art, it is significantly less likely to be patented. In that sense, contributing knowledge to standard-setting committees and technological know-how submitted to patent offices are substitutes. However, patents claimed in advance of entering technical committees can protect at the same time companies against unintended knowledge leaks in standardization processes, which is confirmed by higher patent intensities of entrants (Blind et al. 2021). In addition, in the long run, contributing firms might align their R&D activities, their patent portfolios (e.g. Berger et al. 2012), and eventually product characteristics to the standards that they contributed to, as to realize complementarities. For example, Toh and Miller (2017) find that the inclination to disclose technologies in standardization processes increases when firms' complementary technologies are less challenged by competitors. Complementary to this, Miller and Toh (2022) highlight further the relevance of the portfolio of firm-specific complementary technologies not disclosed in standardization for their returns.

In summary, the exploration of the combinations of publishing, patenting, and standard development reveals tensions between patenting and the two other disclosure practices. However, there are also opportunities by combining in particular patenting and standard development even beyond declaring standard-essential patents. Eventually, there is a lack of empirical evidence of the relationship between these disclosure practice combinations and firms' innovation performance.

3. Data

3.1. Data bases

The German part of the European Community Innovation Survey in 2015 builds the core of our sample and is extended by information from the Scopus database and the German patent office. The three datasets are matched at the firm-level based on a string matching of the firms' name and address information. The matching between the German Community Innovation Survey and the patent database is directly provided by the ZEW – Leibniz Centre for European Economic Research. Information on scientific publications is added by utilizing previous work of Krieger et al. (2021).

The German Community Innovation Survey is conducted yearly by the ZEW. It is set up as a representative sample of firms in the German manufacturing and service industries with five or more employees and concentrates on gathering information about their innovation activities and success (Peters and Rammer 2013). Next to information on innovation, the dataset also includes additional firm characteristics, such as a firm's industry classification, its revenue, or its number of employees. Most important for our analysis, there are different focus topics each year that cover supplementary questions. In the 2015 survey, standardization was such a focus topic. It is the only large-scale and comprehensive source covering the participation of German firms in standardization committees and consortia and, thus, their engagement in developing standards. The questions were not part of the European-wide Community Innovation Survey and, therefore, specific to Germany. The 2015 survey is up-to-date the first and only wave covering questions on the development of standards. Thus, it corresponds to the best available database for our investigation.

Scopus is the largest database on abstracts and citations for peer-reviewed literature. Krieger et al. (2021) identify all articles, letters, notes, reviews, and conference proceedings published by at least one author affiliated with a German firm in Scopus between 2005 and mid-2017 and match them to the Mannheim Enterprise Panel. The Mannheim Enterprise Panel is the most comprehensive firm-level database in Germany next to the official Business Register and provides the sample frame of the

German Community Innovation Survey (Bersch et al. 2014). Therefore, we are able to use their generated matching to add publication information to our sample of firms.

Patent information stems from the German Patent Office and is provided by the ZEW. Our sample covers all applications the office received within the period from 1896 to 2017. It includes information on the time of application, names, and addresses of patent applicants, application dates, and each application's international patent classification.

3.2. Variable construction

Product innovation performance – We use the share of a firm's total revenue with new or significantly improved products and services that are new to the market as a measure for product innovation performance. A product or service new to the market is defined as a product first marketed by a questioned firm. The reference year of the share corresponds to 2014, and the innovative products and services related to the share were implemented between 2012 and 2014.

Publishing – All articles, letters, notes, reviews, and conference proceedings of a firm are used to measure the publication activities of firms. To ensure comparability to our results on developing standards, we generate an indicator variable that takes the value of one if a firm published in one of the listed outlets between 2012 and 2014, and zero otherwise.

Patenting – We consider all patent applications at the German patent office as patenting activities in our analysis. Adapting again to the definition of our variable on standard development, we generate an indicator variable which is equal to one if a firm applied for at least one patent between 2012 and 2014 and zero otherwise.

Development of standards –To identify the active participation of firms in the development of new standards, we combine two yes-no statements:

i. Active participation in formal standardization committees. (yes/no)
ii. Active participation in informal standardization consortia. (yes/no)

Our variable is equal to one if a firm answered yes for at least one of the two statements and zero otherwise. Both questions relate to firms' participation between 2012 and 2014.

Controls – We estimate the relationship between engaging in publishing, patenting, and standards development practices with the revenue share of market novelties while sequentially and simultaneously controlling for factors related to our investigated practices and product innovation performance. The majority of controls and fixed effects is well established in the empirical literature and frequently used (e.g. Czarnitzki et al. 2020). Their reference year corresponds to 2014. We create indicator variables for our used continuous control variables as described in Table 1 to allow for a heterogeneous relationship between them and the innovation performance of a firm across the controls' distribution.

Innovation inputs: Firms that devote more resources to innovation activities are more likely to introduce new or significantly improved products or services. Moreover, they are more likely to engage in knowledge disclosure practices. We, therefore, control for the innovation intensity of firms measured as the amount of a firm's innovation expenditures divided by its revenues. Following the same argumentation, we also include a firm's share of employees holding a university degree.

Firm structure: Larger and older firms are associated with lower resource constraints. Thus, they are less constrained with regard to investing in innovation and allocating resources to the engagement in disclosure practices. At the same time, smaller and younger firms often introduce innovations that are more novel and use a significant amount of their recourses to protect and promote them. Thus, we control for firm size measured by a firm's number of employees as full-time equivalent and a firm's age in years. Innovation dynamics naturally differ between industries, and the development of standards, patenting and publishing naturally too. As a result, we include fixed effects for 21 industries.[2] Furthermore, the ownership structure of a firm is considered. The ownership structure influences firms' governance structures, and their access to resources. Both are related to the innovation performance of firms and the engagement in disclosure practices. Hence, we include a variable to indicate a firm's membership in a national company group, as well as a variable with regard to its membership in a multinational company group. Further, we add a variable on a firm's participation in international markets. It indicates if a firm has export revenues or not and controls for firms learning from exporting.

Market environment: In addition to the typically used control variables, we add two controls on a firm's market environment and fixed effects on its regional competition and learning possibilities. First, we create a control considering the predictability of the technological development within a firm's market, and, second, a control for the average duration of product life cycles faced by a firm. Short product life and unpredictable technological development might reduce the effectiveness of disclosure practices, whereas they might increase a firm's incentive to innovate at the same time. Both variables are based on statements on a firm's competitive situation in the German Community Innovation Survey:

i. Products/services become outdated quickly. (applies fully/somewhat/very little/not at all)
ii. The technological development is difficult to predict. (applies fully/somewhat/very little/not at all)

[2] The 21 industries are shown in Table A.1 in the appendix.

We define a variable as zero of a firm answered not at all and as one otherwise. Finally, we use state-industry fixed effects. They cover all aggregate state-specific industry differences. Thus, they control, for instance, for industry-specific agglomerations in different German states or state policies fostering individual industries.

3.3. Descriptive statistics

Our estimation sample covers 3,287 innovation-active firms. We define innovation-active firms as firms having positive innovation expenditures in 2014 or being at least occasionally active in internal R&D between 2012 and 2014. Table 1 shows the descriptive statistics of our estimation sample. Firms in the sample draw on average 4% of their revenue from products and services new to the market. Moreover, 23% of firms have positive revenues based on market novelties.

In terms of firm structure, the average sample firm has 318 employees. However, the distribution of employee numbers is skewed: the median firm has 29.5 employees, and 61% of the sample has less than 50. Only 12% of firms qualify as large by having 250 or more employees. The average sample firm is 33.9 years old, and 31% of the sample is a member of a national or multinational company group. Furthermore, 59% of our sample exports. Concerning the market environment, most firms operate in environments with fastly outdated products (70%) and a difficult to predict technological development (81%). Regarding innovation inputs, the average firm spends 7% of its revenues on innovation, whereas 23% of sample firms have no innovation expenditures. Moreover, firms' average share of employees with university degrees corresponds to 27%, and 12% of the firms in the sample report employing no employees with a university degree.

Table 1: Descriptive statistics

Variables	Mean	Median	Min.	Max.	Sdt. dev.
Product innovation performance					
Revenue share of products new to the market	0.04	0.00	0.00	1.00	0.12
Firm structure					
Number of employees in FTE	318	29.50	0.50	114,875	3602
Less than 50 (0/1)	0.61	-	-	-	-
Between 50 and less than 250 (0/1)	0.26	-	-	-	-
250 and more (0/1)	0.12	-	-	-	-
Age in years	33.90	23.00	0.50	526.00	37.96
Less than 7 (0/1)	0.08	-	-	-	-
Between 7 and less than 21 (0/1)	0.35	-	-	-	-
21 and more (0/1)	0.53	-	-	-	-
National company group (0/1)	0.15	-	-	-	-
Multinational company group (0/1)	0.16	-	-	-	-
Exporter (0/1)	0.59	-	-	-	-
Market environment					
Products become outdated quickly (0/1)	0.70	-	-	-	-
Technological development is difficult to predict (0/1)	0.81	-	-	-	-
Innovation inputs					
Innovation intensity - innvation expenditures / revenues	0.07	0.02	0.00	3.33	0.20
Intensity equal to zero (0/1)	0.23	-	-	-	-
Lower 50% percentile of firms with positive intensity (0/1)	0.38	-	-	-	-
Upper 50% percentile of firms with positive intensity (0/1)	0.39	-	-	-	-
Share of employees with university degree	0.27	0.15	0.00	1.00	0.29
Share equal to zero (0/1)	0.12	-	-	-	-
Lower 50% percentile of firms with positive share (0/1)	0.42	-	-	-	-
Upper 50% percentile of firms with positive share (0/1)	0.46	-	-	-	-

Note: Number of observations for each variable equals 3287.

Figure 1 presents the combinations of firms' engagement in publishing, patenting, and standard development practices. We observe that 74% of the sample engages in none of the three practices. Firms developing standards make up 17% of the sample, patenting firms 13%, and publishing firms 2%. Patenting and standard development practices are carried out alone more often than publishing. 58% of patenting firms do not develop standards or publish, and 69% of firms developing standards do not patent or publish. However, only 38% of publishing firms do not engage in patenting or the development of standards.

Even though patenting and the development of standards are mostly carried out alone, they are frequently combined. 39% of patenting firms develop standards, and 30% of the firms developing standards apply for patents. Publishing is used less often by patenting firms and firms developing standards. 8% of patenting firms publish, as do 5% of firms engaging in standard development.

Publishing firms, however, in most cases participate in patenting and the development of standards. 51% of publishing firms patent, 41% of publishing firms engage in standard development, and 30% of them engage in patenting and the development of standards.

Figure 1: Distribution of practices

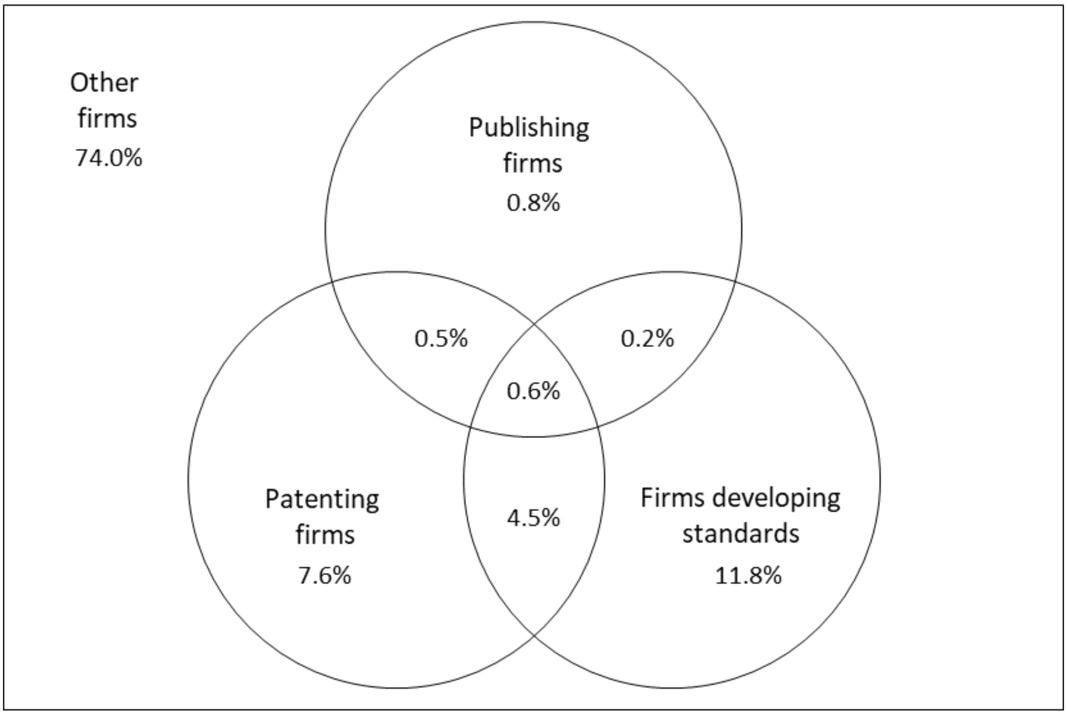

Table 2 presents firms' average revenue shares from market novelties for each combination of practices. Firms engaging in any practice combination show larger revenue shares than firms not engaging in any practices. Firms not engaging in any practices have an average revenue share of 3%. Firms that only publish show the highest shares of 11%. Moreover, revenue shares are high among firms that publish and develop standards and only patent with 8%. A similarly high share can be found for firms engaging in all three practices with 7%. Firms that patent and develop standards, firms that publish and patent, and firms only developing standards report lower shares of 6%, 4%, and 5%.

While Table 2 shows that the revenue shares from market novelties vary among the combinations of the three practices, the overall picture remains mixed. The only emerging result is that firms that do not engage in any practice have a lower revenue share on average. However, even this result needs to be interpreted with caution, as other variables driving the engagement in disclosure practices and innovation performance, such as our described control variables, are not taken into account in this descriptive comparison. Moreover, only between 8 and 26 firms engage in the different combinations concerning publishing. Thus, the samples for these practice combinations are small.

Table 2: Innovation performance by practice combination

Practice combination			Market novelty revenue share	Obs.
PUB	*PAT*	*STAND*		
0	0	0	0.03	2433
1	0	0	0.11	26
0	1	0	0.08	250
0	0	1	0.05	387
1	1	0	0.04	15
1	0	1	0.08	8
0	1	1	0.06	147
1	1	1	0.07	21

Notes: The table indicates the average revenue shares of market novelties and the number of firms within each combination of practices. The active engagement in a practice is indicated with 1. No engagement is indicated by 0.

Table 3 illustrates the importance of firms' industry affiliation by comparing the engagement in practice combinations across industries.[3] The share of firms engaging in at least one practice varies across industries. The share is highest in high-tech and medium high-tech manufacturing industries, where 49% and 45% of firms engage in at least one practice. Firms in medium low-tech and low-tech manufacturing engage less with 30% and 23%. Among firms in the high-tech knowledge-intensive services industry, 23% engage in at least one practice. The engagement is lower among other service industries, reaching 15% in knowledge-intensive market services, 13% in other knowledge-intensive services, and 5% in knowledge-intensive financial services. Firms in other industries engage to 12% in at least one practice.

Furthermore, the distribution of practices combinations differs across industries. The high-tech manufacturing industry has the largest shares of firms engaging in all practice combinations, except for only publishing and engaging in all three practices. The combination of all three practices occurs the most often in the medium high-tech manufacturing industry and only publishing in the high-tech knowledge-intensive services industry. Moreover, the three industries jointly cover the second-highest shares for all practice combinations but only publishing. The second-highest share for only publishing is covered by the industry of other knowledge-intensive services. Our results for the medium-high tech and high-tech manufacturing industry are particularly driven by the chemicals/pharmaceuticals, electronics/electrical, machinery/equipment, and vehicles industries. They strongly engage in all

[3] Table A.1 in Appendix 1 displays engagement by detailed industries.

combinations of practices. The results for the knowledge-intensive high-tech services industry are largely induced by IT/telecommunication services and technical engineering/R&D services.

In the medium low-tech manufacturing industry, patenting and standards development practices, and their combination, are relatively prevalent with an engagement share of 11%, 13%, and 5%. The same is the case for the low-tech manufacturing industry, with respectively 7%, 11%, and 4%. In general, service industries engage predominantly in standards development. Furthermore, 7% of firms in the high-tech knowledge-intensive services industry patent. Other practice combinations are relatively rare in service industries.

Table 3: Engagement in practice combinations by industry

			Practice combination							
		PUB	0	1	0	0	1	1	0	1
		PAT	0	0	1	0	1	0	1	1
	Obs.	*STAND*	0	0	0	1	0	1	1	1
Manufacturing										
High-tech	262		50.8%	1.9%	15.6%	15.6%	1.9%	0.8%	12.2%	1.1%
Medium high-tech	524		55.2%	1.0%	15.3%	14.1%	0.8%	0.8%	10.9%	2.1%
Medium low-tech	511		69.9%	0.2%	11.4%	12.7%	0.0%	0.2%	5.3%	0.4%
Low-tech	489		77.5%	0.2%	7.0%	11.2%	0.4%	0.0%	3.5%	0.2%
Services										
High-tech knowledge-intensive	346		76.6%	2.6%	6.6%	11.3%	0.9%	0.0%	1.2%	0.9%
Knowledge-intensive market	479		84.6%	0.2%	1.5%	12.7%	0.0%	0.2%	0.8%	0.0%
Knowledge-intensive financial	104		95.2%	0.0%	0.0%	4.8%	0.0%	0.0%	0.0%	0.0%
Other knowledge-intensive	48		87.5%	2.1%	0.0%	10.4%	0.0%	0.0%	0.0%	0.0%
Others	524		88.5%	0.6%	1.3%	8.0%	0.2%	0.0%	1.1%	0.2%
Total	3,287		74.0%	0.8%	7.6%	11.8%	0.5%	0.2%	4.5%	0.6%

Notes: Each cell indicates the percentage of firms in the sample that makes use of a particular practice combination by industry class.

Table 4 presents the averages of additional firm characteristics for each practice combination. Firms that engage in any practice are on average larger than firms that do not engage, and firms that combine all practices are on average the largest. The size differences seem to be the largest for firms that incorporate publishing in their practices. This is hardly surprising, as publishing implies the generation of research insights, which typically requires high investment and specific physical and knowledge assets (e.g., Simeth and Lhuillery 2015).

The observation that publishing requires high R&D investment is also reflected in the average innovation intensity. The average intensity is very high among firms that only publish and firms that combine publishing and patenting with 27%. In comparison, the innovation intensity among firms that do not engage in any practices is 6%, and the other practice combinations average around 10%. Likewise, employees in firms that publish are to a larger extent university-educated, reaching 40% of the workforce among firms that only publish, 33% among firms that publish and patent, and 43% among firms that combine publishing and standards development. In addition, publishing firms are more likely to be part of national or multinational company groups.

Concerning export behavior, the strongest difference appears to be between firms that engage in any or no practice. 51% of firms engaging in none of the three practices export. However, more than 70% of firms export in all practice combinations, whereas most shares are even above 90%. Differences related to firms' market environments are smaller. Most noticeably, firms that only publish are more likely to report that their products are outdated quickly as well as that the technological development in their market is difficult to predict.

Table 4: Firm characteristics by practice combination

	Practice Combinations							
PUB	0	1	0	0	1	1	0	1
PAT	0	0	1	0	1	0	1	1
STAND	0	0	0	1	0	1	1	1
Number of employees (FTE)	78	807	210	544	892	1468	1562	9994
Age (years)	33	36	37	37	41	22	44	53
National company group (0/1)	0.13	0.14	0.16	0.20	0.13	0.13	0.17	0.19
Multinational company group (0/1)	0.08	0.25	0.26	0.21	0.47	0.63	0.42	0.62
Exporter (0/1)	0.39	0.96	0.87	0.62	0.93	1.00	0.93	0.95
Products become outdated quickly (0/1)	0.61	0.89	0.74	0.66	0.87	0.63	0.74	0.76
Technological development is difficult to predict (0/1)	0.71	0.93	0.87	0.79	0.80	0.75	0.89	0.90
Innovation intensity	0.03	0.25	0.11	0.07	0.27	0.10	0.09	0.10
Share of employees with university degree	0.22	0.40	0.25	0.25	0.33	0.43	0.24	0.24
Observations	2433	28	272	496	15	8	149	21

Note: Each cell indicates mean characteristics of our sample firms that make use of a specific combination of practices.

4. Empirical strategy

Our empirical analysis explores the relationship between engaging in publishing, patenting, and standard development and the performance of firms' new to the market product innovations. It focuses on whether the individual practices operate as complements or substitutes. Whether organizational practices are complementary has long been of interest in the innovation literature. However, empirically testing for complementarity is challenging. Historically, testing for complementarity took an adoption or a production function approach (Athey and Stern 1998).

The adoption function approach considers conditional correlations between different practices from reduced-form regressions (Arora 1996). While straightforward to implement, it is criticized as the discovered correlations between practices might be driven by biases due to omitted variables or measurement error. Moreover, positive correlations between adopting different practices demonstrate their joint adoption, but not their complementarity in performance (Carree et al. 2011).

The production function approach explicitly considers the relationship between performance and the different combinations of practices. The approach relies on the notion of supermodularity (Topkis 1998). In the supermodularity framework, two practices x_i and x_j are considered to be complementary in a production function $f(x_i, x_j)$ if and only if $f(1,0) + f(0,1) \leq f(0,0) + f(1,1)$, where 0 and 1 indicate whether the practice is implemented (Mohnen and Röller 2005). The framework can be extended to an arbitrary number of practices, while only requiring to test pairwise combinations of practices through sets of inequalities. Mohnen and Röller (2005) develop the framework and propose a Wald test based on the critical values computed by Kodde and Palm (1986). This approach has been widely used in innovation research, among others by Bianchini et al. (2018), Cassiman and Veugelers (2006), Catozella and Vivarelli (2014), Leiponen (2005), Lucena (2011), and Resende et al. (2014).

The test proposed by Mohnen and Röller (2005) leaves a sizeable grey area in which there is no conclusion concerning complementarity. Moreover, the critical values of the test statistics are difficult to compute, and the tests are nontrivial to implement using conventional statistical software (Carree et al. 2011). As an alternative, Carree et al. (2011) propose an approach that tests for multiple inequalities but is simpler to implement. In particular, they propose to estimate an objective function $f(x_1, \dots, x_n)$ containing all individual practices and their possible interactions terms. Then, practices x_1 and x_2 are complements in the objective function if their cross-derivative ($\delta^2 f / \delta x_1 \delta x_2$) is non-negative for all values of $(x_1, \dots, x_n)$, and strictly positive for at least one value. If the cross-derivative is non-positive for all values of $(x_1, \dots, x_n)$, and strictly negative for at least one value, the practices are substitutes. This yields a set of easily testable restrictions. Moreover, Carree et al. (2011) demonstrates through Monte Carlo simulations that their test outperforms alternatives as long as the performance impact of practices is sufficiently strong. As a result, the test of Carree et al. (2011) has, particularly more recently, been used by various innovation researchers (among others: Añón Higón et al. 2017, Arvantis et al. 2015, Belderbos et al. 2006, Crass & Peters 2014, Love et al. 2014, and Sabidussi et al. 2018).[4]

We follow Carree et al. (2011) and estimate the following model to test for the existence of complementarity and substitutional relations between firms' engagement in publishing, patenting, and standard development practices:

[4] Belderbos et al. (2006) is the initial application of the method, which is then formalized in Carree et al. (2011).

$$Y_i = \alpha + \boldsymbol{\beta} f(PUB_i, PAT_i, STAND_i) + \boldsymbol{X_i}\delta + \boldsymbol{\theta_i} + \epsilon_i.$$

Y_i represents the revenue share from products new to the market of firm i. The variable PUB_i corresponds to a dichotomous variable equal to one if a firm engaged in publishing and zero otherwise. The variables PAT_i and $STAND_i$ are defined in the same manner, but target patenting and standard development practices. The objective function $f(PUB_i, PAT_i, STAND_i)$ covers the individual variables PUB_i, PAT_i, and $STAND_i$, as well as their interaction terms.[5] Following Carree et al. (2011) in their testing framework for the signs of cross-derivatives, this results in the following two testable restrictions per combination of practices in our analysis:

Publishing and patenting: R1: $\beta_{PUB \times PAT} = 0$ R2: $\beta_{PUB \times PAT} + \beta_{PUB \times PAT \times STAND} = 0$

Publishing & developing standards: R1: $\beta_{PUB \times STAND} = 0$ R2: $\beta_{PUB \times STAND} + \beta_{PUB \times PAT \times STAND} = 0$

Patenting & developing standards: R1: $\beta_{PAT \times STAND} = 0$ R2: $\beta_{PAT \times STAND} + \beta_{PUB \times PAT \times STAND} = 0$

The indices of β coefficients represent the interaction term they are related to in our model. Two practices are complements if restriction R1 and restriction R2 are both non-negative, and at least one is strictly positive. They are substitutes if restrictions R1 and R2 are both non-positive, and at least one is strictly negative. Opposing strict inequalities are inconclusive with regard to the complementarity and substitutional relations of two practices. Concerning the remaining variables in our model, $\boldsymbol{X_i}$ is a vector of control variables covering a firm's structure, innovation inputs, and market environment, $\boldsymbol{\theta_i}$ represents different combinations of industry and state fixed effects, α corresponds to the constant, and ϵ_i is to the error term. All estimations are based on OLS regressions, and standard errors are heteroscedasticity robust.[6] The significance levels of our cross-derivative tests are corrected with the Bonferroni procedure, as they are tested simultaneously in a regression model and pose multiple restrictions.

A limitation to both the Mohnen and Röller (2005) and the Carree et al. (2011) approach is that estimates need to be consistent and not otherwise affected by unobserved heterogeneity (Athey and Stern 1998). If estimates are not consistent, the conclusions concerning complementarity can be

[5] $f(PUB_i, PAT_i, STAND_i)$ covers $PUB_i, PAT_i, STAND_i, PUB_i \times PAT_i, PUB_i \times STAND_i, PAT_i \times STAND_i, PUB_i \times PAT_i \times STAND_i$.

[6] In addition, we applied fractional response models to account for the truncated nature of the outcome variable. The results remain robust.

biased. Previous studies have approached this mainly by using panel data, often applying dynamic panel methods (e.g., Arvantis et al. 2015, Bianchini et al. 2018, Leiponen 2005, Love et al. 2014, Resende et al. 2014). As a second approach for ensuring consistency, studies have applied two-step procedures to control for selection into practices (Athey and Stern 1998, Cassiman and Veugelers 2006). However, these procedures impose the challenge of finding defensible exclusion restrictions (Cassiman and Veugelers 2006, Love et al. 2014). Lastly, studies tried to obtain consistent estimates through instrumental variables (Mohnen and Röller 2005). However, only few studies have found appropriate and strong instruments (Love et al. 2014). In regard to this, Mohnen and Röller (2005) note that most instruments in the context of innovation survey data, on which we rely, are likely to be endogenous and that exogenous instruments are difficult to obtain in this context without panel data or external variation to exploit (p. 1445). Likewise, Cassiman and Veugelers (2006) conclude that instrumental variables approaches would be unlikely to yield better estimates in the absence of strong instruments and could even turn counterproductive. Love et al. (2014), for instance, apply the two-step approach of Cassiman and Veugelers (2006) through sector-level instruments. They found the results of their application implausible and decided to rely on standard regression results instead.

Our study suffers from the same limitations because our cross-sectional dataset does not allow to apply panel estimators. Even if a panel were available, however, we would have to deal with the issue that firm's choices to engage in patenting, publishing, and standard development are long-term strategic decisions that are unlikely to change in the short term.[7] Moreover, such strategic changes are hard to observe as publications, patents, and standards result from multi-year investments that are decided on long before they materialize. This does not necessarily hamper the estimation of performance effects, as long as they are driven by the resulting publications, patents, and standards. However, it makes it more difficult to model the decision to adopt these strategies as the decision remains unobserved. Thus, it is in our context even more difficult to correct for selection through observed publications, patents, and standards. We do not have access to exogenous instruments or policy shocks that affect the price of engaging in publishing, patenting, or standards development without affecting innovation performance. Thus, we rely on reduced-form estimates for our complementarity tests. We acknowledge the resulting descriptive nature of our evidence as a limitation to the study. Nevertheless, the analysis provides valuable insights by investigating the unexamined complementary and substitutional relations between different disclosure practices.

[7] Most firms contribute to standardization committees as part of longer-term commitments and are unlikely to vary in their engagement between two years. This can be seen in the very small numbers of entries into the German Standardization Body DIN based on a matching with the German Community Innovation Survey conducted in 2011 by Blind et al. (2020).

Moreover, the German Community Innovation Survey allows us to control for a variety of factors that are likely to influence practice engagement as well as innovation performance.

As a robustness check, we specify a random effects panel model. The random effects model controls for unobserved time-constant firm-level differences. However, it assumes that the unobserved firm-specific differences are uncorrelated with our practice and control variables. If this assumption is violated the estimates can be biased and inconsistent. While having restrictive assumptions, the random effects specification provides a robustness check for unobserved firm-level heterogeneity. To implement the robustness check, we add the 2014 wave of the German Community Innovation Survey to our data, and impute the values of all our practice combinations from the wave of 2015. Our results do not change in a qualitative way.

5. Results

Table 5 reports the results. Column 1 regresses the revenue share of market novelties on the three practices and their interaction terms without adding any controls. The supermodularity tests indicate that publishing and patenting are substitutes in the revenue share of market novelties ($p<0.01$), as are patenting and standard development ($p<0.05$). Thus, combining these practices does not yield a positive premium on top of the two base effects of the individual practices, but, on the contrary, decreases their joint effect on innovation performance. We find no significant complementary or substitutional relations between publishing and standard development.

In columns 2 through 6, we gradually add control variables to investigate to what extent our base findings in column 1 are confounded by firm characteristics. Column 2 controls for industry fixed effects, accounting for industry-wide differences in technology dynamics and the roles of publishing, patenting, and standards. Our supermodularity tests do not change qualitatively. The substitutional relationship between publishing and patenting remains robust ($p<0.01$). However, the substitutional relation between patenting and standards development becomes weakly statistically significant ($p<0.10$).

Column 3 controls for other firm characteristics. Medium-sized and large-sized firms draw a smaller share of their revenues from market novelties than small firms – which is likely driven by scale effects – as do medium-aged and old firms compared to young firms. Exporting firms draw a higher share of revenues from market novelties. The results of our supermodularity tests remain the same as in column 2. Column 4 controls for firms' market environment. We find that firms in markets with short product life cycles report higher revenue shares of market novelties, whereas there is no association of revenue shares with technological uncertainty. Again, our previous conclusions hold. The substitutional relation between patenting and the development of standards increases in significance compared to column 2 and 3 ($p<0.05$), whereas the significance of the relationship between patenting and publishing decreased in significance ($p<0.05$).

Column 5 controls for firms' innovation intensity and their share of highly educated employees. Compared to firms without innovation expenditures, firms with a low innovation intensity derive a 1-percentage point higher share of their revenue from market novelties, and firms with high innovation intensity derive a 5-percentage points higher share. Firms with a low share of university-educated employees do not have a higher revenue share from market novelties than firms without university-educated employees, but firms with a high share achieve a 2-percentage points higher revenue share. The substitution between publishing and patenting remains statistically significant ($p<0.05$). However, the substitution between patenting and standards development remains robust but turns weakly significant again ($p<0.10$).

Column 6 combines the controls introduced in columns 2-5. The relationships documented above remain largely robust in this specification. We find a significant substitution between publishing and patenting ($p<0.05$) and a significant substitution between patenting and standard development ($p<0.05$). Moreover, being an exporter becomes statistically insignificant, whereas having a low share of university-educated employees becomes weakly significant.

As a robustness check, we apply a random firm effects panel estimator. We add the 2014 wave of the German Community Innovation Survey to our data and impute the values of all our practice combinations from the wave of 2015. Table A2 in the appendix presents the results of the random effects estimations. Applying the random effects does not have a qualitative impact on the analysis. The relationships described before remain robust. They still indicate a substitution between publishing and patenting as well as between patenting and developing standards. However, the former turns weakly significant in one specification of this model ($p<0.10$).

Table 5: Practices and market novelty performance

Outcome: Revenue share of market novelties (0-1)		(1)	(2)	(3)	(4)	(5)	(6)
PUB (0/1)		0.08**	0.07**	0.07**	0.07*	0.06*	0.06*
		(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
PAT (0/1)		0.05***	0.04***	0.05***	0.04***	0.04***	0.04***
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
STAND (0/1)		0.02**	0.01*	0.02***	0.02**	0.01*	0.02**
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
PUB × PAT (0/1)		-0.12***	-0.12***	-0.11***	-0.11***	-0.10**	-0.10**
		(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)
PUB × STAND (0/1)		-0.04	-0.03	-0.03	-0.04	-0.04	-0.04
		(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)
PAT × STAND (0/1)		-0.04**	-0.04**	-0.03**	-0.04**	-0.03**	-0.04**
		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
PUB × PAT × STAND (0/1)		0.09	0.09	0.08	0.11*	0.09	0.11*
		(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)
Medium sized firm (0/1)				-0.02***			-0.01**
				(0.00)			(0.00)
Large sized firm (0/1)				-0.03***			-0.03***
				(0.01)			(0.01)
Medium age firm (0/1)				-0.03***			-0.03***
				(0.01)			(0.01)
Old firm (0/1)				-0.05***			-0.04***
				(0.01)			(0.01)
National company group (0/1)				-0.00			-0.00
				(0.01)			(0.01)
Multinational company group (0/1)				-0.00			-0.00
				(0.01)			(0.01)
Exporter (0/1)				0.02***			0.01
				(0.00)			(0.01)
Products become outdated quickly (0/1)					0.02***		0.01***
					(0.00)		(0.00)
Technological development is difficult to predict (0/1)					0.00		-0.00
					(0.01)		(0.01)
Low innovation intensity (0/1)						0.01***	0.01***
						(0.00)	(0.00)
High innovation intensity (0/1)						0.05***	0.04***
						(0.00)	(0.01)
Low share of employees with university degree (0/1)						0.00	0.01*
						(0.00)	(0.01)
High share of employees with university degree (0/1)						0.02***	0.03***
						(0.01)	(0.01)
Constant		0.03***	0.01***	0.06***	0.02***	-0.00	0.02**
		(0.00)	(0.01)	(0.01)	(0.00)	(0.00)	(0.01)
Industry FE		NO	YES	NO	NO	NO	NO
Industry-state FE		NO	NO	NO	YES	NO	YES
Supermodularity tests							
PUB × PAT	$\beta_{PUB\times PAT}$	SUB***	SUB***	SUB***	SUB**	SUB**	SUB**
	$\beta_{PUB\times PAT} + \beta_{PUB\times PAT\times STAND}$	NO	NO	NO	NO	NO	NO
PUB × STAND	$\beta_{PUB\times STAND}$	NO	NO	NO	NO	NO	NO
	$\beta_{PUB\times STAND} + \beta_{PUB\times PAT\times STAND}$	NO	NO	NO	NO	NO	NO
PAT × STAND	$\beta_{PAT\times STAND}$	SUB**	SUB*	SUB*	SUB**	SUB*	SUB**
	$\beta_{PAT\times STAND} + \beta_{PUB\times PAT\times STAND}$	NO	NO	NO	NO	NO	NO
R squared		0.02	0.04	0.05	0.10	0.06	0.14
Observations		3287	3287	3287	3287	3287	3287

Regression estimates are based on pooled OLS. Heteroscedasticity robust standard errors are in parentheses. The supermodularity tests follow the procedure by Carree et al. (2011). "SUB" indicates two practices are substitutes. "COMP" indicates two practices are complements. "NO" indicates no relationship between two practices. P-values correspond to * p<0.1 ** p<0.05 *** p<0.01.

7. Discussion

Our analyses based on a sample of innovation-active firms in Germany complemented by external data sources on publishing and patenting have revealed several insights. First, we show that innovation-active firms combine publishing, patenting, and developing standards to varying degrees across industries and firm characteristics. With this, we contribute to understanding the combinations of these knowledge disclosure practices as they have not been studied jointly before. Firms that combine publishing, patenting, and standard development are primarily situated in high-tech and medium high-tech manufacturing industries. While publishing is relatively common among firms in the high-tech knowledge-intense service industry, this industry is less likely to engage in patenting or standardization, most potentially due to its naturally limited patenting possibilities and its still low standardization activity. In terms of detailed industries, the phenomenon of combining practices is most common in the chemical, pharmaceutical, electronics, and machinery industries, as well as in the technical engineering, and R&D services industries. Furthermore, firms that combine practices tend to be markedly larger and more internationally oriented than firms that pursue a single practice. Across all combinations of practices, innovation intensity is high, underscoring the peculiar knowledge assets required to realize the three different practices. It also stands out that firms engaging in any of the different practices are more frequently situated in dynamic market environments, in which products become outdated quickly and technological progress is difficult to predict. In this regard, publishing of scientific results contributes to firms' freedom to operate, because it prevents competitors' to patent in their technological domain. Patenting helps to secure the own freedom to operate, and to protect the exclusive use of the patented technology. Finally, standards can stabilize the technological environment in general and in particular help to exploit the own technology portfolio (e.g. Baron et al. 2016).

Second, through regression analyses and tests for supermodularity, we show that publishing and patenting serve as substitutes in the share of revenue that innovation-active firms receive from market novelties. We also find patenting and developing standards to be substitutes, whereas there is no significant relationship between publishing and standard-setting activities. These findings indicate tensions between the proprietary disclosure of knowledge through patent documents and the non-proprietary disclosure of knowledge through publications and contributions to standard development on the firm level. Our findings, therefore, complement the already existing insights on the tensions at the technology level, e.g. related to publications by Choudhury and Khanna (2015) or related to standards by Bekkers et al. (2020b). At the same time, it is often argued that there might exist potential positive synergies between the three examined practices. We have to stress that our analysis concerns the short run and the general engagement in the three knowledge disclosure practices. The disclosure through specifically interrelated publications and patents probably yields long-term benefits that allow firms to develop more innovative and successful products. However, studying these dynamics would require much longer time series than are available. In addition, firms might only realize such synergies on the technology level, but not at the firm level, where the numerous strategic considerations related to the three practices are difficult to align and, therefore, more likely to generate conflicts. Eventually, firms' strategic disclosure of knowledge via scientific publications and the development of standards are in natural tension with their engagement in patenting. The disclosure of technological knowledge via both practices adds to the prior art and thus restricts firms' patenting possibilities despite the synergies described in the literature.

Due to the cross-sectional dataset, our analysis is descriptive, not causal, and remains on the firm and not on the technology level. Further research will be required to uncover the causal impact of choosing to pursue different disclosure practices for the appropriation of specific forms of innovation output, and the dynamics therein. Studying these phenomena on the technology or product level would be a significant extension of our analysis. However, this poses to be challenging, as data on publishing, patenting, and standards cannot easily be linked to specific technologies or products.

8. Conclusion

Our analysis contributes to understanding how combinations of publishing, patenting, and the development of standards relate to innovation success. Based on a sample of innovation-active firms in Germany, matched to patenting and publication information, we show that publishing and patenting, and patenting and developing standards, are substitutes in terms of new-to-the-market innovation performance. Because it is often argued that there are positive synergies between practices, our findings highlight less investigated negative relations between different forms of knowledge disclosure practices. However, even though we find substitutional relations between practices on the firm level, synergies might be realizable on the technology level. Nonetheless, our findings indicate that firms' strategic disclosure of knowledge via scientific publications and the development of standards are in tension with their patenting activities.

Our analysis has implications for innovation managers and policy makers. First, for innovation managers, the revealed tensions between disclosing own know-how via scientific publications or standards and patenting calls for approaches to mitigate or even solve them, e.g. by improving the timing of activities or by shaping the disclosed content in a coordinated way to avoid conflicts. Second, the question arises to what extent synergies between the three practices could be exploited while taking into account the existing tensions. Achieving this likely requires more firm-internal capacities and coordination, taking the numerous strategic considerations related to the three practices and their combinations into account.

Policy makers responsible for innovation policy should make the beneficiaries of their support programs aware of the possible combinations between publishing, patenting, and developing standards in their intellectual property management strategies and provide guidance and training to allow the exploitation of their synergies. This is especially important considering that the substitution effects documented here imply that open disclosure is costly in terms of appropriability, whereas such disclosure might generate substantial knowledge spillovers to the economy as a whole. Moreover, in most publicly funded R&D programs, the participating organizations are expected to publish the results open access. However, firms might be granted a grace period to apply for patents in advance. This option might be important to prevent innovative companies from withdrawing from such programs, as their involvement is needed to generate excellent and commercially applicable R&D results. Furthermore, the tension between patents and the development of openly accessible standards has been addressed and mostly successfully resolved via the declaration of standard essential patents in the areas of information and communication technologies, in particular mobile communication. However, this interlinkage has only slowly started to be rolled out to other technologies heavily relying on standards (e.g., Bekkers et al. 2020a). Within these technology fields, the awareness for this option has to be increased in industry, public research organizations, and standard-setting bodies. Finally, the missing tension between scientific publishing and standardization can be taken as an opportunity to push the dissemination of the former by the latter, e.g., the referencing of scientific publications in standards promotes the diffusion and the implementation of scientific knowledge into industries and other organizations implementing standards. This opportunity is not widespread and known among the scientific community, but also the funding organizations (see Blind and Fenton 2022). However, it is starting to take up, e.g., in the evaluations of the framework program of the European Commission or in the performance reporting of the German research societies.

Our research faces at least three limitations. First, our analyses are based on cross-sectional data. We have no plausible exogenous variation to test for causal relationships between the three disclosure strategies themselves or between them and innovation performance. In particular, we have no information about the specific tensions or synergies of the three approaches but are limited to comparing the average performance across their different combinations.

Second, a plausible explanation for our findings is that synergies between knowledge disclosure practices are only realizable on the level of technologies or products. However, our analysis remains on the firm level. Future research will be required to uncover the effect of pursuing different disclosure practices for the appropriation of specific forms of innovation output, and the dynamics therein. However, studying these phenomena on the product level will be challenging, as these data, in particular on scientific publications and standards, are not easily observable or linked to products. For example, it should also control for the connections between individual publications, patents and standards and include firms' organizational capacities, such as patent and standardization departments. Identifying the interrelations between individual publications, patents, and standards, however, is also not trivial (e.g. Murray 2002). As our analysis is on the level of the firm, we cannot consider the dimension of individual researchers, even though complementary to firms' strategies their individual motives and incentives play important roles, especially for corporate publishing (Furukawa and Goto, 2006), but also for patenting (Sauermann and Cohen, 2010) and standardization (Blind et al. 2022). Future research should investigate how the motives and incentives of corporate scientists influence firm-level engagement in these practices.

Third, the technological uncertainties, the competitive setting, and the regulatory framework of a firm have not been considered in-depth, even though they make the use of different practice combinations potentially more or less attractive. For example, firms might engage in standard development to influence the implementation of industry regulations in industries where generic regulations reference standards. In this regard, investigating sources of industry heterogeneity controlling for the different strategic dimensions of the three practices, e.g. common publications with research organizations by pharmaceutical companies, would have been an interesting addition to this paper. However, the distribution of the three practices was too thin and made this infeasible.

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Appendix

Table A.1: Engagement in practice combinations by detailed industry

			Combination of practices							
		PUB	0	1	0	0	1	1	0	1
		PAT	0	0	1	0	1	0	1	1
	Obs.	*STAND*	0	0	0	1	0	1	1	1
Food/beverages/tobacco	118		84.7%	0.8%	2.5%	11.0%	0.0%	0.0%	0.8%	0.0%
Textiles/clothing	125		76.0%	0.0%	9.6%	9.6%	0.8%	0.0%	4.0%	0.0%
Wood/paper	88		73.9%	0.0%	4.5%	17.0%	0.0%	0.0%	4.5%	0.0%
Chemicals/pharmaceuticals	137		60.6%	5.1%	10.2%	13.9%	0.7%	0.7%	5.8%	2.9%
Rubber/plastics	100		70.0%	0.0%	15.0%	6.0%	0.0%	0.0%	9.0%	0.0%
Glass/ceramics/concrete	72		54.2%	0.0%	13.9%	20.8%	0.0%	1.4%	9.7%	0.0%
Metals	254		73.6%	0.0%	8.7%	13.4%	0.0%	0.0%	3.5%	0.8%
Electronics/electrical	394		58.1%	0.8%	13.7%	13.5%	1.0%	0.8%	11.4%	0.8%
Machinery/equipment	260		52.7%	1.2%	18.1%	12.3%	1.2%	0.8%	11.2%	2.7%
Vehicles	96		59.4%	1.0%	12.5%	15.6%	1.0%	0.0%	9.4%	1.0%
Furniture/other manufacturing	150		67.3%	0.0%	11.3%	14.0%	1.3%	0.0%	5.3%	0.7%
Energy/mining/oil	76		85.5%	0.0%	3.9%	10.5%	0.0%	0.0%	0.0%	0.0%
Water supply/waste/recycling	104		84.6%	0.0%	1.9%	10.6%	0.0%	0.0%	1.9%	1.0%
Wholesale trade	92		88.0%	1.1%	4.3%	6.5%	0.0%	0.0%	0.0%	0.0%
Transportation/postal services	141		92.9%	0.0%	0.0%	7.1%	0.0%	0.0%	0.0%	0.0%
Printing/publishing/media	127		89.8%	0.0%	3.1%	5.5%	0.0%	0.0%	1.6%	0.0%
IT-services/telecommunications	225		82.2%	1.3%	3.1%	12.0%	0.0%	0.0%	0.9%	0.4%
Financial services	104		94.2%	0.0%	0.0%	5.8%	0.0%	0.0%	0.0%	0.0%
Technical engineering/R&D	297		72.1%	2.4%	5.7%	16.5%	1.0%	0.0%	2.0%	0.3%
Consulting/advertising	186		92.5%	0.0%	0.5%	6.5%	0.0%	0.5%	0.0%	0.0%
Business-oriented services	141		86.5%	0.0%	1.4%	11.3%	0.0%	0.0%	0.7%	0.0%

Notes: Each cell indicates the percentage of firms in the sample that makes use of a particular practice combination by industry class.

Table A2: Practices and market novelties – random effects estimations

Outcome: Revenue share of market novelties (0-1)		(1)	(2)	(3)	(4)	(5)	(6)
PUB (0/1)		0.06**	0.05*	0.06**	0.06*	0.05*	0.05*
		(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
PAT (0/1)		0.05***	0.04***	0.05***	0.04***	0.04***	0.04***
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
STAND (0/1)		0.02***	0.01**	0.02***	0.02***	0.01**	0.02***
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
PUB × PAT (0/1)		-0.10***	-0.10***	-0.09***	-0.09**	-0.09**	-0.08**
		(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)
PUB × STAND (0/1)		-0.04	-0.03	-0.03	-0.04	-0.04	-0.04
		(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)
PAT × STAND (0/1)		-0.04**	-0.04**	-0.04**	-0.05***	-0.04**	-0.04**
		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
PUB × PAT × STAND (0/1)		0.08	0.08	0.08	0.09*	0.09	0.09*
		(0.06)	(0.06)	(0.05)	(0.06)	(0.06)	(0.05)
Medium sized firm (0/1)				-0.02***			-0.01***
				(0.00)			(0.00)
Large sized firm (0/1)				-0.03***			-0.03***
				(0.01)			(0.01)
Medium age firm (0/1)				-0.02**			-0.02**
				(0.01)			(0.01)
Old firm (0/1)				-0.03***			-0.03***
				(0.01)			(0.01)
National company group (0/1)				-0.00			-0.00
				(0.00)			(0.00)
Multinational company group (0/1)				-0.00			-0.01
				(0.01)			(0.01)
Exporter (0/1)				0.02***			0.01**
				(0.00)			(0.00)
Products become outdated quickly (0/1)					0.01***		0.01***
					(0.00)		(0.00)
Technological development is difficult to predict (0/1)					-0.00		-0.01
					(0.00)		(0.00)
Low innovation intensity (0/1)						0.01***	0.01***
						(0.00)	(0.00)
High innovation intensity (0/1)						0.03***	0.03***
						(0.00)	(0.00)
Low share of employees with university degree (0/1)						0.00	0.01*
						(0.00)	(0.00)
High share of employees with university degree (0/1)						0.02***	0.02***
						(0.00)	(0.01)
Constant		0.10***	0.05***	0.10***	0.07***	0.03***	0.02
		(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
Industry dummies		NO	YES	NO	NO	NO	NO
Industry-state dummies		NO	NO	NO	YES	NO	YES
Supermodularity tests							
PUB × PAT	$\beta_{PUB \times PAT}$	SUB**	SUB**	SUB**	SUB**	SUB**	SUB*
	$\beta_{PUB \times PAT} + \beta_{PUB \times PAT \times STAND}$	NO	NO	NO	NO	NO	NO
PUB × STAND	$\beta_{PUB \times STAND}$	NO	NO	NO	NO	NO	NO
	$\beta_{PUB \times STAND} + \beta_{PUB \times PAT \times STAND}$	NO	NO	NO	NO	NO	NO
PAT × STAND	$\beta_{PAT \times STAND}$	SUB**	SUB**	SUB**	SUB**	SUB**	SUB**
	$\beta_{PAT \times STAND} + \beta_{PUB \times PAT \times STAND}$	NO	NO	NO	NO	NO	NO
R squared		0.02	0.04	0.05	0.09	0.06	0.13
Observations		5013	5013	5013	5013	5013	5013

Regression estimates are based on random effects regressions. Standard errors are in parentheses and clustered at the firm-level. The supermodularity tests follow the procedure by Carree et al. (2011). "SUB" indicates two practices are substitutes. "COMP" indicates two practices are complements. "NO" indicates no relationship between two practices. P-values correspond to * p<0.1 ** p<0.05 *** p<0.01.

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