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Innovations and productivity: the shift during the 2008 crisis

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ABSTRACT
This paper investigates how the recent crisis of 2008 changed relations between innovation and firm performance in Western Europe. We apply a structural framework of CDM modelling, which incorporates different stages of the knowledge creation process and takes into account the complex nature of innovations. The study is based on a balanced panel data of 420 listed manufacturing firms from the U.K., Germany and France. All the information is gathered from common sources, thereby reducing subjectivity, a typical problem in the field. We found, the crisis resulted in appreciable changes in the model. The most important evidence is enhancement of the role of firm resources in the post-recession period. We also reveal larger barriers for innovations, increased uncertainty and lower state dependence in R&D engagement, product creation and economic performance. These results could indicate the 'cleaning effect' of the crisis, which has worsened the business environment and enhanced competition.

KEYWORDS
Innovations; economic crisis; CDM model

JEL CODES
O31; O32; D22; D24

1. Introduction

The recent slowdown began at the end of 2008 and resulted in strong changes in the business environment and corporate behaviour. A decline in market demand, distress within the financial sector and increased macroeconomic uncertainty notably reduced firms' opportunities and incentives for innovative activity conjoined with long-term investments and high risks. Most countries and industries suffered a substantial drop in R&D expenditures and patenting in 2009–2010. There is awareness that the destructive consequences of recessions can undermine groundwork for long-term social and economic development. Thus, the influence of the crisis on innovations is an important topic for scholars and policy-makers. It is important to explore for which firms the adverse impact was more important, which will allow for outlining preferable strands of governmental policy.

Firm-level characteristics play a significant role in shaping innovation activity (Archibugi, Filippetti, and Frenz 2013a). Strong heterogeneity motivates analysis innovation at the micro-level rather than the aggregate level. A wide spectrum of studies is devoted to the impact of the crisis on corporate innovations. Researchers found that a good financial position (Paunov 2012), past innovations (Archibugi, Filippetti, and Frenz 2013a) and developed

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NIS (Filippetti and Archibugi 2011) enable maintaining innovative activity at a higher level in deteriorated conditions. Nevertheless, there remains a lack of research on the topic. Most papers consider short-run responses to shocks and omit post-crisis development. For long-term-oriented policy, we need to know what the steady changes in firms' drivers are that are linked to fundamental differences between periods. Studies generally concentrate on narrow aspects and ignore the complexity of innovations. Most of their findings relate to R&D. However, firms invest in order to invent new products and technologies and use them to provide a competitive advantage in the future. For a better understanding of R&D drivers, we also need to explore processes of knowledge generation and exploitation.

The research question of the current study is whether and how the 2008 crisis affected complex relationships between innovations and performance at the micro-level. Answering this novel question serves as the main contribution of the paper. We implement the well-known CDM approach and consider a complex model of the innovation process that includes the decision to invest in R&D, the amount to invest, the creation of new products, patenting and obtaining economic benefits. We construct two models for periods before and after the downturn, compare them and reveal intertemporal changes regarding the different aspects of firms' innovativeness.

The data-set is a balanced panel of 420 listed manufacturing companies from the United Kingdom, Germany and France for 2004–2012. The panel structure provides some advantages including the possibility to analyse the same firms in terms of their dynamics. All information was gathered from common sources that are unique for CDM models, thus reducing the subjectivity of the analysis, a typical problem for papers based on CIS surveys. The application of alternative data sources may be considered as an additional novelty of the study.

We reveal significant shifts for most aspects of innovative behaviour, especially notable for R&D and knowledge creation processes. Overall, there is an increased role of resources and the internal abilities of companies that denote their higher caution and rationality in a harsher and more competitive environment. As we explain, this is the result of the positive effect of the crisis forcing corporations to be more efficient. Negative alterations include increased uncertainty, larger barriers for innovations and the enhanced importance of financial constraints for small and young firms. These vulnerabilities should be the focus of implemented government policy.

The remainder of the paper is structured as follows. The next section (2) is a literature review that presents a review of studies concerning the recent crisis, a description of the CDM approach and the formulation of hypotheses. The data (3), model and methodology (4) are then discussed. Finally, empirical results with a discussion (5) and conclusions (6) are presented.

2. Literature review

2.1. The 2008 crisis and innovation

Global economic downturns differ in terms of how they originate and spread across countries and industries, as well as in their after-effects. An important feature of the 2008 crisis is that it was primarily engendered by imperfections in financial markets. The credit crunch in the U.S. mortgage market at the end of 2007 was followed by a recession in the U.S. economy. Under high commodity and energy prices, the crisis spread to world financial systems, affecting other countries in the second half of 2008. The downturn resulted in a drop in demand in other sectors, forcing firms to curtail production or go bankrupt. Increasing risks and high distrust among investors reduced investment opportunities. External sources of funding such as long-term credits, equity and debt issuing became quite expensive, leading to the consequent cutting of long-term programmes in 2008–2009. A survey of CFOs from different countries at the end of 2008 illustrated the important role of financial constraints, i.e. the inability to borrow external funds forced the bypassing of attractive investment opportunities (Campello, Graham, and Harvey 2010).

The crisis had a strong negative influence on innovations worldwide. Companies started to stop or reduce R&D projects in the fourth quarter of 2008. However, the most significant drop took place in 2009, when business expenditure (BERD) fell by 4.5% in the OECD area and by 3.1% in the European Union. The number of PCT patent filings reduced by 4.8% in 2009. Innovative entrepreneurship (firm creation and venture capital formation) also reduced (OECD 2012). Guellec and Wunsch-Vincent (2009) show that severe financial constraints were the main factor in the BERD decline: cash flows decreased and creditors and investors became more risk-averse. Another negative factor was the high internationalisation of some companies (such as exporters and MNEs). The pressure of the crisis was harsher for the R&D expenditures of smaller companies. The key important problems faced by European SMEs were a low demand and a lack of financial resources (Ramalho, Rodríguez-Meza, and Yang 2009).

Many countries implemented new policies focused primarily on the infrastructure for innovation, as well as financial assistance to businesses and their own investments. The profile and efficiency of policy differ across countries. Guellec and Wunsch-Vincent (2009) report that a bold policy led to positive structural changes in Finland and South Korea. OECD Outlook (2012) distinguishes the main tools such as the direct support of R&D and education, tax subsidy and support for SMEs as helping to overcome credit constraints and other difficulties. R&D in higher education (+4.8%) and government sectors (+3.8%) grew in 2009; however, this support dropped later in 2010–2011, when the budgetary crisis developed (OECD 2012, 2013).

Global recovery began in 2010, accompanied by a growth in productivity, R&D and entrepreneurship. However, the recession affected countries and industries to varying degrees and recovery processes were also unequal (OECD 2012, 2013). The decline in sales, R&D and employment was more significant for medium-technology sectors (automotive) than others. At the same time, high-technology industries (software) demonstrated on average a lower drop in sales in 2009 and positive dynamics in R&D in 2009–2010. BERD continued to grow in 2009 in some developed countries like France, South Korea and Japan, and began to recover in most European countries from 2010 (Eurostat). Rapidly developing economics (BRIICS) were also less affected. The slowdown detected the inherent weaknesses of some economies in southern and eastern Europe (e.g. Greece), and decelerated their post-crisis development.

The crisis of 2008 engendered much academic study, especially in the fields of financial markets and macroeconomics. However, the impact of the crisis on innovations at the firm level remains a poorly explored field of research. Empirical studies on this topic are presented in Appendix 1 and involve some important issues. The most popular questions relate to the determinants for innovation expenditures: why firms decided to stop investing in the recession; who are the post-crisis innovators; were the factors of investment in new conditions the same as before the crisis? (Kanerva and Hollanders 2009; Filippetti and Archibugi 2011; Laperche, Lefebvre, and Langlet 2011; Paunov 2012; Archibugi, Filippetti, and Frenz 2013a, 2013b). The estimated pure role of size and age differs across these research papers. In total, they do not prove that small and young businesses suffered more than well-established corporations. Archibugi, Filippetti, and Frenz (2013a, 2013b) show that both creative accumulation and destruction processes coexist, but that their proportion changes: younger and smaller firms relying on new market opportunities became more active in R&D after the downturn. Studies also report the impeding role of financial constraints, the positive effect of public funds (Paunov 2012) and past innovations (Kanerva and Hollanders 2009; Archibugi, Filippetti, and Frenz 2013a). These factors may explain why SMEs were more inclined to downscale or stop R&D projects. The role of international orientation was found to be ambiguous.

Another important subject relates to policy implications: is the current policy efficient in terms of supporting firm innovativeness and if not, how can authorities improve it? Filippetti and Archibugi (2011) report noticeable differences in the dynamics of innovations across European countries and relate them to distinctions of NIS. Strong national systems were useful for protecting R&D projects during the downturn. The major factors of NIS were the quality of human resources, specialisation in high technologies and a developed financial system. Hud and Hussinger (2015) investigate the role of a concrete instrument (subsidy) in supporting R&D and show than this tool stimulates activity of German SMEs. However, these subsidies were inefficient during the crisis (in 2009), because they crown out business expenditures. The effect was positive again after the recovery (in 2010), but less prominent than before the crisis.

Finally, some papers raise the question of the role of knowledge for firm performance in the new business environment. The answer appears positive: inventive strategy brings better results (Antonioli et al. 2011; Prorokowski 2014) and enhances the chances of survival (Sidorkin and Srholec 2014) in an unfavourable economic climate. On the contrary, Brencic, Pfajfar, and Raškovic (2012) found a negative effect of innovations in Slovenia; this is explained by switching of firms' attention to retaining customers and cost cutting. Cincera and Veugelers (2014) detect a post-crisis fall in the return to R&D in all countries. Antonioli et al. (2011) show that only some types of strategies such as organisational and technological innovations were efficient in Italy.

There remains a lack of studies on the topic. Most of the considered papers analyse only firms' immediate responses to the deteriorated environment and do not focus on the time of post-crisis development. Some researchers refer to this point, but their data cover the recovery period only to a small degree. They use cross sections of short panels (Archibugi, Filippetti, and Frenz 2013a, 2013b) and as such, their conclusions about intertemporal changes are not entirely reliable. The recent crisis, in spite of its financial origins, may lead to a strong and permanent structural shift in economies, deconstructing old business models and forcing the implementation of new schemes of functioning. Therefore, it is important to reveal these shifts and compare fundamental differences in innovative behaviour prior to and following the 2008 crisis. This analysis requires newer and better data encompassing a number of years during each of these periods.

Another shortcoming of the overviewed studies is that they consider narrow aspects of the innovation process and do not take into account its complexity. Factors of R&D are analysed irrespective of the expected benefits of these investments. Firms spend on R&D

in order to obtain a competitive advantage in the future. On the other hand, studies on performance simply measure the role of innovations during the crisis and ignore that firms have strong difficulties when start or continuing R&D projects. Additionally, studies (with the exception of Sidorkin and Srholec 2014) generally do not discern between the creation of knowledge and its exploitation, as is proposed in the concept of knowledge production function (Pakes and Griliches 1984). Indeed, the return to R&D depends both on the ability to generate new products and technologies, as well as the capacity to gain economic profit by employing these inventions. While the first aspect relates more to internal firm capacity, the second is connected to a greater extent with the external market and institutional conditions. Both the creation and use of innovations may be influenced by the 2008 crisis and as such, it is preferable to disentangle them. As we propose, the CDM approach addressing complexity issues is a convenient framework for analysis.

2.2. The CDM modelling framework

The analysis of relationships between innovation activity and firm performance presents several difficulties. Some scholars estimate the direct contribution of research and development (Wakelin 2001; Antonelli and Colombelli 2011); but since the start of the 1980s, scientists have perceived R&D as a firm's innovative efforts (Griliches 1979; Pakes and Griliches 1984). What really influences economic results is the innovative output created by these efforts. Thus, knowledge generation and firm performance should be separated in the analysis.

Another problem is selectivity. Some studies analyse only those firms that have formally invested in R&D. However, firms reporting zero expenses may partake in informal R&D or other investments (e.g. the purchasing of IPR) and thereby generate new knowledge (Griffith et al. 2006). Finally, R&D and inventions are endogenous because they depend on expectations about future profits and cash-flows (Griliches 1979; Crépon, Duguet, and Mairesse 1998; Jefferson et al. 2006).

All these issues are taken into account in the CDM approach based on the study of Crépon, Duguet, and Mairesse (1998; named after authors). Their structural model combines four equations: a decision about R&D, the value of R&D investments, the creation of new knowledge (patents or the sale of new products) and productivity. The main contributions of the paper are: combining separate lines of studies into one model; the addition of a selection stage to the analysis; development of a clear framework for econometric modelling; employing detailed micro-data from CIS surveys (Crépon, Duguet, and Mairesse 1998; Hall and Mairesse 2006; Lööf and Heshmati 2006). The paper by Crépon et al. engendered many studies that share a similar vision of the innovation process (Hall 2011). This system framework is known as the CDM approach.

Subsequent studies have modified the original model in such aspects as structure and the specification of equations, utilised indicators and estimation methods. Studies within the CDM approach find strong links between R&D, innovations and performance. Generally, analyses of different countries and industries yield comparable results (Janz, Lööf, and Peters 2004; Griffith et al. 2006; Lööf and Heshmati 2006; Mairesse and Robin 2009; Musolesi and Huiban 2010; Hall 2011).

Three applied econometric methods can be singled out. The first is a simultaneous analysis of equations (Crépon, Duguet, and Mairesse 1998; Mairesse and Robin 2009), which enhances the efficiency of the results but generally requires stronger assumptions about residuals and is more complicated. The second is a step-by-step procedure (Duguet 2006; Griffith et al. 2006), where the predicted values of endogenous input and output variables are used in the subsequent stages of the model. This method is much simpler. The final approach is to independently estimate each equation (Chudnovsky, López, and Pupato 2006; Jefferson et al. 2006). The advantage of suing this approach is its simplicity and flexibility; additionally, it does not require inter-equational assumptions.

Studies employing the CDM approach generally use information gained from innovation surveys, mainly CIS (Community Innovation Surveys). They provide detailed micro-data about firm activity such as various indicators of input and output, labour quality, the influence of demand and competition. The comparability of the CIS methodology makes it possible for researchers to conduct inter-country and inter-industry analyses (Lööf et al. 2001; Janz, Lööf, and Peters 2004; Griffith et al. 2006). Nevertheless, data from surveys have disadvantages such as the subjectivity of self-assessment and imprecise quantitative measures (Antonelli and Colombelli 2011). Few studies apply the CDM approach for the analysis of firms following the 2008 crisis. One exception is a paper by Sidorkin and Srholec (2014); however, this study concentrates on the immediate period of the recession and not on the recovery period. Moreover, there are no attempts at analysing intertemporal changes in the model. One reason for these gaps is that CIS data for this period is largely absent, while the lag between gathering and processing of information is significant. A second reason is that survey waves generally embrace different firms and as such, the samples are not fully comparable. CIS does not provide a well-balanced panel, which impedes dynamic analysis (Hall 2011).

2.3. Changes in drivers of innovations: hypotheses

Following the CDM approach, we consider different aspects of firm innovation activity and formulate separate hypotheses relating to them. There is a wide scope of literature on the factors of R&D, knowledge production and firm performance, and on the factors of their dynamics. However, intertemporal shift in the underlying mechanisms of innovations remain an underexplored topic and provides no clear-cut research background. Therefore, our hypotheses and arguments are based on empirical papers about the recent crisis, as well as general studies on innovations and microeconomic theory.

Financial crises worsen business environments and diminish the incentives of enterprises for investing in knowledge. There are various reasons for this: a drop in demand, an increase in input prices, low opportunities for attracting external funds and higher uncertainty, among others. Contrariwise, innovations enhance market position in an environment of heightened competition and reduce the risk of bankruptcy (Sidorkin and Srholec 2014; Fernandes and Paunov 2015), which may motivate firms to spend more.

The recent crisis could have changed corporate perception of demand. Schmookler's hypothesis of demand pull as a driver of innovations has many empirical confirmations (Scherer 1982; Kleinknecht and Verspagen 1990; Geroski and Walters 1995). Generally, researchers find pro-cyclical behaviour of R&D expenses, i.e. they are larger in upswings (Barlevy 2007; Filippetti and Archibugi 2011). However, counter-cyclical dynamics is also possible. Profit decline and sharp competition in recessions encourage seeking out new competitive practices and introducing new products and technologies (Aghion and Saint-Paul 1998; OECD 2012; Hud and Hussinger 2015). A decline in opportunities costs for innovations in a recession is lower than a drop in economic results. In this instance, it may be preferable to make long-term investments in knowledge during the crisis and obtain higher payoffs at the peak of the recovery (OECD 2012). In the case of all events, the reaction to a demand slump is the result of rational choice. March (1991) suggests that firms have a trade-off between exploitation (cost cutting) and exploration (product development). In this instance, the optimal balance between them depends on the specific features of company and the recession.

Corporate investments are sensitive to financial constraints. Internal sources are more popular for the funding of innovations (Hall and Lerner 2010). Hall (1992) shows that cash flow dynamics causes progress in R&D and this effect prevails over the demand pull. However, external sources are also important. Brown and Petersen (2009) found that public equity becomes more attractive for the financing of R&D. Bank crediting also enables freeing up internal funds for the financing of risky investments. In total, venture capital varies according to business cycles and causes pro-cyclical R&D behaviour (Lerner 2010; OECD 2012). The 2008 crisis reduced corporate internal funds through a decline in demand and profitability. It also affected financial markets and external funds: stockholders and creditors become more risk-averse and avoided high-risk projects. The negative role of financial restrictions in 2008–2009 was more considerable for smaller and younger firms. Consequently, financial position, size and age appeared to enhance the importance of R&D activity in the post-crisis time.

Research and development are long-term activities that yield unpredictable returns. Most investments in knowledge are irreversible, compared to tangible assets. Thus, higher uncertainty about the future reduces incentives for risk-adverse investors. Theoretical models show that firms both reduce investment and become less responsible to their environment in times of instability (Bloom 2007; Bloom, Bond, and Van Reenen 2007). The global character of the recent downturn enhanced a vulnerability to external shocks. In this study, we therefore suppose that the role of most drivers of R&D should be lower after the 2008 crisis.

Firm innovation behaviour tends to be persistent over time (Cefis and Orsenigo 2001) and various explanations can be put forward for this (Peters 2009). However, state dependence may weaken or strengthen as a result of external shocks. Filippetti and Archibugi (2011) found a strong persistence in some countries during the 2008 crisis and link this with the national environment. Archibugi, Filippetti, and Frenz (2013a) reveal that this steadiness had been more prominent compared to ordinary periods. This is explained by the long-term orientation of some firms (due to expensive R&D department or corporate strategy).

Hypothesis 1: The 2008 crisis has led to statistically significant changes in the role of drivers configuring corporate R&D investment.

There are some arguments for supposing that the specificity of knowledge production has changed. The first relates to a change in the structure of the research portfolio: firms tend to invest in short-term, cheaper and less risky projects. This may result in lower novelty and the lower market value of inventions. On the other hand, during recession and recovery periods, companies compete in a more difficult business environment. A recession compels them to allocate and exploit innovation inputs more rationally and efficiently. Lerner (2010) suggests that a return to venture investment is lower during boom periods, due to misleading market signals or the over-optimistic perspectives of investors.

The next discussion is connected with a balance between two Schumpeterian processes: ‘creative accumulation’ and the ‘creative destruction’. The first implies continuous growth of knowledge and competencies within the organisation. The second assumes that new inventions disrupt market balance, pushing out old products and technologies; moreover, new sectors and industries may arise. Empirical papers support both hypotheses (Breschi, Malerba, and Orsenigo 2000; Freeman and Louça 2001; Perez 2003). However, in times of turbulence, the regime of creative destruction prevails. The power relations between firms are destroyed and sectoral structure changes. This provides an opportunity to young flexible firms with new products or low-cost technologies to grow and push out other clumsy enterprises. The crisis may be propitious for the launch of breakthrough products, thereby creating new markets. This may be especially useful for smaller enterprises. Archibugi, Filippetti, and Frenz (2013b) note that older, larger corporations are less flexible and have no necessary competencies. These factors argue for possible changes in the common efficiency of invention activities and in the role of separate factors such as firm age and size.

Finally, we propose that changes in input prices and opportunity costs can lead to changes in innovation strategies. Firms may switch from expensive in-house R&D to external R&D, knowledge acquisitions or imitation. They may also rely more on ideas, capabilities and experience as embodied by personnel, technology and partners (collaboration).

Hypothesis 2: The firm’s knowledge production function changed during the crisis.

Some papers examine the stability of firm production functions over time and estimate a change in the role of R&D capital. Griliches (1986) and Rogers (2006) do not reveal significant changes in the coefficient for knowledge; however, a review paper by Wieser (2005) indicates worldwide growth in the elasticity of output to R&D from 1970s to 1990s. The drawbacks of these studies are: a direct estimation of links between R&D and performance; no explanations for possible changes; they analyse a long series of data and do not consider discrete shifts linked to concrete economic shocks.

The arguments for why the model of firm performance changed during the crisis are on the whole the same as in the case of knowledge production. Reliance on less risky and expensive strategies reduces the novelty and value of inventions, as well as their importance for economic results. On the other hand, enhanced competition has forced firms to be more efficient. Creative destruction processes has a ‘cleaning impact’ on the economy, in which poor performers exit the market, high-efficient firms entrench their own position and new entrants have a chance to gain a foothold on the market.

A firm’s economic results could depend on the macroeconomic situation and market structure, even to a greater extent than innovation output. Changes in prices, the appearance and development of new sectors, as well as government policy are possible factors that can affect the demand for economic resources in new conditions. For example, firms could gain higher benefits from knowledge due to a rise in demand for innovative low-price goods (OECD 2012).

Hypothesis 3: Firm production function changed during the crisis.

The stated hypotheses relate to typical elements of the CDM approach. However, they can be itemised in keeping with the concrete structure of the model. For example, within H1, we may distinguish changes in the participation in R&D activity and in investment intensity.

3. Data

For the purposes of the study, we decided to analyse the panel data of listed companies and use open sources of information. The reasons for this were manifold. Panel structure allows for analysing the same firms before and after the crisis, and to reveal intertemporal shifts. It also enables to account for firm specificity and persistence in innovations, to overcome the endogeneity problem and to gain more stable and reliable estimates. It is quite difficult to gather good panel data via anonymous surveys; thus, for this study, we relied on open sources offering this opportunity, i.e. commercial databases (Amadeus, Thompson, Bloomberg, Orbis), annual reports and corporate sites. Another advantage of these sources is the objectivity of their data. On the other hand, many firms do not disclose any information. For this reason, we considered only publicly traded companies, as they are transparent and well-represented in databases.

We analyse manufacturing enterprises representing the U.K., Germany and France. These are large high-innovative Western European economies that were affected by the crisis to a lesser extent. Recovery processes began in 2010; as such, we can distinguish pre- and post-crisis periods with greater certainty. Additionally, the databases contain a reasonably large number of manufacturing firms based in these countries.

The general population for our study comprises all public manufacturing companies from the three countries. In order to formulate the actual sample, we apply the Amadeus database (of Bureau van Dijk, BvD) and impose the following restrictions:

- firms from the U.K., Germany and France;
- manufacturing industry (two-digit NACE codes: 10–33);
- listed companies (at the start of 2013[1]);
- firms that were active in 2004–2012; this period of time includes some years both before and after the crisis, providing two corresponding sub-panels;
- financial statements for all years are available in the Amadeus database.

The obtained data-set includes 420 manufacturing enterprises (U.K.: 150, Germany: 135, France: 135). They were grouped by two-digit NACE classification into eight sectors: food (45 firms, 10.7% codes: 10–12), chemistry (67, 16%, codes 19–21), non-metal products (45, 10.7%, codes 22–23), metal products (31, 7.4%, codes 24–25), electrical goods (96, 22.9%, codes 26–27), machinery (41, 8%, codes 28), transport (30, 7.1%, codes 29–30) and others (65, 15.5%).

Note that our sample does not represent all firms in these countries. Public companies are relatively large and efficient. Due to the panel structure, we needed to ignore possible attrition and selection biases, as some firms went bankrupt or were reorganised during the analysed period. Consequently, the findings are conditional on firm survival. Newly listed corporations are also not included in the analysis. These are the natural consequences stemming from our data gathering conditions. Therefore, the results of our analysis may be of primary importance to innovation policy oriented towards well-established companies.

The data were split into two sub-panels: pre- (2004–2008) and post-crisis (2010–2012). As we assume the negative effect of the downturn at the end of 2008 led to immediate firm response rather than to serious structural shifts, we label this year as ‘pre-crisis’; the

[1]This is the time when we began to gather our database. After doing so, we induced minor changes.

most important alterations in the macroeconomic environment and corporate behaviour occurred later, in 2009. Despite prolonged recession in some regions, 2010 can truly be characterised as the 'post-crisis year' in highly developed economies (such as the U.K., Germany and France). Indeed, our panel is unbalanced due to missing values; however, these appear to be random (mistakes in sources or delays in disclosure) and as such, we could accept the panel as balanced.

The Amadeus database provided the largest share of financial data. For inserting missing values, we also used statements from Bloomberg, Thompson Reuters and corporate sites. R&D expenditures since 1994 were taken from Bloomberg. Patent statistics (number of patents granted) was gathered from Orbis (QPAT). Additionally, we use a spectrum of non-financial indicators that are accessible from corporate sites and in annual reports. An extremely important variable is a dummy for whether the firm reports about received awards for a new product. External recognition indicates novelty and the high value of new goods, and reflects its competitive advantages on the market. The general proxies for product innovations from surveys (dummy or innovative sales) may be imprecise and subjective. They also do not measure the quality and significance of invention. To the best of our knowledge, we are the first to apply the award for new products as a proxy for innovative output in the CDM model.

Table 1 reports the key indicators of our database. For understanding sample specificity, it also includes total statistics on the manufacturing industry in the analysed countries. We present the dynamics of key variables and their heterogeneity by country, age (younger and older firms) and size (smaller and larger firms). The final two subgroups are the result of dividing the sample by median of size (1128.5 employees) and of foundation date (1970). Definitions and descriptive statistics of all the variables are presented in Appendix 1.

A comparison with total manufacturing data shows that analysed firms are on average considerably larger and more innovative than in the industry as a whole. At the same time, there are some common features. Average productivity and personnel expenses are close, signifying a similar degree of total efficiency and quality of human resources. The dynamic patterns of indicators are also overall comparable. However, the decline in innovation indicators (R&D and patents) during the crisis was greater for our sample. Possible reasons for this are the differences in data sources, the disregarding of knowledge-intensive entrants and a larger negative effect of the crisis on public companies. In summary, we analyse relatively large and knowledge-intensive firms that in other respects reflect common features and tendencies within the industry.

Sales, employment and average labour costs in the sample demonstrate a drop in 2009, followed by growth in 2010. Decline and recovery of R&D and patent intensities is slower that can be explained by the inertness of innovation processes. The percentage of firms given awards even grew during the crisis.

Our sample is quite heterogeneous. On average, German firms are larger and more innovative. French companies have the highest productivity but the lowest level of R&D activity. English firms are smaller, less productive and to a lower degree engaged in patenting and award winning. Larger and older companies are more productive and have smaller personnel costs. They are more frequently involved in R&D, award winning and patenting. However, their average innovation intensity (in R&D and patents) is much lower than that of smaller and younger firms; this gap will increase if we correct the share of innovators.

Table 1. Key variables: dynamics, heterogeneity and representativeness.

Variable	Total	2004	2005	2006	2007	2008	2009	2010	2011	2012	U.K.	GE	FR	Y	Old	Small	Large
Sample of the study																	
Employees per firm	13,039	12,102	12,227	12,281	12,728	13,223	13,038	13,262	13,717	14,797	7569	18,172	14,165	6225	19,731	393	25,487
Sales per firm, mln Eu	3344	2780	2984	3059	3227	3371	3089	3537	3900	4168	1817	5298	3092	1658	5002	111	6571
Sales per empl., th Eu	247.1	212.8	229.4	240.0	257.9	253.9	227.4	255.5	274.1	273.6	203.4	255.9	288.3	234.6	259.4	243.3	250.9
Personnel costs per empl., th Eu	48.4	44.0	46.9	48.8	48.5	46.3	46.7	49.4	51.3	53.6	46.4	52.3	46.7	51.5	45.3	52.2	44.6
R&D per empl., th Eu	9.6	6.1	10.9	10.9	11.8	11.3	9.8	7.6	8.5	9.0	11.0	13.6	3.9	15.5	3.7	13.5	5.7
Firms with new patents granted, %	44.9	–	46.2	44.3	46.0	45.0	42.9	45.2	43.6	45.7	32.6	55.0	48.3	44.1	45.6	30.7	59.0
Patents per 1000 empl.	7.0	–	7.8	8.5	7.3	7.7	7.0	6.6	4.9	6.3	10.3	4.7	5.5	8.4	5.6	11.3	2.8
R&D investors, %	57.1	52.4	55.7	55.7	58.6	59.5	60.2	59.5	57.9	54.3	62.9	67.3	40.4	56.1	58.1	44.6	69.6
Firms with awards, %	16.2	10.2	12.6	13.6	14.8	18.1	20.0	18.6	21.9	15.7	8.1	24.0	17.3	14.3	18.0	11.4	20.9
Total manufacturing																	
Employees per firm	23.2	23.1	22.9	24.0	23.8	23.7	23.5	22.4	23.1	22.7	21.2	34.4	14.5	–	–	–	–
Sales per firm, mln Eu	5.88	5.19	5.41	5.83	6.07	6.39	5.54	5.80	6.41	6.40	4.66	8.82	4.00	–	–	–	–
Sales per empl., th Eu	253.2	224.5	236.2	242.7	255.4	270.3	235.9	258.8	277.9	282.5	219.5	256.5	276.0	–	–	–	–
Personnel costs per employee, th Eu	44.8	42.35	43.47	43.23	44.10	45.78	44.76	45.52	46.35	48.36	36.6	47.5	46.3	–	–	–	–
R&D per empl., th Eu	5.06	–	–	–	4.59	4.98	4.92	4.99	5.28	5.64	2.96	6.03	4.72	–	–	–	–
Patents in the industry per 1000 empl.	2.77	2.56	2.77	2.77	2.78	2.85	3.02	2.97	2.92	2.34	1.82	3.28	2.53	–	–	–	–

Notes: The table represents the mean values of variables. Financial indicators are expressed in Euro (nominal values). The data on general population was taken from www.ec.europa.eu/eurostat/data/database. We use data for the total manufacturing firms in Germany, the U.K. and France. Relevant average values are obtained as simple ratios of aggregated measures (sales, R&D expenditures, number of employees, etc.). This contrasts the case of our sample (upper part of the table), where we calculate relative measures for each firm and then find mean values. However, we experimented with alternative methods of averaging and reveal no serious differences.

Table 2. Persistence in innovations in the sample for 2005–2012 (observations).

	R&D doing			Innovation awards			Patenting		
$t-1$	Yes (t)	No (t)	Total	Yes (t)	No (t)	Total	Yes (t)	No (t)	Total
Yes ($t-1$)	116	1.314	1.430	331	214	545	1.112	203	1.315
No ($t-1$)	1.822	108	1.930	237	2.578	2.815	201	1.424	1.625
Total	1.938	1.422	3.360	568	2.792	3.360	1.313	1.627	2.940

Notes: 2004 was excluded as a starting period (it enters as a lagged value in 2005). For new patents we exclude the two first years, because by definition, this value is the difference in the number of total patents granted.

The innovative activity of firms in the sample is extremely persistent, especially for involvement in R&D. Transition matrices for R&D, awards and patenting are shown in Table 2. The degree of persistence appears to be higher than in other papers (Cefis and Orsenigo 2001; Peters 2009; Huergo and Moreno 2011). Perhaps this stability is a feature of large public companies. Regardless, we take it into account in our methodology.

4. Model and methodology

The empirical part of the study is based on a complex analysis of various aspects of firms' innovation activity. The model consists of five equations (1)–(5):

$$R\&D\ doing_{it} = \begin{cases} 1 & \text{if } R\&D\ doing^{*}_{it} = X_{1it}\beta_1 + \varepsilon_{1it} \geq 0 \\ 0 & \text{if } R\&D\ doing^{*}_{it} = X_{1it}\beta_1 + \varepsilon_{1it} < 0 \end{cases} \quad (1)$$

$$R\&D\ intensity_{it} = \begin{cases} \log\left(R\&D\ intensity_{it}\right) = X_{2it}\beta_2 + \varepsilon_{2it} & \text{if } R\&D\ doing_{it} = 1 \\ NA & \text{if } R\&D\ doing_{it} = 0 \end{cases} \quad (2)$$

$$Awards_{it} = \begin{cases} 1 & \text{if } a_{R1}\log\left(R\&D\ Capital\ Intensity_{it-1}\right) + X_{3it}\beta_3 + \varepsilon_{3it} \geq 0 \\ 0 & \text{if } a_{R1}\log\left(R\&D\ Capital\ Intensity_{it-1}\right) + X_{3it}\beta_3 + \varepsilon_{3it} < 0 \end{cases} \quad (3)$$

$$Patents_{it} = \exp\{a_{R2}\log(R\&D\ Capital\ Intensity_{it-1}) + X_{4it}\beta_4 + \varepsilon_{4it}\} \quad (4)$$

$$Q_{it} = a_A Awards_{it-1} + a_P \log(Patent\ Intensity_{it-1}) + X_{5it}\beta_5 + \varepsilon_{5it} \quad (5)$$

where X_{1it}–X_{5it} are control variables, β_1–β_5 are coefficients and ε_{1it}–ε_{5it} are errors in equations. The latent variable $RD\_doing^{*}_{it}$ in (1) determines whether a firm will invest in R&D, while RD_doing_{it} is the observable dummy for actual investment. Conditional on investing in R&D of i-th firm, we observe innovative intensity $R\&D\ intensity_{it}$ measured by logarithm of R&D expenses per employee. Equations (3) and (4) are knowledge production functions. We apply two variables for innovative output: number of granted patents $Patents_{it}$ and award for product innovation $Awards_{it}$. The first defines protection of recently generated

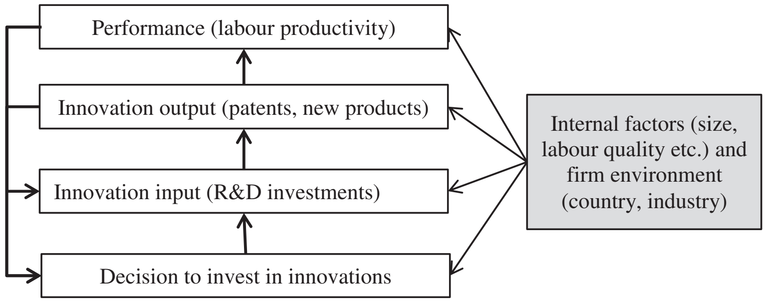

Figure 1. Diagram of the model of the study.

knowledge; the second reflects the creation of revolutionary products. Innovation functions depend on R&D capital, which is a stock of past expenditures (see Appendix 2). Both outputs imply competitive advantages for a firm. Equation (5) shows the impact of outputs on firm performance Q_i (labour productivity or sales per employee in logarithm). R&D stages involve possible feedback effects from (3) to (5). Our model is visualised in Figure 1.

We estimate two models (1)–(5) for periods before and after the crisis. We then compare them and explore how each step of transforming corporate innovativeness into performance has been changed by the recent crisis. The system approach allows for analysing shifts in different aspects of knowledge creation as one complex.

For simplicity and flexibility, we follow Chudnovsky, López, and Pupato (2006) and Jefferson et al. (2006) and estimate equations (1)–(5) separately. Important problems in the estimation are endogeneity, unobserved individual effect and the high persistence of dependent variables. For reducing endogeneity, we use the lagged values of all factors in regressions with the exception of strictly exogenous factors (location, age, country, sector and year). High persistence of both inputs and outputs in innovations may be due to true state dependence. Identification of production function with omitted factors also requires the inclusion of a lagged dependent variable. Estimation of dynamic models requires the use of special techniques. For continuous indicators (R&D intensity and productivity), we can apply system GMM. Despite additional assumptions, system GMM appears to be preferable, as it performs better with highly persistent variables (Bond 2002). An additional issue in non-linear dynamic models is the initial conditions problem. For some types of these models (probit and Poisson), it is possible to implement the approach of Wooldridge (2005). This is based on specifying the individual effect on initial conditions of the dependent variable and can be estimated as a random effect model. We adopt this approach and estimate equations for *R&D doing*, *Awards* and *Patents*.[2]

[2]Wooldridge proposed specifying the errors as $\mu_{it} = \alpha y_{i0} + \beta X_c + \xi_i + \varepsilon_{it}$ where y_{i0} is the initial condition, X_c are time-invariant factors, ξ_i is individual random effect and ε_{it} is idiosyncratic term. Our approach slightly differs, because we exclude mean values of time-variant factors βX_c. This decision is motivated by the high persistence of these variables and the sample size. Double influence of the same factors (directly and indirectly via individual errors) can lead to multicollinearity issues. This simplification is not crucial for estimation as the highest share of persistence appears to be connected with the initial condition of the dependent variable (inherent innovativeness). Note that coefficients by factors include both direct and indirect effects.

Equation (1) is estimated by random effect probit model with *lagged R&D doing* and *initial condition* effect.[3] For R&D intensity (2), we apply system GMM with *lagged dependent variable* and *inverse Mills' ratio* obtained from (1). The final term corrects for possible selection bias. An extended set of control variables for both investment equations is common. *Location in capital city* relates to the external environment and innovative infrastructure. *Association* is linked with opportunities of cooperation and related spillovers. *Productivity*, *Patent dummy* and *Award* display feedback effects from past results. Three variables indicate the financial state of the company: *Equity*, *Liquidity* and *Profitability*. The experience has shown that financial limitations were significant obstacles for R&D during the crisis. As in most of the following models, we include *Age* and *Size*, which are mostly responsible for firm heterogeneity. Due to the discreteness of R&D doing and the high persistence of investment, we worry about multicollinearity and unreliable estimates of (1) and (2). Therefore, we perform preliminary analysis on the full sample and exclude variables on the ground of low significance or high correlation with other factors.

There is ambiguity about the persistence effect for innovative output. There is possible true state dependence in inventions. The steadiness and long-time effect of inputs also contribute to higher persistence in output. R&D capital comprises long series of past investments and its application enables disentangling these effects. This contrasts the view of Huergo and Moreno (2011), which distinguish between recent R&D expenses and lagged output; in their case, the lag also captures the long-term impact of investments. Ignoring state dependence can lead to overestimating coefficients. Nevertheless, we are also concerned about the possible multicollinearity issue caused by low within variance of factors. Even if lagged output is not important, it is dependent on almost the same values of variables. This may lead to underestimation bias. Thus, we estimate two alternative models for patents and awards: with and without state dependence. Factors of innovative functions (3) an (4) are the same. In addition to lagged output and initial value, they include *R&D capital intensity*, *Labour quality*, *Capital intensity*, *Size* and *Age*. Personnel and physical assets are resources enabling invention or absorption of external knowledge. Moreover, people, production plant and equipment may embody new ideas within themselves. Models of awards and patents are estimated by MLE (probit and Poisson regressions with random effects).

Note that productivity equation is the transformed Cobb–Douglas production function with possibly endogenous individual effect. Factors in (5) are lagged *Productivity*, innovations, *Labour quality*, *Capital intensity* and *Size*. Four specifications are considered with different innovation variables: *Patents*, *Award*, both *Patents* and *Award* and *R&D capital*. The last version is analysed, because *Patents* and *Awards* may be too noisy proxies for valuable knowledge. The equation is estimated by system GMM.

The paper focuses on analysis of the most common changes in companies and disregards a particular specific in national innovation systems. A number of empirical studies have found common patterns in structural innovation models across Europe (Janz, Lööf, and Peters 2004; Griffith et al. 2006). However, we apply a set of country dummies to control for country heterogeneity. For the same reason, we involve sector and year dummies in all equations.

[3]Initial conditions for analysed subsamples are different. They are measured as values of 2004 (R&D and awards) and 2005 (patents) for the pre-crisis models and values of 2009 (all variables) after the crisis. These conditions are stacked into one variable in the testing models. Preliminary models of R&D doing involve values for 2004.

All factors are typical for studies using the CDM approach. However, we do not directly use some usual indicators, as they are not available in open sources. For example, R&D equations do not include competition level, technology push and market pull. However, we believe that the real influence of omitted variables is well-captured by individual effects, exogenous dummies (country, sector and year specific) and lagged dependent variables.

We employ the logarithms of some factors in order to normalise them and reduce the influence of outliers. There is the question of how to treat zero values of *Patents*, *Patent intensity*, *R&D intensity* and *R&D capital intensity*. To overcome this issue, we assign a small number log (0.0001) to these observations and create additional dummies for non-zero values.

Specification of the model (1)–(5) allowed us to concretise earlier hypotheses. As we propose, the crisis has led to significant changes in the role of drivers, i.e. affecting firm decision to invest in R&D (H1a), R&D intensity (H1b), product creation (H2a), patenting (H2b) and productivity (H3). Analysis of intertemporal shifts is based on combined regressions ('testing models') estimated on the sample, made by the pooling of both sub-periods. Interaction terms between variables and dummy for the post-crisis period is responsible for change in the role of factors. We perform two Wald tests and check for joint insignificance of interaction terms in testing models. The first test examines a joint change with respect to all factors. Note that these include constant, country and sector dummies, which primarily capture environment, that is, institutional framework and economic conditions. Additionally, these variables absorb the influence of omitted variables (e.g. price level), which we were unable to fully control. Thus, we use a second test considering only firm-specific observable determinants. In the context of a micro-level study, the analysis of individual features has higher priority. Both testing models can suffer from a large number of interaction terms. We then conjoin statistical tests with the simple visual analysis of coefficients and marginal effects.

5. Results and discussion

Estimation results of all models are summarised in Tables 3–7. The selection stage is presented first (Table 3). Columns 1–2 correspond to the preliminary analysis of the entire sample (2005–2012). The extended equation includes all possible factors. Additional low-significant variables were not used in order to reduce multicollinearity; however, we retained the *Equity* (financial constraints) and *Productivity* (feedback) factors for economic reasons. Crucial factors for the decision to invest are similar for both periods (columns 3–4) and they include past engagement in R&D (+), initial condition (+) and size (+). However, their role has noticeably changed. The decision to invest in 2010/12 became more dependent on initial conditions (year 2009) and individual effects than on recent history. In other words, investors in the post-crisis time are probably the same firms that did not halt projects during the recession. Larger firms suffered to a lower extent and their incentives to invest were enhanced after the crisis. There is a visible (albeit not significant) growth for the *Equity* coefficient. Internal sources became somewhat more suitable for funding R&D.

Preliminary analysis of R&D intensity equations on the full sample (Table 4, columns 1–3) shows sensitivity to the econometric method. System GMM allows for overcoming the bias caused by lagged intensity and non-zero correlation of individual effects with factors. Variables with low explanatory power (*Association*, *Capital* and *Equity*) were omitted later. Models for both periods have very similar coefficients of firm-specific factors. Current

Table 3. Selection equation.

Variable	RE probit (extended)	RE probit (reduced)	Model of the study (RE probit)		
			2005/2008	2010/2012	Change
R&D doing ($t-1$)	0.643*** (0.057)	0.645*** (0.057)	0.648*** (0.085)	0.451** (0.212)	−0.259** (0.102)
Initial condition: R&D doing	0.609*** (0.090)	0.621*** (0.090)	0.510*** (0.128)	1.032** (0.421)	0.448*** (0.109)
Association ($t-1$)	0.063 (0.057)				
Capital city	−0.023 (0.061)				
Size ($t-1$)	0.093*** (0.019)	0.089*** (0.017)	0.060*** (0.018)	0.087*** (0.026)	0.031* (0.019)
Age	−0.051 (0.035)	−0.058* (0.035)	−0.045 (0.034)	−0.016 (0.044)	0.014 (0.042)
Equity ($t-1$)	0.118 (0.115)	0.132 (0.106)	0.062 (0.115)	0.289* (0.175)	0.149 (0.152)
Liquidity ($t-1$)	0.171 (0.172)				
Profitability ($t-1$)	−0.114 (0.144)				
Productivity ($t-1$)	0.027 (0.034)	0.018 (0.033)	0.021 (0.036)	−0.030 (0.046)	−0.033 (0.045)
Patent dummy ($t-1$)	0.000 (0.045)				
Award ($t-1$)	0.036 (0.057)				
Observations	3291	3291	1635	1238	
Pseudo R^2	68.59%	68.50%	72.16%	73.35%	
Correct predictions	90.19%	90.28%	91.25%	93.86%	

Notes: Figures are marginal effects, parentheses contain standard errors. All equations include a constant, country and sector dummies. The final column contains interaction terms between factors and a post-crisis dummy in the testing model.

*Significance at 10%.

**Significance at 5%.

***Significance at 1%.

Table 4. Innovation intensity equation.

Variable	OLS	FE	GMM system	Model of the study (GMM system) 2005/2008	2010/2012	Change
R&D intensity ($t-1$)	0.841*** (0.026)		0.400*** (0.087)	0.328*** (0.113)	0.366 * (0.205)	0.003 (0.225)
Dummy for R&D intensity ($t-1$) > 0	−8.476*** (0.331)		−4.142*** (0.947)	−3.514*** (1.191)	−3.949* (2.291)	−0.220 (2.439)
Association ($t-1$)	0.060 (0.038)		0.142 (0.101)			
Capital city	−0.033 (0.033)		−0.078 (0.093)			
Size ($t-1$)	−0.006 (0.011)	−0.248** (0.115)	−0.019 (0.028)	−0.044* (0.026)	−0.012 (0.032)	0.022 (0.029)
Age	−0.023 (0.021)		−0.103* (0.053)	−0.102* (0.057)	−0.126 (0.077)	−0.024 (0.057)
Equity ($t-1$)	0.002 (0.105)	0.175 (0.270)	0.326 (0.241)			
Liquidity ($t-1$)	0.853*** (0.178)	0.637*** (0.228)	1.593*** (0.364)	2.023*** (0.466)	1.984*** (0.690)	0.142 (0.689)
Profitability ($t-1$)	−0.550** (0.220)	−0.384 (0.250)	−1.033*** (0.383)	−1.286*** (0.396)	−1.103** (0.463)	0.155 (0.480)
Productivity ($t-1$)	0.119*** (0.044)	−0.075 (0.070)	0.325*** (0.103)	0.418*** (0.152)	0.351** (0.150)	−0.046 (0.169)
Patent dummy ($t-1$)	0.114*** (0.037)	0.029 (0.035)	0.158** (0.063)	0.284*** (0.082)	0.129 (0.079)	−0.131 (0.091)
Award ($t-1$)	0.054 (0.038)	0.019 (0.024)	0.122*** (0.047)	0.105 (0.068)	0.180*** (0.070)	0.091 (0.085)
Inverse Mills' ratio	−0.044 (0.091)	−0.052 (0.075)	−0.119 (0.168)	−0.273 (0.254)	−0.198 (0.275)	−0.064 (0.359)
Observations	1894	1894	1894	937	706	
R^2	83.30%	5.96%	75.38%	70.27%	77.63%	
Hansen test			40.99%	94.96%	30.41%	

Notes: Robust errors are Windmeijer corrected for finite sample bias. Instruments include 2–3th lags of intensity and of R&D dummy and all control variables. Hansen test is for equations in first differences. . .
*Significance at 10%.
**Significance at 5%.
***Significance at 1%.

Table 5. Innovation function: awards.

	Model 1 (state dependence)			Model 2		
Variable	2005/2008	2010/2012	Change	2005/2008	2010/2012	Change
Award ($t-1$)	0.082** (0.034)	−0.012 (0.018)	−0.044* (0.025)			
Initial condition: Award	0.146*** (0.027)	0.157*** (0.041)	−0.032 (0.031)			
R&D capital intensity ($t-1$)	0.009 (0.006)	0.021*** (0.008)	0.014* (0.008)	0.010** (0.005)	0.025*** (0.008)	0.007 (0.005)
Dummy for R&D capital ($t-1$) > 0	−0.082 (0.069)	−0.210** (0.088)	−0.129 (0.092)	−0.105* (0.055)	−0.232*** (0.090)	−0.050 (0.059)
Labour quality ($t-1$)	0.008 (0.019)	0.015 (0.020)	0.016 (0.027)	0.012 (0.013)	0.018 (0.020)	0.008 (0.018)
Capital intensity ($t-1$)	0.007 (0.010)	−0.011 (0.010)	−0.024** (0.012)	0.006 (0.007)	−0.008 (0.010)	−0.021** (0.009)
Size (t-1)	0.007* (0.004)	0.019*** (0.006)	0.014*** (0.006)	0.009** (0.004)	0.021*** (0.007)	0.009** (0.004)
Age	−0.002 (0.009)	0.004 (0.010)	0.004 (0.011)	0.002 (0.006)	0.000 (0.010)	−0.001 (0.007)
Observations	1616	1219		1616	1219	
Pseudo R^2	44.93%	34.88%		40.20%	28.36%	
Correct predictions	86.76%	83.35%		88.06%	83.76%	

*Significance at 10%.
** Significance at 5%.
***Significance at 1%.

Table 6. Innovation function: patents.

	Model 1 (state dependence)			Model 2		
Variable	2006/2008	2010/2012	Change	2005/2008	2010/2012	Change
Log of patents ($t-1$)	0.143*** (0.035)	0.198*** (0.035)	0.448*** (0.119)			
Dummy for patents ($t-1$) > 0	0.064 (0.197)	−0.231 (0.170)	−1.102** (0.525)			
Initial condition: log of patents	1.027*** (0.107)	0.946*** (0.110)	−0.330*** (0.109)			
Initial condition: patent dummy (patents > 0)	2.155*** (0.306)	2.310*** (0.330)	−0.402 (0.544)			
R&D capital intensity ($t-1$)	0.287*** (0.054)	0.457*** (0.083)	−0.796*** (0.121)	3.932*** (0.750)	5.594*** (1.077)	−10.110*** (1.807)
Dummy for R&D capital ($t-1$) > 0	−2.794*** (0.623)	−4.821*** (0.993)	10.095*** (1.545)	−39.84*** (7.89)	−73.25*** (14.45)	124.30*** (22.26)
Labour quality ($t-1$)	−0.376*** (0.099)	−0.210* (0.112)	2.619*** (0.396)	−1.551*** (0.515)	−0.218 (0.716)	24.461*** (4.428)
Capital intensity ($t-1$)	0.050 (0.053)	0.248*** (0.090)	−0.207*** (0.054)	0.673 (0.475)	3.033*** (0.876)	1.162*** (0.418)
Size ($t-1$)	0.177*** (0.047)	0.443*** (0.077)	0.234*** (0.047)	3.465*** (0.523)	7.302*** (1.301)	2.920*** (0.529)
Age	−0.605*** (0.121)	−0.724*** (0.173)	−0.722*** (0.129)	−13.582*** (2.630)	−9.937*** (2.577)	−7.052*** (1.377)
Observations	1216	1219		1616	1219	
Log likelihood	−2575.6	−4112.9		−3945.5	−4267.7	

*Significance at 10%.
** Significance at 5%.
***Significance at 1%.

intensity is positively influenced by past R&D doing and intensity. Negative signs of R&D dummies only show that the arbitrarily chosen value of intensity for zero investments log (0.0001) underrate the role of these observations. The factors *Size* and *Age* have a slight negative effect, slightly more perceptible that before the crisis. As expected, financial constraints (*Liquidity*) are an important hampering factor. Contrarily, the negative impact of *Profitability* has no clear interpretation. Higher earning power leads to better financial opportunities. On the other hand, it may denote low competition and a soft environment, which disincentives the drive to innovate. We found a positive effect of past *Productivity*, which captures effects of internal efficiency and market demand. Positive feedback effects from the *Patent dummy* (pre-crisis) and *Award* (post-crisis) denote that companies may start or continue R&D projects orientated towards achieved success. The insignificance of *IMR* is unexpected and not in line with previous papers. Selectivity did not have an effect on the analysed firms; one possible reason for this is the decision to begin R&D and the choice of investment level, depending on various unobservable factors. A less agreeable reason is the data source. Firms may invest in R&D but randomly report doing so in financial statements. No visible changes were observed in the role of all the noted factors, but the equation altered considerably with regard to country dummies (not presented), emphasising the importance of NIS. German and French firms experienced a larger drop in R&D due to unobservable country specifics than the U.K. companies.

Models of innovative awards (Table 5) with and without lagged variables led to close results; however, the inclusion of past awards greatly reduces a quantitative effect and the significance of other factors. There is a decline in *Lagged Award* alongside a slight growth in the role of *Initial Conditions*. *R&D capital intensity* is an important factor. Moreover, the effect of investment increases after the crisis. A number of explanations can be suggested for this. Firms may be more careful and rational in their choice of new projects. However, note that R&D capital consists mainly of fairly old expenses. Alternatively, firms become more successful in the exploitation of their current knowledge base. Despite negative signs by *Dummy of R&D capital*, the pure effect of input is positive. A decline in this variable indicates that a low level of R&D activity becomes less beneficial. *Capital intensity* is insignificant in both periods; however, we observe a degree of drop in appropriate marginal effects. *Labour quality* is not a prominent factor in any instance. *Size* is important for product innovation and its role increased. This may be linked to larger opportunities for big enterprises for cooperation, investment in training, informal innovations and knowledge acquisition, among others.

In summary for the creation of breakthrough products, firms in the post-crisis time need to rely more on their own innovative efforts and internal capacity than on past achievements and knowledge embodied in physical assets. The diminished quality of model fit may be charged to increased common uncertainty.

Estimates of marginal effects from patent equations (Table 6) are similar in both models, but the values in the dynamic version are lower in magnitude. As in the award functions, the *Initial conditions* are much more important that recent efforts (*Lagged patents*). Patent granting is also subject more specifically to recent knowledge protection than to internal ability. In contrast, however, there is moderate enhancing of state dependence via growth of *Lagged Patents* and a decline in *Initial Patents*. The drop in effect by the *Patents Dummy* denotes that low activity will complicate patenting in future.

The role of R&D is significant and strengthens following the crisis. Due to the long-term effect of investment and slow granting procedure, we assume the consequence of this to be the better ability of companies to exploit current knowledge and transform it into ultimate outcomes. As in the case of awards, a strong drop in *R&D capital dummy* denotes that output decreased for firms with low level of innovative activity. *Labour quality* has a negative sign in models that are difficult to interpret clearly. The average quality of personnel may be irrelevant, while research activity is often concentrated in small divisions. Another explanation is that protecting ideas is more beneficial for firms with lower human capital and invention ability. *Capital intensity* is a crucial factor following the crisis. Increased role of *Labour quality* (less negative) and *Capital intensity* may denote that firms are better able to exploit their own resources. As in the case of awards, there is high and growing importance of *Size*. The negative effects of *Age* may signify that younger, flexible firms have higher and increasing incentives for IPR protection.

These estimates are not, however, entirely satisfactory for two reasons. Marginal effects by some variables (labour quality, age, size) contradict the preliminary observations of descriptive statistics. For example, *Labour quality* has a strong positive correlation with patent variables, but its impact is negative. Another challenge is that estimated changes in the testing model do not match to real difference in effects (Table 6). Thus, previous conclusions about shifts were based on simple visual comparisons. Count models with overdispersion are sensible to assumptions; we therefore experimented with alternative specifications and techniques (fixed effects, normal distribution of effects, linear feedback model and second lags of factors), but the results remain similar. Our explanation for this dilemma is a time-variant behaviour of individual effects and changing variance, which require more sophisticated methods.

Estimations of productivity equations are presented in Table 7. In summary, these results depend slightly on utilised knowledge indicators. Regardless of the proxy applied, it is insignificant in all models, as well as its changes. Experiments with other instruments and specifications (longer lags, exclusion of state dependence, etc.) yield similar coefficients by R&D and award and patents (not shown). Some explanations are possible. First, innovations may be an unimportant driver of success for large public enterprises. Secondly, the applied proxies of knowledge or performance are imperfect. Finally, our sample is not very large and therefore not wholly representative.

Past productivity is a positive and significant factor only in the first period. As in the case of R&D and awards, we again found a drop in true state dependence following the downturn. Moreover, this effect disappeared. The exacerbated business environment led to faster market dynamics; thus, firms needed to regularly prove their own competitive capacity. *Labour quality* and *Capital intensity* are important in most models. Their role, especially in terms of human quality, became more prominent in the post-crisis period and as a result, firms derive more benefit from their own resources. *Size* is not a significant factor in any instance.

In conclusion, the strong decline in the forecasting power of all models should be noted. This relates to the growing volatility of real and financial markets. Another reason is the enhanced importance of uncovered factors of economic success.

Table 8 presents statistical tests of joint changes in the model. Results of test №1 show strong differences in each stage of the innovative process with the exception of productivity equation. However, test №2 indicates that internal drivers of R&D intensity and performance

Table 7. Productivity equations.

Variable	Model 1 (patents)			Model 2 (awards)			Model 3 (patents + awards)			Model 4 (R&D capital intensity)		
	2006/2008	2010/2012	Change	2005/2008	2010/2012	Change	2006/2008	2010/2012	Change	2005/2008	2010/2012	Change
Productivity ($t-1$)	0.498*** (0.178)	−0.296 (0.416)	−0.691** (0.320)	0.482** (0.212)	−0.296 (0.412)	−0.648* (0.367)	0.497*** (0.181)	−0.277 (0.409)	−0.668** (0.321)	0.481** (0.213)	−0.367 (0.434)	−0.675* (0.372)
Patent intensity ($t-1$)	−0.014 (0.012)	−0.003 (0.019)	0.011 (0.015)				−0.014 (0.012)	−0.004 (0.019)	0.010 (0.015)			
Dummy for patents ($t-1$) > 0)	0.111 (0.112)	0.008 (0.176)	−0.097 (0.148)				0.111 (0.113)	0.013 (0.176)	−0.092 (0.147)			
Award ($t-1$)				−0.001 (0.025)	0.041 (0.030)	0.052 (0.035)	0.004 (0.031)	0.042 (0.030)	0.048 (0.038)			
R&D capital intensity ($t-1$)										−0.005 (0.013)	−0.040 (0.030)	−0.026 (0.023)
Dummy for R&D capital ($t-1$) > 0										0.058 (0.146)	0.381 (0.325)	0.252 (0.248)
Labour quality ($t-1$)	0.261** (0.128)	0.957*** (0.334)	0.636** (0.266)	0.261* (0.158)	0.949*** (0.331)	0.603** (0.300)	0.262** (0.129)	0.938*** (0.328)	0.614** (0.265)	0.265(0.168)	1.059*** (0.37)	0.655** (0.319)
Capital intensity ($t-1$)	0.057 (0.042)	0.224*** (0.081)	0.140** (0.062)	0.076* (0.040)	0.225*** (0.081)	0.119* (0.062)	0.058 (0.042)	0.221*** (0.08)	0.136** (0.062)	0.077* (0.040)	0.237*** (0.086)	0.124** (0.063)
Size (t-1)	0.009 (0.008)	0.023 (0.016)	0.015 (0.012)	0.009 (0.01)	0.020 (0.015)	0.013 (0.012)	0.009 (0.008)	0.021 (0.016)	0.012 (0.012)	0.009 (0.010)	0.030* (0.018)	0.019 (0.014)
Constant	1.152*** (0.381)	2.135*** (0.728)	0.914 (0.567)	1.282*** (0.407)	2.198*** (0.658)	0.806 (0.647)	1.155*** (0.387)	2.119*** (0.719)	0.898 (0.572)	1.228*** (0.363)	1.766*** (0.605)	0.479 (0.568)
Observations	1206	1191		1598	1191		1206	1191		1598	1191	
R^2	82.23%	32.05%		81.97%	32.14%		82.19%	33.59%		81.96%	27.92%	
Hansen test	70.01%	94.71%		99.72%	96.05%		70.06%	96.02%		99.46%	96.17%	

Notes: First values are coefficients; parentheses contain robust standard errors with the Windmeijer correction for finite sample bias. All equations include a set comprising country, year and sector dummies. The final column contains interaction terms between factors and a post-crisis dummy taken from the testing model. The models are estimated by system GMM; the set of instruments includes second- and third lags of productivity and all control variables (assumed to be predetermined). A Hansen test is performed for equations in first differences.

*Significance at 10%.

**Significance at 5%.

***Significance at 1%.

Table 8. Wald tests for intertemporal shifts (*p*-values, %).

		Basic model		Test No. 2: Robustness checks							
Hyp.	Equation	Test 1	Test 2	U.K.	GE	FR	Large	Small	Old	Young	Other years
H1a	R&D doing	0.39	0.13	21.47	23.90	14.67	9.52	9.22	0.55	12.40	0.02
H1b	R&D intensity	0.71	59.89	32.79	0.06	55.77	6.27	19.61	90.02	29.78	95.78
H2a	Awards (dynamic)	1.16	0.47	2.71	20.50	15.90	4.45	15.39	3.70	19.20	28.87
	Awards (without lag)	0.21	0.16	5.23	14.91	27.36	3.62	13.78	6.42	12.81	26.49
H2b	Patents (dynamic)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Patents (without lag)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H3	Productivity (patents)	23.11	16.22	7.37	0.00	87.09	46.11	4.52	93.47	27.94	71.18
	Productivity (awards)	17.47	17.13	38.85	0.00	76.03	28.12	10.96	17.77	38.88	51.76
	Productivity (patents and awards)	27.15	20.72	9.76	31.76	91.52	36.19	4.73	87.84	44.45	72.09
	Productivity (R&D)	28.77	37.66	63.71	0.00	74.72	75.67	22.78	90.34	50.84	61.81

had similar importance before and after the crisis. Thus, it confirms only H1a, H2a and H2b, but rejects H1b and H3. Disparate results for various stages may be explained as follows. Higher uncertainty, risk aversion and entry barriers impeded all innovative activity, irrespective of its size. This altered the role of internal factors for the decision to innovate, but not for R&D intensity. Firms became more cautious and efficient in the exploitation of their own resources for knowledge creation; this is less visible for yielding economic results. As we explain, innovative activity is complex and manifold and firms have many options to improve its efficiency, while production process is routine.

We are concerned about the reliability of our findings due to sample non-uniformity. Therefore, some robustness checks were conducted (Appendix 3). These tested whether the model is sensible for use in terms of country-specific, corporate size and age. We also suspect that the analysed periods are not fully relevant. Additional checks excluded 2008 and 2010, which partially overlap the crisis period. We then outline common findings.

There is high heterogeneity of coefficients in equations for different countries, size and age. However, some common features exist. The dynamics of coefficients in the selection model is comparable: lagged R&D and equity becomes more relevant factors, while the role of initial conditions declines. Liquidity is valuable for R&D intensity, especially for smaller and newer firms after the crisis, confirming the negative role of worsened financial restrictions. In most stages (R&D, innovations and productivity), the coefficients by lagged dependent variables reduced. The impact of R&D on innovations increased. In general, the role of labour quality and capital intensity for patents and performance improved. Knowledge is not significant for productivity. The choice of a wider interval of crisis (2008/2010) has no perceptible impact on estimates. In most of the checks, test №2 confirms the same hypotheses as in the main model (Table 8). However, there are some large differences for certain types of firm and stages of the model. This could also indicate a considerable unaccounted firm heterogeneity.

6. Conclusions

This study aimed to reveal substantive shifts in the firm innovation process occurring during the 2008 downturn. Different aspects were considered from the decision to invest in R&D to economic return from new knowledge. We constructed models for periods before and after the crisis, compared them and revealed intertemporal changes at each stage of the process.

The empirical results are manifold. Overall, the 2008 crisis led to strong alterations in most aspects of the innovation process. The most perceptible changes occurred in participation in R&D and the knowledge creation (breakthrough products and patents). Concurrently, shifts in R&D intensity were linked primarily with the external environment, while the role of firm-specific factors remained constant. Production function was not significantly changed.

The key changes with respect to concrete variables and stages can be summarised as follow. The decision to invest in R&D, product awards and economic results appear to be less dependent on recent history and more on firm features. The efficiency of R&D efforts in knowledge creation noticeably increased. However, the maintenance of low level of R&D intensity became less beneficial. This implies increased entry barriers for innovations. Firm size was found to be a positive significant driver of R&D intensity and inventions; in fact, its importance increased. Human and physical capitals became more valuable resources for patent granting and firm productivity in the post-crisis period. Liquidity constraints were found to be important for the R&D intensity of small and young companies only. Their role has increased over time, which may be an after-effect of the financial sector crisis. There is also some evidence of increased economic volatility. Increased risk is a possible reason for why R&D activity became less efficient for smaller companies and firms with low-grade innovative abilities. It also relates favourably to higher entry barriers.

As we assumed, these finding provide evidence of the positive cleaning effect of the crisis. The decline in market demand and appearance of new entrants led to faster market dynamics and strengthened competition for existing companies. A harsher environment enforces rational behaviour and exploiting one's own resources (labour, physical assets, innovations) with higher efficiency. Firms with a good resource base and a better ability to generate knowledge retain incentives for R&D in the current, more competitive environment, whereas such investment became unattractive for less-capable firms and those with low resource potential. The negative impact is that some companies were discriminated against following the crisis. Smaller firms are on average more innovative but they suffered to a greater degree after the crisis. Higher entry barriers for innovations and increased uncertainty may deter them from initiating new risky projects. Implemented government policy is needed to account for the unequal influence of recessions and corporate heterogeneity.

This paper is the first to research permanent shifts in firms' innovative behaviour as a result of the recent economic slowdown. However, the study is imperfect and the topic requires further exploration. The first point to highlight here relates to the specificity of our sample. On average, in the countries analysed here, public companies active in 2004–2012 were relatively large, highly innovative and competitive when compared to manufacturing firms. Therefore, our findings should be considered carefully if extrapolated for general innovation policy. Another problem is possible heterogeneity in the sample. Robustness checks show some perceptible distinctions between the models estimated for different countries, firm size and firm age groups. Finally, we are anxious that our variables may not be a good substitute for survey data. In particular, it is possible that patents and awards imprecisely measure the knowledge crucial for successful competition. On the other hand, an open source provides an alternative view of innovations and complements the results of other papers based on CIS. For conducting a comprehensive analysis, we need to gather data about the same enterprises from both surveys and open sources. All of these issues present the challenges for future studies in this area.

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Appendix 1. Empirical studies on the crisis of 2008 and firms' innovations at the micro-level

Study	Data and sample	Key findings
Kanerva and Hollanders (2009)	4195 innovative firms from 27 EU countries	Among firms, 23% decreased investment in innovations in 2008. This reduction was less remarkable for companies with a high share of innovative products and services, firms relying on innovation strategies but not on cost cutting, firms from medium and high knowledge-intensive sectors, companies serving international and public procurement markets and R&D performers. Firm size and the amount of innovation expenditures do not impact on the likelihood of this reduction
Antonioli et al. (2011)	555 Italian manufacturing firms in 2006–2009	The main issue is a link between innovative strategy and firm performance. Past innovative activity helps to weather the crisis through new products, processes and organisation/HRM practices. Firm performance depends positively on organisational and technological strategies, whereas training programmes, ICT and environmental innovations are negative determinants
Filippetti and Archibugi (2011)	5238 firms from 27 EU countries in 2006–2008	There are noticeable differences in innovation investments across European countries. National innovation systems were useful for supporting investment in R&D projects during the downturn. The major structural factors of R&D were the quality of human resources, specialisation in the high-technology sector and a developed financial system. The authors reveal significant persistence in investments for many firms in spite of the crisis. At the same time, companies became less willing to initiate new risky projects
Laperche, Lefebvre, and Langlet (2011)	Eight large French industrial groups, enquiry in 2009–2010	The crisis impacted R&D in a pro-cyclical manner, but qualitatively more so than quantitatively: companies reduced expenses and avoid risky projects. The role of IPR changed differently between firms. Collaborative strategies of innovations became more actual
Brencic, Pfajfar, and Raškovic (2012)	101 best Slovenian employers in 2008–2009	Innovations had a negative effect on firm performance during the crisis. Contrariwise, the authors reveal a positive role of HRM practices. This may be related to short-term switching of enterprises in order to retain customers and effect cost reduction
Paunov (2012)	1548 Latin American firms in 2008–2009	The research question is why many companies stopped ongoing innovation projects. The main factors were financial constraints and negative demand push. Younger businesses and firms linked to foreign markets particularly suffered in the downturn. Public funds helped to prevent discontinuation; size was unimportant
Archibugi, Filippetti, and Frenz (2013a)	Under 2500 enterprises from the U.K. in 2004, 2006 and 2008 (balanced panel)	The determinants of innovative behaviour changed during the crisis compared to the pre-crisis period. Corporate size and economic performance became less important, while the influence of past product innovations and explorative strategies increased. These results are similar for manufacturing and service industries
Archibugi, Filippetti, and Frenz (2013b)	3959 firms from 27 EU countries; analysed periods: pre-crisis (before 2008), during crisis (2008) and post-crisis (expectation about 2009)	The crisis considerably changed the characteristics of the dynamics of R&D (increase, maintenance or decrease). Firms increasing investment before the crisis were larger, older, had higher innovation intensity and relied more on formal R&D and collaboration with suppliers and customers. After the downturn, dynamics of R&D was positive for smaller, younger firms exploring new market opportunities and was less connected with a strategy of cost cutting
Cincera and Veugelers (2014)	1034 firms (large R&D spenders), from around the world (mostly EU and the U.S.A.) in 2000–2011 (7789 obs.)	The return to R&D investment is much higher in the U.S.A. than in Europe. The crisis led to a strong drop in the return for all firms. The U.S.A. and Europe have different conditions for young innovative companies ('Yollies'). U.S. Yollies are more successful in R&D than their older counterparts. In Europe, the return to R&D is low even for Yollies and for companies in high-technology sectors. Yollies' premium dropped during the crisis but remains positive in the U.S.A.

Prorokowski (2014)	13 Polish innovative listed companies, 2008–2009 (quarterly data)	An innovative strategy was effective for Polish enterprises during the time of the most recent crisis. The development of new products significantly enhanced the international competitiveness of innovative firms and their export opportunities
Sidorkin and Srholec (2014)	904 firms from Eastern Europe in 2005–2010	Pre-crisis innovation activity is the main factor reducing the likelihood of bankruptcy during the crisis, in addition to managers' experience. Foreign competitors and the delayed payments of taxes increased the probability of bankruptcy
Hud and Hussinger (2015)	Germany's SMEs in 2006–2010 (10,527 observations, 1016 of which relate to recipients of R&D subsidies)	On average, the influence of R&D subsidies on SMEs' R&D investment was positive. However, it was negative during the crisis year (2009), evidence for a crowding out effect. The subsidy effect in 2010 was smaller than in pre-crisis years, but still positive and significant, a sign of fast recovery within the German economy

Appendix 2. Definition of variables and descriptive statistics

Variable	Description	Obs.	Min.	Mean	Med.	Max.	St. D.
Age	Age from the foundation date (log)	3780	0.00	3.65	3.66	5.28	0.94
Award	Dummy, =1 if company reports about innovation award for new product	3780	0.080	0.16	0.00	1.00	0.37
Association	Dummy, =1 if the firm reports that it is a member of any business association	3780	0.00	0.30	0.00	1.00	0.46
Capital city	Dummy, =1 if the firms is located in the capital (metropolitan area)	3780	0.00	0.35	0.00	1.00	0.48
Capital intensity	Tangible fixed assets per employee, thous Euro (log)	3690	−0.66	3.50	3.50	6.67	1.00
Equity	Ratio of shareholder funds to capital	3770	−0.45	0.46	0.45	1.00	0.21
Labour quality	Personnel costs per employee, thous Euro (log)	3635	−0.20	3.66	3.70	5.87	0.52
Liquidity	The ratio of cash to all assets	3770	0.00	0.12	0.08	0.96	0.13
Patents	Number of new patents, change in the total patents' number of the firm	3360	0.0	40.7	0.0	3 080	201.6
Patent dummy	Dummy, =1 if firm granted patents	3360	0.00	0.45	0.00	1.00	0.50
Patent intensity	New patents per employee, (log)	1480	−5.33	1.11	1.26	6.98	1.79
Patent intensity (zero-corrected)	New patents per employee, (log) = log(0.0001) if patents = 0	3333	−9.21	−4.63	−9.21	6.98	5.27
Productivity	Sales per employee, thous Euro (log)	3686	0.43	5.15	5.14	8.35	0.72
Profitability	Ratio of retained earnings to capital	3770	−0.93	0.02	0.04	0.32	0.13
R&D capital	R&D capital, mln Euro	3780	0.0	683.4	6.0	34,845	3258
R&D capital dummy	Dummy, =1 if R&D capital > 0	3780	0.00	0.72	1.00	1.00	0.45
R&D capital intensity	R&D capital per employee, thous Euro (log)	2667	−7.13	2.66	2.80	8.88	1.86
R&D capital intensity (zero-corrected)	R&D capital per employee, thous Euro (log) = log(0.0001) if R&D capital = 0	3780	−9.21	−0.84	1.94	8.88	5.63
R&D	R&D expenditure, mln Euro	3780	0.0	123.3	0.6	8158	581.6
R&D doing	Dummy, 1 if the firm invest in R&D	3780	0.00	0.57	1.00	1.00	0.50
R&D intensity (not logarithm)	R&D per employee, thous Euro	3693	0.0	9.4	0.8	1 807	67.5
R&D intensity (log form)	R&D per employee, thous Euro (log)	2126	−6.04	1.41	1.44	7.50	1.54
R&D intensity (zero-corrected)	R&D per employee, thous Euro (log) = log(0.0001) if R&D = 0	3748	−9.21	−3.19	−0.35	7.50	5.39
Size	Number of employees (log)	3693	0.69	7.20	7.01	13.16	2.17

Notes: All financial variables are in Euro in comparable prices for 2004. The data on inflation was taken from Eurostat (www.ec.europa.eu/eurostat/data/database). We used labour cost indices in the manufacturing industry for personnel costs and national GPD deflators for R&D investment. Sales were corrected by producers' price indices according to two-digit NACE Rev. 2 classification. Mairesse and Jaumandreu (2005) show that industry deflators are good enough for accounting the firm-specific differences in price level.

There were a few notable outliers for variables *Profitability*, *Capital intensity* and *Equity*. We replaced them with the boundary values (0.5 and 99.5% of initial distribution). Others variables (size, labour quality, capital intensity, etc.) did not suffer from overdispersion and outlying values after we took logarithms.

The R&D capital is calculated by a perpetual inventory formula with the generally assumed depreciation rate of 15% (Wakelin 2001). R&D expenditures (real values) accumulate starting from 1994, the time when the data became available. Initial capital stock (1993) is obtained as a ratio of average real expenditure in 1994–2003 to 15%.

Appendix 3. Robustness checks

Variable (*Equation*)	United Kingdom		Germany		France		Larger firms		Smaller firms		Older firms		Younger firms		Alternative dates	
	05/08	10/12	05/08	10/12	05/08	10/12	05/08	10/12	05/08	10/12	05/08	10/12	05/08	10/12	05/07	11/12
Lagged doing (*R&D doing*)	0.59* (0.15)	0.36 (0.31)	0.50* (0.18)	0.71* (0.19)	0.50* (0.13)	0.28 (0.18)	0.44* (0.18)	0.25* (0.13)	0.65* (0.10)	0.32 (0.22)	0.66* (0.13)	0.14 (0.34)	0.65* (0.11)	0.63* (0.12)	0.86* (0.11)	0.64* (0.09)
Equity (*R&D doing*)	0.00 (0.13)	0.28 (0.24)	0.06 (0.13)	−0.15 (0.19)	−0.11 (0.34)	0.70* (0.36)	−0.02 (0.13)	0.13 (0.12)	0.17 (0.14)	0.26 (0.18)	−0.06 (0.20)	0.12 (0.41)	0.06 (0.15)	0.26 (0.16)	−0.01 (0.10)	0.30* (0.15)
Lagged intensity (*R&D intensity*)	0.44* (0.13)	0.60* (0.14)	0.88* (0.11)	−0.19 (0.26)	−0.08 (0.25)	0.02 (0.33)	0.10 (0.17)	0.61* (0.22)	0.52* (0.11)	0.23 (0.24)	0.50* (0.17)	0.51* (0.16)	0.37* (0.10)	−0.28 (0.39)	0.43* (0.11)	0.51 (0.32)
Liquidity (*R&D intensity*)	1.54* (0.62)	1.84* (0.77)	0.94* (0.47)	1.78* (0.75)	2.49* (1.21)	0.01 (0.88)	1.66* (0.51)	1.00* (0.60)	1.50* (0.64)	2.24* (0.64)	0.55 (0.42)	0.93 (0.62)	1.91* (0.56)	3.16* (0.79)	1.90* (0.49)	1.87* (0.95)
Lagged awards (*R&D intensity*)	0.26 (0.21)	0.13 (0.10)	−0.14* (0.05)	0.20* (0.06)	0.17 (0.15)	0.24* (0.13)	0.04 (0.07)	0.12* (0.07)	−0.05 (0.16)	0.14 (0.13)	0.11 (0.07)	0.16* (0.06)	−0.02 (0.12)	0.23 (0.15)	0.15* (0.08)	0.22 (0.16)
Lagged patents (*R&D intensity*)	0.40* (0.14)	0.10 (0.08)	0.05 (0.08)	0.33* (0.14)	0.51* (0.16)	0.22* (0.13)	0.33* (0.12)	0.06 (0.08)	0.26* (0.12)	0.19* (0.11)	0.13 (0.08)	0.06 (0.07)	0.35* (0.12)	0.29* (0.17)	0.29* (0.08)	0.23 (0.17)
Lagged awards (*Awards*)	0.04 (0.04)	0.05 (0.04)	0.21* (0.04)	−0.1* (0.05)	0.02 (0.03)	−0.03 (0.05)	0.08* (0.04)	−0.06 (0.05)	0.09* (0.05)	0.01 (0.03)	0.12* (0.05)	−0.05 (0.03)	0.05 (0.04)	0.03 (0.05)	0.13* (0.05)	0.17* (0.02)
R&D intensity (*Awards*)	0.01 (0.01)	0.02* (0.01)	−0.01 (0.01)	0.08* (0.03)	0.02 (0.01)	0.02 (0.01)	0.03* (0.01)	0.06* (0.02)	0 (0.01)	0.02* (0.01)	0.03* (0.01)	0.05* (0.02)	0 (0.01)	0.02* (0.01)	0.01* (0.01)	0.02* (0.01)
Lagged patents (*Patents*)	0.00 (0.03)	0.85 (0.68)	0.56* (0.11)	0.75* (0.10)	0.01 (0.07)	−0.58* (0.16)	0.29* (0.12)	0.71* (0.15)	0.06* (0.03)	−0.00 (0.04)	0.01 (0.05)	−0.11* (0.04)	0.08* (0.05)	0.69* (0.08)	0.01 (0.05)	−0.47* (0.07)
R&D intensity (*Patents*)	−0.09* (0.05)	0.77 (1.29)	0.92* (0.21)	0.21* (0.12)	0.22* (0.10)	1.64* (0.47)	1.24* (0.25)	3.28* (0.82)	0.01 (0.03)	0.05 (0.03)	0.43* (0.08)	0.37* (0.11)	0.13* (0.06)	0.16* (0.07)	0.12* (0.06)	0.54* (0.11)
Patent intensity (*Productivity*)	−0.02 (0.03)	0.02 (0.02)	0.00 (0.01)	−0.01 (0.03)	−0.01 (0.02)	−0.02 (0.01)	0.00 (0.01)	−0.02 (0.01)	−0.02 (0.03)	0.03 (0.04)	−0.00 (0.01)	−0.00 (0.01)	−0.03 (0.02)	−0.02 (0.02)	−0.03 (0.02)	−0.00 (0.02)
Awards (*Productivity*)	−0.10* (0.05)	0.01 (0.05)	−0.02 (0.02)	0.04 (0.03)	0.02 (0.09)	0.04 (0.04)	−0.02 (0.02)	0.02 (0.02)	0.01 (0.06)	0.01 (0.01)	−0.04 (0.03)	0.03* (0.02)	0.02 (0.05)	0.02 (0.05)	−0.02 (0.03)	0.01 (0.02)
R&D intensity (*Productivity*)	−0.01 (0.02)	−0.01 (0.03)	0.01 (0.01)	−0.02 (0.06)	−0.02 (0.04)	−0.01 (0.02)	−0.01 (0.01)	−0.02 (0.02)	0.01 (0.02)	−0.03 (0.04)	−0.02 (0.02)	0.01 (0.02)	−0.00 (0.02)	−0.05 (0.04)	−0.03 (0.03)	−0.02 (0.02)

Notes: We re-estimated the model for different subsamples in the data. The above table represents marginal effects by key variables of interest. Symbol *denote significance at 10% level. Standard errors are in parentheses. We omit other results for space-saving reasons. The equations for patents and awards are both estimated in versions with state dependence. We present the results of three different productivity models each with a single measure for innovations (patent intensity, awards or R&D capital intensity). All models and estimation techniques are similar to those previously applied. The single exception is an absence of national dummies in country-specific models.