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Document Version
Accepted author manuscript

Published in:
Journal of Banking & Finance

DOI:
10.1016/j.jbankfin.2020.105961

Publication date:
2020

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PII: S0378-4266(20)30223-5
DOI: https://doi.org/10.1016/j.jbankfin.2020.105961
Reference: JBF 105961

To appear in: *Journal of Banking and Finance*

Received date: 14 March 2018
Accepted date: 22 September 2020

Please cite this article as: Marek Giebel , Kornelius Kraft , Bank credit supply and firm innovation behavior in the financial crisis, *Journal of Banking and Finance* (2020), doi: https://doi.org/10.1016/j.jbankfin.2020.105961

Bank credit supply and firm innovation behavior in the financial crisis

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Abstract

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*JEL Classification***:** G01, G21, G30, L20, O16, O30, O31, O32

Keywords: Financing of innovation, credit supply, financial crisis, innovation behavior, firm strategy

Acknowledgements: We thank two referees and the associate editor for extensive and very helpful comments. We also thank the Deutsche Forschungsgemeinschaft for funding this research by the research grant KR 929/7-1.

Funding: This work was supported by the Deutsche Forschungsgemeinschaft [grant number KR 929/7-1].

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Abstract

We analyze the change in firms' innovation behavior (short-term adjustment and long-term strategy) in reaction to the credit supply shock to banks in the recent financial crisis 2008/2009. Using a matched bank-firm data set for Germany, we utilize the exogenous variation caused by the interbank market disruptions on credit supply in instrumental variable estimations. Concerning the short-term innovation adjustment in 2009, our results show that (i) current innovation activities, (ii) the initiation of additional innovation and (iii) the reallocation of unused labor resources to the innovation department are affected by the shock to bank financing. We find that the effect is more pronounced for product innovation than for process innovation. Investigating the impact on the long-term innovation strategy in reaction to the crisis, we find that (iv) the sensitivity to adopting any innovation-related strategy to cope with the crisis could not be attributed to the negative bank credit supply shock.

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1. Introduction

The financial crisis of 2008/2009 marks a period of turbulences in the banking sector that were followed by adverse effects on the real economy. In Germany, these effects manifested for example as a decrease in GDP (-5%), exports (-14.2%) and fixed investments (-8.8%) in 2009 compared to 2008 (OCED 2010). Aside of these general economic indicators, OECD (2012) also shows that for Germany long-term investments like R&D expenditures from business enterprises shrink by 3% and patent filing by about 11.5% from 2008 to 2009. Similar figures are observed for many other OECD countries including Canada, the UK and the US. Aside of these descriptive observations, it is empirically established that in response to the reduction in bank credit supply (e.g. Ivashina and Scharfstein 2010; Iyer et al. 2014; Liberti and Sturgess 2018), firms have reduced, among other things, their labor demand (e.g. Chodorow-Reich 2014), investment (e.g. Cingano et al. 2016; Dwenger et al. 2018; Vermoesen et al. 2013) or trade activities (Chor and Manova 2012). However, detailed empirical evidence concerning the impact of bank credit supply restrictions as determinant of innovation behavior of their corporate customers in the financial crisis is scarce.

Studying the relation between bank credit supply and innovation in the recent financial crisis is of particular interest for several reasons: A negative shock to bank credit supply which has adverse effects on innovation consequently affects growth, development and competitiveness negatively.[1] Moreover, the financing of innovation differs from – and is more difficult than – the financing of normal assets, which is rooted in the special characteristics of innovation projects (i.e. a long duration, huge uncertainties and other risks) (e.g. Hall 2002; Hall and Lerner 2010; He and Tian 2018; Kerr and Nanda 2015). Additionally, the existence of a relation between bank financing and innovation remains under discussion (Hall and Lerner 2010; Kerr and Nanda 2015).

Consequently, the aim of this paper is to investigate the effect of individual main bank changes in credit supply during the recent financial crisis on their corporate customers' immediate innovation adjustments and innovation strategy. In that respect we determine the impact of bank credit supply changes on (i) ongoing, current innovation activities, (ii) the initiation of additional innovation and (iii) the reallocation of unused labor to the innovation department. Moreover, we investigate whether the crisis-induced variation in bank credit supply leads to (iv) more emphasis on innovation-related strategies in reaction to the crisis.

Our data basis is the 2010 wave of the Mannheim Innovation Panel (MIP), which is the German part of the Community Innovation Survey (CIS). The MIP provides general information on firms, including basic characteristics like size and turnover but also information regarding innovation activity. We make use of a special section of the 2010 questionnaire, which, with the help of precise and sensitive questions, directly addresses the effects of the financial crisis on innovation activities. On the one hand the questions allow for a detailed investigation of the impact of the financial crisis on current innovations activities, as well as the initiation of new, additional innovations. Moreover, we can distinguish the latter in product and process innovation.[2] On the other hand, by using detailed survey measures we are able to overcome problems when applying R&D and patent-related measures. These are, for example, that R&D does not provide information about the innovative strategy of the firm, which in many cases prefer secrecy to patenting (He and Tian 2018), and that process innovations are especially poorly captured by patents and R&D (e.g. Bellstam et al. 2020). Secondly, an advantage of the MIP is that we are able to identify the firm's main bank. This in turn enables us to combine firm information with bank balance sheets information taken from Bankscope, compiled by Bureau van Djjk. By this we are able to study the effects of the financial crisis on i) the external financial restrictions and

ii) the consequences of this on the real sector, in our case the innovation activities of the corporate customers of the banks. Hence, the financial crisis acts like a natural experiment.

Our identification strategy is based on the shock to the interbank market that emerged after the collapse of the Lehman bank. This resulted in higher risk premiums and liquidity shortages for banks that relied heavily on the interbank market to obtain financial resources. The individual dependence of the banks on the interbank market is used by us as an instrument to explain credit growth. This allows us to overcome potential endogeneity issues when regressing innovation outcomes on bank lending. On the one hand these may result from possible omitted variable bias affecting the estimated relation between credit growth and innovation. On the other hand a firm's financial strength might change simultaneously with the financial strength of banks. Consequently, our instrumental variable approach allows us to identify the effect of changes in bank credit supply on current and prospective corporate innovation activities during the financial crisis.

We show that the effects of the crisis on a bank's refinancing capabilities and the corresponding changes in its credit supply significantly explain the reduction in innovation activities among business customers due to (self-reported) increased difficulties in financing innovation. Accordingly, we find that firm innovation activities react sensitively to bank financing. In that respect, by identifying the mechanism of how innovation is reduced, we make an important step further than existing studies that investigate the relationship between the crisis and innovation (e.g. Archibugi et al. 2013a & therewith connected 2013b; Campello et al. 2010; Filippetti and Archibugi 2011; Giebel and Kraft 2019; Huber 2018; Paunov 2012). Firstly, we show that current innovation activities are affected by the negative shock to bank financing. Thus, we find that a decrease in bank lending increases the probability of reducing innovation activities due to

funding shortages. Moreover, our results contribute to the discussion on the different effects of bank financing on product and process innovation (e.g. Alessandrini et al. 2010; Benfratello et al. 2008). Thus, secondly, we show that business customers with relations to a bank with lower credit growth are less likely to initiate additional innovation activities during the crisis. In that respect, lower loan growth leads to a lower probability of initiating additional product innovation. Moreover, we find a weaker (negative) effect of lower loan growth on the probability of initiating additional process innovation. Thirdly, our results indicate that firms which have access to a bank with lower loan growth are less likely to allocate unused resources like labor to the innovation department. Several robustness tests (i.e. accounting for a possible endogenous matching of firms and banks, handling demand effects and refining the definition of key variables) support the validity of our results.

Tests on the heterogeneity of our results reveal that the sensitivity of innovation to changes in credit supply is predominantly relevant for firms which are more likely to be internally constrained. Thus, firms which faced a sales contraction in the crisis adjusted their innovation depending on the change in bank lending. Moreover, firms that react more sensitively to reductions in sales or profits in the crisis are also more sensitive to the bank credit supply shock. These results might point towards an additionality of bank financing rather than a complementarity to internal financing. Further tests reveal that firms which are not part of a firm group or which are smaller are likely to suffer more severely from the credit supply reduction in the recent financial crisis. While younger firms are more likely reducing their current innovation activities in result, no reaction in that respect is found for older firms. The latter show a decreasing likelihood of initiating new innovation projects due to reductions in credit supply. This effect is not found for larger firms or those which are part of a firm group.

Lastly, we do not find a link between the change in credit supply and the impact of any innovation-related strategy in reaction to the crisis. Thus, we show that the firm's emphasis on cost reducing strategies to react to the changing economic conditions of the crisis is independent of the change in bank credit supply. Moreover, the change in bank credit supply does not affect the firm's impact of an exploration or exploitation strategy to react to the crisis. Thus, the bank credit supply shock affects the immediate innovation behavior but not the innovation strategy in reaction to the crisis. This holds even if we estimate the impact on condition of being affected by the crisis (or not) or on condition of an innovation adjustment in the short run (or not).

Summarizing our approach to combine information from banks with data from their corporate customers allows a derivation of new insights on a) the firm innovation behavior during the financial crisis[3], b) the relevance of bank financing for innovation[4] and c) enrich the literature on credit supply shocks on firm outcomes by concentrating on innovation[5]. We complement the very recent analysis of Huber (2018), who tests for the effect of the bank credit supply shock of Commerzbank-related firms on, among others, productivity and employment. Huber (2018) also tests for the persistency of negative bank shock to Commerzbank related firms by analyzing patenting. The differences to Huber (2018) are the following: i) our measure of the bank credit supply shock allows for a more detailed identification and interpretation of the effects of a negative bank shock and ii), we expand on Huber's (2018) analysis by providing information on the immediate decisions of firms concerning their innovation activities based on the loan supply by banks, while patents react with a considerable lag to shocks[6]. For a similar reason we extend the work of Giebel and Kraft (2019) which shows that innovation expenditure decreases for firms affected by the negative shock to the interbank market. However, similar to Huber (2018), their

innovation measure does not allow for a detailed determination of the underlying changes in innovation behavior and strategy.

The remainder of the paper is structured as follows. The second section covers a description of the channels affecting the innovation activity of firms during the financial crisis. The third section covers a description of the data and variables, as well as methodology. The results are described in section four. Section five comprises descriptions and results for robustness tests and extensions. The sixth and last section concludes.

2. Bank financing and innovation in the recent financial crisis

2.1. Bank financing and innovation

In the case of a perfect capital market, it might be no problem to obtain the necessary amount of funding for investment projects of any type (Modigliani and Miller 1958). However, capital market imperfections and asymmetric information problems lead to restricted access to external funding (Holmstrom and Tirole 1997; Stiglitz and Weiss 1981). Accordingly, the characteristics of innovation projects lead to a large gap between internal and external costs of financing, resulting in an underinvestment in innovation (Hall 2002; Hall and Lerner 2010; Hottenrott and Peters 2012).[7]

As already mentioned, the relation between bank financing and innovation is critically discussed (e.g. Hall and Lerner 2010; Kerr and Nanda 2015), as the characteristics of innovation (e.g. low collateral, large uncertainties) may make bank financing difficult for innovation (Hall and Lerner 2010).[8] Despite the well-known direct problems associated with externally financing innovations there may be an indirect relation between bank credit and innovation expenditures. Firms can obtain loans from banks for projects other than innovation that offer collateral. The internal

financial means that are freed as a result can then be utilized for innovation projects. If external financing is restricted, these internal resources are withdrawn from innovation activities and reallocated to other purposes which are more necessary for business operations. In this indirect way, constraints on the external capital market also have an effect on internally financed expenditures such as innovations.[9]

2.2. Bank credit supply shock and firm innovation in the recent financial crisis

As most firms in bank-based economies like Germany depend to some degree on bank loans[10] (e.g. Agarwal and Elston 2001; Berger and Udell 1995; Boot 2000) a negative shock to bank lending like the recent financial crisis will affect the availability of financing. This is first rooted in the fact that, in all likelihood, a negative shock to banks will lead to a lower supply of bank credit in general (Chava and Purnanandam 2011; Kahle and Stulz 2013; Upper and Worms 2004).[11] Secondly, a negative shock to banks leads to adverse effects on borrowing costs (Upper and Worms 2004). This is the consequence of the increased asymmetric information problem between borrower and lender (Mishkin 1992), lower valuation of collateral (Bernanke and Gertler 1990) and the increase in the perception of risk (Bloom 2007).[12]

As the recent financial crisis was also accompanied by a reduction in demand, it is unclear if and how firms adjust their innovation activity in a recession. It could be procyclical if a decline in demand reduces the incentives for innovation activities (Schmookler 1966; Shleifer 1986). Conversely, it is discussed whether in a downturn investments in physical capital are reduced first and innovation activities are intensified in turn. Opportunity costs decline in a recession and resources (including labor) could be used for innovation activities instead of in production (e.g. Aghion and Saint-Paul 1998; Davis and Haltiwanger 1990). These decisions continue to be

influenced by individual financial restrictions. Without financial constraints, innovation spending would be countercyclical and procyclical if restrictions are relevant (Aghion et al. 2010; Aghion et al. 2012).

Following these considerations, a reduction in actual innovation activities during the financial crisis due to a bank credit supply shock occur for several reasons: A direct effect can be seen when companies finance innovation activities with borrowed funds and credit becomes scarcer. The indirect effect described above in the case of a shortage of external resources works by reallocating capital within companies (e.g. Lamont 1997; Shin and Stulz 1998; Stein 1997).[13] This enables firms to shift capital from innovation projects to activities that are more important for the survival of the company in the short term.

H1: Firms' immediate adjustment of innovation activities due to funding shortages during the recent financial crisis depends on the credit supply of their main bank.

Bank financing might affect the decisions to initiate new product and process innovation projects. Both types differ with respect to several characteristics like goals, external financing requirements and subjectivity to asymmetric information. Even if this is the case, both types of innovation might be affected by financial constraints.[14] Product innovations are primarily conducted to increase the firm's sales (market share) and competitiveness (Alessandrini et al. 2010; Dosi 1988). As mentioned above, there are arguments that innovation activities are implemented counter-cyclically, since in times of weak demand, resources are not needed for capacity expansion and might be reallocated to R&D. Even if the incentives to introduce product innovation exist, their introduction depends on the financial strength of the firm. On the one hand, the asymmetric information problem for product innovation is large in early stages as this

type of innovation requires a lot of creativity and strategic thinking (Alessandrini et al. 2010). On the other hand, product innovation makes capital investments for commercialization and production necessary (Alessandrini et al. 2010). Consequently, the initiation of product innovation is likely affected by financial constraints in the recent financial crisis.

H2: The initiation of additional product innovation is subject to the availability of bank financing in the financial crisis.

Reasons to conduct a process innovation include, for example, reaching the technological state of the art, reducing costs or increasing competitiveness (Alessandrini et al. 2010; Dosi 1988; Peters et al. 2017). Thus, in a recession or depression long-run cost reductions have presumably high priority. Process innovation is usually implemented by new investment in equipment and machinery (e.g. Sirilli and Evangelista 1998) and this in turn is frequently realized by external financing (Berggren et al. 2000; Hall and Khan 2003). Consequently, the initiation of process innovation might be affected by financial constraints.

H3: The initiation of process innovation is subject to the availability of bank financing in the financial crisis.

So far, we have discussed various possible effects of a credit crunch on short-term reactions to innovation activities. It remains questionable whether firms solely adjust their innovation in the short run or put higher emphasis on specific long-run strategies to cope with the consequences of the financial crisis. Innovation strategies are of particular interest in this context as the financial crisis might have led to permanent (negative) effects if firms change their long-run strategies. This would have obvious implications for the success of innovations (Burgelman et al. 2001) as well as growth and survival probabilities of the firms involved (Guan et al. 2009). As the decision

on their strategy is made when engaging in innovation (e.g. Tushman and O'Reilly 1996), the question arises whether the credit supply reduction during the financial crisis led to the alteration of long-run strategies at all.

If companies had considered the credit crunch to be a temporary phenomenon, they probably would not have changed long-term strategies. However, the duration of the financial crisis could not be reliably predicted. If there are any adjustments in strategy, this could on the one hand be a stronger focus on cost reductions. On the other hand, companies might attempt to overcome the crisis by strengthening their market position through more product innovations. Whatever the objective of a new strategy is, the need for revision will probably also be influenced by the availability of external resources during the crisis. This will likely lead to an emphasis on product innovations if financial resources are available (Hambrick and Snow 1977) and on cost reductions (process innovations) if they are not (e.g. Nanda and Nicholas 2014). Consequently, it could be expected that firms adjust their innovation strategy in the financial crisis depending on the credit supply of their main bank.

H4: A firm's adjustments to its innovation strategy during the financial crisis depend on the credit supply of its main bank.

3. Data and empirical strategy

3.1. Data and variables

To investigate the transmission of specific bank shocks on the innovation activities of their corporate customers, we use the 2010 wave of the Mannheim Innovation Panel (MIP) in combination with bank balance sheet data from Bankscope. The MIP represents the German section of the European CIS Survey.[15] It has been conducted annually since 1993 and focusses on

the innovation activities of firms. Besides general firm information, the survey includes data on the innovative nature of firms. Thus, the MIP comprises information about innovation activities as well as special sections regarding, for example, the financing of innovation. The MIP 2010 wave includes a specific section on the consequences of the financial crisis on innovation and this allows us to identify the effects of the negative shock to bank credit supply on firms' innovative activity during the crisis. In addition, we are able to identify each firm's main bank with which it has commercial relations on a continuous basis. Applying a German bank identification code, we compile a data set that consists of firm data from the MIP and bank balance sheet information for the firm's main bank. Data for bank balance sheet information are obtained from the Bankscope database, which is distributed by Bureau van Dijk. Additionally, Bankscope also provides data regarding the deposit structure of banks.[16] Applying this matching procedure leads to our final sample which consists of 1465 non-financial firms. Our sample includes firms from the manufacturing industry (NACE Rev. 2.0 divisions 5 to 39) and the knowledge-intensive services (NACE Rev. 2.0 divisions 58 to 66 and 69 to 73). With respect to the sampled firms in the MIP, these industries account for roughly all firms except for those which are active in the non-knowledge-intensive services.[17]

To construct the outcome variables necessary to answer our main research question, we use a unique item from the MIP survey in 2010 which surveys managers' evaluation of the consequences of the financial crisis on innovation by posing the following question: "In 2009, did your company implement the following changes to its innovation activities as a result of the economic crisis?". To test for hypothesis H1, we first utilize the subsequent yes-no question: "Reduction of innovation activities due to funding shortages". The resulting dummy variable 'Reduction of innovation activities' takes unit value if the firms answered the question in the

affirmative and zero if not. In addition, we consider two yes-no questions on the initiation of innovation activity in 2009 due to the financial crisis. The first question is on additional product innovation or services: “Initiation of additional innovation activities to introduce new products / services”. It is followed by information collection on process innovation: “Initiation of additional innovation activities to introduce new / improved processes”. We create two dummies, ‘Initiation of product innovation’ and ‘Initiation of process innovation’. Unit value is assigned if the companies answer the questions affirmatively and zero if this is not the case. Besides testing for hypothesis H1, these two questions allow for testing hypothesis H2 concerning the effect of financial constraints on the initialization of new product innovation projects (H2) and hypothesis H3 for the initiation of process innovation.

Furthermore, the following yes-no question on the reallocation of human resources to increase innovation capacity is included: “Use of free human resources for increased innovation activities” to test for hypothesis H3. We create the variable ‘Reallocation of human resources to innovation’ and assign unit value if the firm undertook this measure and zero if not. For the test concerning any changes in innovation strategy (hypothesis H4), the following question concerning strategic changes is utilized: “Which impact do the following strategic actions in response to changes in economic conditions have on your company?” with the sub-items “Reduction of production/service costs”, “Renewal of existing production and service offers” and “Extension of supply to new market segments / customer groups” which are measured on a four point scale from no impact to high impact.

We also have access to several firm-specific variables as of 2009 which serve as control variables. The baseline explanatory variables include standard variables such as the logarithm of age ‘Log of Age’, size measured by the logarithm of the number of employees ‘Log of

Employees‘, and its square ‘Log of Employees squared’ and membership to a group of firms ‘Part of firm group’. Additionally, a rating index ‘Firm rating’ is included to represent risks associated with the individual companies.[18] The index is computed by Creditreform, the leading credit rating agency in Germany. A higher value of the ‘Firm rating’ index indicates a higher probability of default by a particular firm. This variable reflects the internal financial situation as well as access to external financing (e.g. Czarnitzki and Hottenrott 2011a & 2011b). Using the credit rating indicator, we also account for the fact that the firm rating gained more importance due to the Basle II accord.

Moreover, we control for potential demand effects in specific regions and industries. However, the argument could be raised that demand effects do not play a large role in Germany as the economy was in good standing before the crisis and the changes in economic conditions (e.g. unemployment) were moderate compared to other economies (e.g. OECD 2010; OECD 2012). Nevertheless, we follow works like Cingano et al. (2016), De Jonghe et al. (2020), Degryse et al. (2019) and Dwenger et al. (2018) and deal with this issue by including industry times federal state fixed effects.

In addition, we specify a set of dummy variables based on a question concerning the significance of reduced profits or increased losses as a consequence of the crisis of 2008/2009: “Which impact did the following consequences of the economic crisis 2008/2009 have for your company?” with the sub-item “Decrease in profits respectively increase in losses”. This question allows for a direct assessment of the dependence on and availability of internal financing. The resulting dummy variables are called ‘High influence of profit reduction’, ‘Med influence of profit reduction’, ‘Low influence of profit reduction’ and have unit value if the firm evaluated the importance of the profit reduction as high, medium or low. Assigning no importance at all to

profit reduction serves as the base category. We construct a similar set of variables for the sub-item "Decrease in sales". This is an additional control variable to account for the impact of demand on the firm.

Due to our data matching, we are able to utilize bank balance sheet information from the Bankscope database.[19] As we want to investigate the impact of a bank credit supply shock on firm innovation activities, we follow works like Dwenger et al. (2018) and use the loans the bank grants to all of its customers. This variable covers the full loans provided by the bank and therefore allows us to determine to what extent banks adjusted them. The impact of the crisis was greatest in 2009 (e.g. Bundesbank 2009; IMF 2016) such that the change in loans from 2008 to 2009 covers the extent to which the bank was affected by the turmoil on financial markets. Consequently, we generate the variable $\Delta\text{Credit\_Supply}_{ij}$ which measures the growth in bank credit supply from 2008 to 2009.[20]

In addition to the loan information, we are able to exploit the interbank market usage of banks. Following Cingano et al. (2016) and Iyer et al. (2014), we calculate the share of interbank market borrowing to total bank assets 'Interbank' as the measure for interbank market dependence of banks. We take the resulting figure as of 2006, before the financial crisis emerged. This variable is subsequently applied to account for the influence of the financial crisis on the relevance of interbank borrowing in relation to total assets. Descriptive statistics for our baseline sample are shown in Table 1.

Table 1: Descriptive statistics (N=1465)

	Description	Mean	SD	Median
Dependent variables				
Innovation reduction	Indicator variable whether 'Reduction of innovation activities' is answered in the affirmative or not	0.201	0.401	0
Product innovation	Indicator variable whether 'Initiation of additional innovation activities to introduce new products / services' is answered in the affirmative	0.448	0.498	0
Process innovation	Indicator variable whether 'Initiation of additional innovation activities to introduce new / improved processes' is answered in the affirmative	0.440	0.497	0
Labor reallocation	Indicator variable whether 'Use of free human resources for increased innovation activities' is answered in the affirmative	0.272	0.445	0
Product / service cost reduction	Impact of the strategic action 'Reduction of production/ service costs' in response to the financial crisis	2.151	0.959	2
Production and offer renewal	Impact of the strategic action 'Renewal of existing production and service offers' in response to the financial crisis	1.703	0.995	2
Extension of supply to new markets	Impact of the strategic action 'Extension of supply to new market segments / customer groups' in response to the financial crisis	1.986	0.977	2
Firm variables				
Employees	Number of employees measured in thousands	0.269	1.277	0.040
Age	Firm age in years	29.532	32.745	18
Group	Indicator variable whether the firm is part of a firm group	0.451	0.498	0
Firm rating	Rating index	227.042	50.601	222
Impact of profit reduction	Variable that indicates the impact of a decrease in profits or increase in losses in the economic crisis 2008/2009 on the company	1.743	1.162	2
Impact of decrease in sales	Variable that indicates the impact of a decrease in sales in the economic crisis 2008/2009 on the company	1.715	1.154	2
Bank balance sheet information				
Interbank	Ratio of interbank borrowing to total assets as of 2006	0.255	0.117	0.298
ΔCredit_Supply	Bank growth of credit from 2008 to 2009	-0.044	0.177	-0.020

3.2. Empirical strategy

We are interested in measuring the impact of changes in the loan supply of banks during the financial crisis on the innovation behavior of firms. Thus, the relationship between bank loan growth and innovation activity might be described as follows:

$$\text{Innovation}_i = \beta_0 + \beta_1 \Delta\text{Credit\_Supply}_{ij} + \beta_k X_{k,i} + \eta_i + \varepsilon_i \quad (1)$$

where Innovation_i represents the above-mentioned outcomes: reducing innovation expenditures due to funding shortages during the financial crisis, initiating new product or process innovations or reallocating of human resources to innovation. The variable $\Delta\text{Credit\_Supply}_{ij}$ comprises the loan growth of a firm's main bank in 2009. Moreover X_k consists of several firm-specific variables as described above and η_i is a set of industry times federal state dummies. The error term is described by ε_i.

The presented specification (1) does not allow a causal interpretation, because a feedback effect might be present, as the left- and right-hand side variables might be determined by some common yet omitted variables (e.g. innovation or investment opportunities). Moreover, we do not have information on the specific bank loans which are transmitted from bank j to firm i but just the general bank lending growth of bank j. Thus, the variable reflects the individual loans granted to firms measured with an error. Next, the financial strength of firms might not be independent from the credit growth of banks such that the credit supply coefficient would not inform us about the effect of the change in lending. In order to identify the causal effect of debt on innovation, we need to instrument our variable of interest $\Delta\text{Credit\_Supply}$.

As the financial crisis affected supply and demand, we use an instrumental variable which shifts the supply side of credit growth to detangle the effects of both sides of the debt market. Our instrumental variable is the interbank relation of the individual banks. Problems with respect to asymmetric information concerning borrower quality prevail on the interbank market (e.g. Freixas and Holthausen 2005; Rochet and Tirole 1996). Consequently, disruptions on the interbank market affect liquidity distribution in the financial system and costs of funds negatively. The financial crisis of 2008/2009 marks a period of stress on financial markets which reached its peak with the breakdown of Lehman Brothers in late 2008 (Acharya and Merrouche 2012). After this event, the turmoil on the interbank market led to loss of trust between banks, resulting in sharply increased spreads, liquidity holding and – related with this – a much lower supply of financial resources (Acharya and Merrouche 2012; Acharya and Skeie 2011; Ashcraft et al. 2011) and in particular for Germany (Craig and Von Peter 2014 and IMF 2016). The Bundesbank (2009) and IMF (2016) point to the possible influence of disruptions on the interbank market on bank lending, and the Bundesbank (2009) presents descriptive evidence on lending reduction to non-financial firms. Moreover, empirical studies show the negative relation between a bank's interbank reliance and bank-firm lending for Portugal (Iyer et al. 2014) and Italy (Cingano et al. 2016). Consequently, we expect that higher interbank market borrowing activities prior to the crisis will exert a negative effect on bank lending during the crisis. It has to be noted that the interbank ratio is assumed not to be directly related to the innovativeness of firms. Firstly, the interbank market activities of banks are not based on the customer business as argued by Cingano et al. (2016). As the interbank market notion reveals, this kind of market is solely for the exchange of liquidity among banks. Moreover, as shown by Giebel and Kraft (2019), the interbank ratio did not exert any significant influence on firm innovation expenditures in the time prior to 2008.

Using this instrument, we apply the following two-stage estimation approach: To begin with, we run a first-stage OLS regression of $\Delta\text{Credit\_Supply}$ on all variables from equation (1) and the variable Interbank which is correlated with our endogenous variable $\Delta\text{Credit\_Supply}$, and with the innovation decision only due to its relation to credit supply. In the second stage, we plug the predicted values of $\Delta\text{Credit\_Supply}$ from the first-stage regression (2) into the equation (1) which leads to equation (3).

$$\Delta\text{Credit\_Supply}_{ij} = \gamma_0 + \gamma_n \,\text{Interbank}_{ij} + \gamma_k X_{k,i} + \eta_i + \mu_i \quad (2)$$

$$\text{Innovation}_i = \beta_0 + \beta_1 \Delta\widehat{\text{Credit\_Supply}}_{ij} + \beta_k X_{k,i} + \eta_i + \varepsilon_i \quad (3)$$

The suitability of our instrument is checked by inspecting the coefficients in the first stage with respect to sign and significance. Moreover, the F-test on instruments excluded from the second stage checks for the validity of the instrument. If the F-statistic exceeds a threshold value of 10, the instruments are assumed to be valid in terms of their influence on the endogenous variable (Staiger and Stock 1997).

4. Main results on bank credit supply and firm innovation

4.1. Interbank market reliance and credit supply

We present the first stage estimation results (Equation (2)) in Table 2. Thus, we regress the credit growth variable on the Interbank to asset ratio as of 2006. As explained above, in the context of the crisis period the negative sign of the (highly significant) Interbank coefficient is to be expected. In the first and second columns of Table 2, we report the simple regression results without any control variables. Both coefficients show a reduction in credit supply by about 7 percent for a 10 percent increase in the interbank borrowing rate. Adding industry times state fixed effects did not alter the estimate remarkably. In columns (3) and (4), we add firm controls

and find that the estimates again do not change by much. The F-value of 161.72 far exceeds the critical value of ten indicating that our instrument is valid with respect to the influence on the endogenous variable.

Table 2: The effect of interbank market borrowing on credit supply

	(1)	(2)	(3)	(4)
Dependent variable	ΔCredit_Supply			
Interbank	-0.664***	-0.706***	-0.637***	-0.675***
	(0.049)	(0.053)	(0.050)	(0.053)
Industry times federal state fixed effects	No	Yes	No	Yes
Firm controls included	No	No	Yes	Yes
F-value of Interbank	181.97	169.96	156.75	161.72
R-squared	0.192	0.326	0.207	0.341
Obs.	1465	1465	1465	1465

Notes: The dependent variable ΔCredit_Supply is constructed as the change in credit supply by banks from 2008 to 2009. The variable Interbank is calculated as the value of interbank borrowing to total assets of the firm's main bank as of 2006. Firm controls comprise size, age, a dummy for being part of a firm group, the firms credit rating and three dummies each for the perception (Low, Medium, High) of the profit reduction and decrease in sales in the crisis. Heteroscedasticity-consistent standard errors are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

4.2. Credit supply and short term innovation adjustments

Finally, we focus on the instrumental variable estimations. Results of the usual Two-Stage Least Squares estimation are given in columns (1) to (4) in Table 3.[21] We begin by analyzing the impact of bank loan growth on the reduction of innovation activities during the crisis due to funding shortages (H1). The coefficient of the loan growth variable is negative and highly significant at the one percent level. This indicates that lower loan growth leads to a higher probability of reducing innovation activities.

The linear marginal effect reveals that a ten-percentage-point decrease in loan growth leads to an increase in the probability of reducing innovation activities due to funding shortages during the crisis by about 4.5 percentage points. Moreover, the coefficient of interest in column (2) is

significant at the five percent level. The effect implies that a decrease in loan growth by ten percentage point leads to a 4.7 percentage point lower probability of initiating a product innovation (column 2). With respect to the initiation of process innovation, we also find a positive effect which is not significant at conventional levels. Thus, firms react sensitively with respect to bank credit supply solely for the initiation of product innovation. These results for product and process innovation support Hypothesis 2 but not Hypothesis 3. Therefore, during the crisis new product developments are apparently initiated if external financial resources are available, but projects that serve cost savings by new processes are not affected.

Table 3: Instrumental variable estimation results for the immediate innovation adjustments

	(1)	(2)	(3)
Dependent variable	Innovation reduction	Product innovation	Process innovation
ΔCredit_Supply	-0.452***	0.470**	0.288
	(0.153)	(0.187)	(0.188)
Log of employees	-0.063**	0.048	0.067*
	(0.031)	(0.038)	(0.038)
Log of employees squared	0.006*	-0.007*	-0.006
	(0.003)	(0.004)	(0.004)
Log of age	-0.008	-0.043**	-0.050**
	(0.016)	(0.019)	(0.020)
Part of firm group	-0.005	-0.021	0.039
	(0.027)	(0.033)	(0.034)
Low influence of sales reduction	0.007	0.116**	0.115*
	(0.044)	(0.059)	(0.060)
Med influence of sales reduction	0.100**	0.128**	0.089
	(0.050)	(0.062)	(0.062)
High influence of sales reduction	0.119**	0.218***	0.124*
	(0.055)	(0.068)	(0.068)
Low influence of profit reduction	0.003	-0.065	-0.102*
	(0.044)	(0.060)	(0.059)
Med influence of profit reduction	0.051	-0.040	0.001
	(0.047)	(0.062)	(0.061)
High influence of profit reduction	0.169***	-0.102	-0.025
	(0.056)	(0.067)	(0.067)
Firm rating	0.001***	-0.001***	-0.000
	(0.000)	(0.000)	(0.000)
R-squared	0.218	0.208	0.188
Obs.	1465	1465	1465

Notes: The dependent variables are indicator variables concerning the changes in the firm's innovation behavior as of 2009. 'Innovation reduction' takes unit value if the firm has reduced its innovation activities due to funding shortages in 2009. 'Product innovation' marks the initiation of an additional product innovation. 'Process innovation' is similarly constructed for process innovation. The variable of interest, ΔCredit_Supply is constructed as the change in credit supply by banks from 2008 to 2009. Each regression includes industry times federal state fixed effects.

Heteroscedasticity-consistent standard errors are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

4.3. Credit supply and firm strategy

Next, we test for the firm's perception of the impact of innovation related strategy in reaction to the crisis, depending on bank credit supply. For this purpose, we again exploit our survey data such that we utilize questions which ask for the importance of strategic actions in response to changes in economic conditions during the crisis: "Which impact do the following strategic actions in response to changes in economic conditions have on your company?". We pick three commonly used (e.g. Archibugi et al. 2013a) innovation related items: "Reduction of production/service costs", "Renewal of existing production and service offers" and "Extension of supply to new market segments / customer groups". Answers were possible on a four-point Likert scale from "no importance" to "high importance". As a strategic action is more likely to be a long-term change, our test informs us whether the change in bank credit supply also affects the emphasis on long term strategic actions of firms. The results of linear regressions in Table 4 reveal that neither opportunity is affected by the change in credit supply.[22]

Table 4: Instrumental variable estimations for the effects on firm strategy

Dependent variable	(1) Product / service cost reduction	(2) Production and offer renewal	(3) Extension of supply to new markets
ΔCredit_Supply	0.021	0.236	0.441
	(0.335)	(0.369)	(0.351)
Log of employees	0.286***	0.125*	0.124
	(0.065)	(0.076)	(0.079)
Log of employees squared	-0.017***	-0.008	-0.013
	(0.006)	(0.008)	(0.008)
Log of age	-0.035	-0.072*	-0.011
	(0.032)	(0.038)	(0.035)
Part of firm group	0.114*	-0.025	0.080
	(0.059)	(0.066)	(0.066)
Low influence of sales reduction	0.227**	0.147	-0.083
	(0.110)	(0.117)	(0.115)
Med influence of sales reduction	0.384***	0.206*	0.064
	(0.117)	(0.122)	(0.124)
High influence of sales reduction	0.507***	0.325**	0.106
	(0.124)	(0.133)	(0.130)
Low influence of profit reduction	-0.014	0.037	0.151
	(0.114)	(0.120)	(0.118)
Med influence of profit reduction	0.235**	0.077	0.259**
	(0.114)	(0.122)	(0.121)
High influence of profit reduction	0.298**	0.066	0.350***
	(0.123)	(0.133)	(0.131)
Firm rating	-0.001	-0.001	-0.000
	(0.000)	(0.001)	(0.001)
R-squared	0.356	0.237	0.218
Obs.	1465	1465	1465

Notes: The dependent variables are indicator variables concerning the changes in the firm's innovation behavior as of 2009. 'Cost reduction' is a four-point scale variable which indicates the impact (None, Low, Average, High) of pursuing a production/service cost reduction strategy to cope with the changing economic conditions during the crisis. 'Offer renewal' and 'Extension of supply to new markets' are constructed similarly for the questions of the impact of the renewal of existing production and service offers and the extension of supply to new market segments/ customer groups. The variable Interbank is calculated as the value of interbank borrowing to total assets of the firm's main bank as of 2006. Each regression includes industry times federal state fixed effects. Heteroscedasticity-consistent standard errors are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

5. Robustness tests and extensions

5.1. Possible endogenous matching of firms and banks

A potential concern with respect to our identification strategy might be our assumption of a random affiliation of banks and their corporate customers. Firstly, the argument might be raised that innovative (high-risk) firms match with banks whose business model is based on funding this kind of firms. Thus, the observed effect on innovation would be rather due to a correlation of the

reduction of risky activities by banks and firms in the downturn than due to the negative shock to bank credit supply. Secondly, it might be the case that firms' financial strength in the downturn is highly related to their banks' exposure to the interbank market shock. In this case, banks with a higher probability of experiencing an interbank liquidity shortage would be related to firms which are more likely to experience worse economic outcomes in economic downturns. Hence, the possibility of a selectivity problem exists such that our estimates rather reflect endogenous matching than a causal effect. If this were the case, our identification strategy would be invalid and the estimation results biased.

We use a re-weighting approach to tackle the possible selectivity problem. To do so, we follow the two-step methodology proposed by Imbens and Wooldridge (2009) as well as Abadie and Cattaneo (2018): First, we estimate the probability of each firm to be treated (the propensity score). Treatment status is defined as being related to a bank in the upper quartile of the interbank distribution.[23] Then, we replicate our regressions of Table 3 and weight each observation by an inverse probability weight, generated from its propensity score.[24] The re-weighting is supposed to equalize the two firm types with respect to the explanatory variables. Consequently, potential differences between the two firm types would be eliminated.

Taking the inverse-probability weights, we re-estimate the specifications whose results are presented in Table 5. If the hypothesis of a sorting of firms and banks according to risk preferences and financial strength is true, our re-weighting approach would lead to drastically different results. The coefficients in Table 5 indicate that the results are comparable to the baseline results in Table 3. Interestingly, the credit supply coefficient is now significant at the five percent level for the initiation of additional process innovation.

Table 5: Re-weighted instrumental variable regressions

	(1)	(2)	(3)	(4)
Dependent variable	First stage	Innovation reduction	Product innovation	Process innovation
ΔCredit_Supply		-0.447***	0.589***	0.467**
		(0.168)	(0.197)	(0.197)
Interbank	-0.659***			
	(0.052)			
R-squared	0.377	0.256	0.252	0.234
Obs.	1462	1462	1462	1462

Notes: The dependent variables are indicator variables concerning the changes in the firm's innovation behavior as of 2009. 'Innovation reduction' takes unit value if the firm has reduced its innovation activities due to funding shortages in 2009. 'Product innovation' marks the initiation of an additional product innovation. 'Process innovation' is similarly constructed for process innovation. The variable Interbank is calculated as the value of interbank borrowing to total assets of the firm's main bank as of 2006. Each regression includes the following firm controls as described in Section 3.1: Log of firm size and its square, log of firm age, a dummy for being part of a firm group, the firms credit rating and three dummies each for the perception (Low, Medium, High) of the profit reduction and decrease in sales in the crisis. Each regression includes industry times federal state fixed effects. Heteroscedasticity-consistent standard errors are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

In addition to the inclusion of industry-federal state fixed effects, we employ a second test to alleviate concerns that the firm-bank matching or demand effects drive the results. The idea is to make the firms from specific industries and geographic areas as similar as possible such that only the difference in the firm's main bank interbank market reliance persists. This allows us to investigate whether the effect is due to the interbank market shock or due to the characteristics of firms and banks. We approach this test as follows: We keep only firms in the bottom and the top quartile of the interbank borrowing to asset ratio distribution such that our sample is restricted to 735 observations. Next, we use two different approaches to make the firms as similar as possible such that only the effect of the shock remains. Firstly, we estimate the probability of being in the top quartile and re-weight the instrumental variable estimations by the calculated inverse-probability weight. Results of this exercise (non-weighted and weighted) are shown in Table 6, Panels A and B. These are quite similar to the results presented above. Additionally, we observe that the coefficients are slightly larger in absolute terms. Again, the significance of the coefficient for process innovation reveals there is an impact of the change in credit supply on the initiation of this innovation type.

Secondly, we want to account for industry and region-specific firm bank matches. The aim of this exercise is to compare a firm with high interbank exposure to a similar firm with low interbank exposure in a similar geographic area and industry. Consequently, the shock effect becomes most important. For this purpose, we use the information on research intensive industries by Gehrke et al. (2013) to sort the firms into high research intensity, medium to low research intensity and irregular to no research activity. For the regional information, we use the information for federal states from Statistisches Bundesamt (2008). We construct four bins according to the share of sales per firm in the federal states. Combining this information leads to 12 groups of firms which are in similar regions and industries. To conduct the empirical test, we first calculate a propensity score for the group of firms in each category based on their size and firm rating. In a second step, we search for the nearest neighbor for each firm in the specific category.[25] Lastly, we apply our estimation approach only to the matched pairs. If our hypothesis of an interbank market related shock on innovation activities is true, we expect to observe diverging innovation outcomes for both types of firms in both approaches. The results in Table 6, Panel C show that we indeed observe significantly different outcomes.[26] Consequently, we can rule-out that demand effects are driving our results.

Table 6: Instrumental variable estimation results for tests concerning demand effects

	(1)	(2)	(3)	(4)
	First stage	Innovation reduction	Product innovation	Process innovation
Panel A: Top and bottom 25% (N= 735)				
ΔCredit_Supply		-0.546***	0.496**	0.404
		(0.207)	(0.246)	(0.245)
Interbank	-0.609***			
	(0.065)			
Panel B: Top and bottom 25%, re-weighted (N= 726)				
ΔCredit_Supply		-0.551***	0.561**	0.469**
		(0.199)	(0.236)	(0.233)
Interbank	-0.617***			
	(0.062)			
Panel C: Top and bottom 25%, matched pairs (N= 620)				
ΔCredit_Supply		-0.780***	0.893***	0.540**
		(0.226)	(0.264)	(0.249)
Interbank	-0.617***			
	(0.079)			

Notes: The dependent variables are indicator variables concerning the changes in the firm's innovation behavior as of 2009. 'Innovation reduction' takes unit value if the firm has reduced its innovation activities due to funding shortages in 2009. 'Product innovation' marks the initiation of an additional product innovation. 'Process innovation' is similarly constructed for process innovation. The variable of interest, ΔCredit_Supply is constructed as the change in credit supply by banks from 2008 to 2009. Coefficients reflect the estimates for ΔCredit_Supply for each subgroup. Each regression includes the following firm controls as described in Section 3.1: Log of firm size and its square, log of firm age, a dummy for being part of a firm group, the firms credit rating and three dummies each for the perception (Low, Medium, High) of the profit reduction and decrease in sales in the crisis. Each regression includes industry times federal state fixed effects. Heteroscedasticity-consistent standard errors are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

5.2. Crisis period refinement

In a further test we want to rule out that our results are driven by the measurement of the outcome variable. A valid argument might be that the innovation investments in firms are planned at least a year before the project starts. Thus, we apply the following two tests. First, we re-estimate our baseline regressions using the credit growth from 2007 to 2008. Secondly, we use the credit growth from 2007 to 2009 to validate our results. The estimations using the described outcome variables are shown in Table 7, Panels A and B. It becomes evident that the refinement of the crisis period does not substantially affect our results. Consequently, the firms exposed to the shock adjust their innovation behavior due to the change in credit supply.

Table 7: Instrumental variable estimation results for different crisis period definitions

Split variable	(1) First stage	(2) Innovation reduction	(3) Product innovation	(4) Process innovation
Panel A: 2007-2008 credit growth in the first stage				
ΔCredit_Supply		-0.633***	0.658**	0.404
		(0.217)	(0.262)	(0.262)
Interbank	-0.482***			
	(0.040)			
Panel B: 2007-2009 credit growth in the first stage				
ΔCredit_Supply		-0.280***	0.291**	0.179
		(0.094)	(0.115)	(0.116)
Interbank	-1.090***			
	(0.071)			

Notes: The dependent variables are indicator variables concerning the changes in the firm's innovation behavior as of 2009. 'Innovation reduction' takes unit value if the firm has reduced its innovation activities due to funding shortages in 2009. 'Product innovation' marks the initiation of an additional product innovation. 'Process innovation' is similarly constructed for process innovation. The variable of interest**,** ΔCredit_Supply is constructed as the change in credit supply by banks as given in the title of each panel. Each regression includes the following firm controls as described in Section 3.1: Log of firm size and its square, log of firm age, a dummy for being part of a firm group, the firms credit rating and three dummies each for the perception (Low, Medium, High) of the profit reduction and decrease in sales in the crisis. Each regression includes industry times federal state fixed effects. Heteroscedasticity-consistent standard errors are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

5.3. Effect heterogeneity

In addition to the previous robustness tests, we analyze the heterogeneity of our results. As argued in Section 2, we expect that firms react more sensitive to bank financing if they are directly affected by the recession and therefore face a lack of internal resources. By testing this hypothesis, we shed additional light on the question whether external financing in terms of bank credit supply affects firm innovation behavior independent of the access to internal resources. As argued above, we expect that this is not the case. Consequently, we assume that the impact of bank credit supply is stronger for firms, which face a reduction in demand or scarce internal means. Moreover, this exercise serves as a placebo test as from a theoretical point of view as there should be no impact on the probability to reduce innovation activities due to funding shortages for firms which were not affected by the reduction in internal means. We exploit our survey data such that we use a variety of indicators to differentiate between firms which are more

or less affected by the recession and the effects of the financial crisis. Results for these tests are displayed in Table 8.

In a first set of tests, we split the firms according to their sensitivity to changes in (i) a sales reduction and (ii) profit reduction due to the crisis. The question was asked as follows: "Which impact did the following consequences of the economic crisis 2008/2009 have for your company?" and includes the sub-items "Decrease in sales" and "Decrease in profits respectively increase in losses". Both questions were asked on a 4-point Likert scale from not sensitive to highly sensitive. We built a group of rather constrained and rather unconstrained firms from each indicator. The rather constrained group of firms consists of those which indicate a high or medium impact of the respective variable. The unconstrained group comprises firms which answer that the respective effect has a low or no impact. The results for the interactions of the credit supply variable with indicator variables for these groups are shown in Panel A and B of Table 8. For the group of rather constrained firms, the credit supply of banks has an impact on the propensity to reduce innovation or to initiate new product innovation. For process innovation there is a statistically significant coefficient only for firms which perceive a high or medium influence of the decrease in sales. Interestingly, for the unconstrained firms, we find no impact of the supply of credit except for the effect of credit supply on the reallocation of labor to the innovation department. These firms are financially sound and might reallocate their internal resource streams in their firm to strengthen their current innovation activities.

Additionally, we add up the values of the decrease in sales and profit measures and split the group of firms at the median. The lower part of the distribution is declared as low sensitivity and the upper part as high sensitivity. The results for estimations for the interaction of these indicator variables with the credit supply variable are shown on Panel C of Table 8. Remarkably, the

results are also fairly similar to the previous tests. Thus, internally constrained firms react more sensitively to the credit supply of banks in the financial crisis. This might imply an additivity of bank financing.

In a further set of tests, we analyze which type of firms are affected to a stronger degree by the financial crisis. For this purpose, we first distinguish between those firms which are part of a firm group and those which are not. Conglomerates are likely to have larger internal capital markets. Thus, they are expected to fund profitable projects which would not be financed by external means due to information asymmetries and agency costs (Shin and Stulz 1998). Their large internal capital market allows them to reallocate their financial resources to valuable investment projects in a recession (e.g. Hovakimian 2011). Thus, the allocation of financial resources in internal capital markets might mitigate restrictions in the supply of external financing (e.g. Matvos and Seru 2014). This consequently leads to the expectation that innovation activities of a firm that is part of a firm group will be less affected by the financial crisis than those of a firm that is not part of a group. The results in Panel D of Table 8 imply that this is indeed the case. Firms which are not part of a group react sensitively to the change in external financing in the recent financial crisis. Those firms which are part of a group and therefore likely to benefit from an internal capital market do not suffer from the credit supply restrictions in the recent financial crisis.

Next, we test whether there is a difference in the vulnerability to the shock with relation to firm size and firm age. It could be expected that smaller and younger firms suffer more severely from adverse conditions on financial markets than larger and older firms (e.g. Gertler and Gilchrist 1994). On the one hand, this is rooted in the lower amount of collateral which these (small or younger) firms can provide. On the other hand, the financial endowment plays a critical role. As

small and young firms are more likely to be facing liquidity constraints (e.g. Gertler and Gilchrist 1994), they are not able to benefit from a capital re-allocation inside the firm. Thus, these firms are probably not able to efficiently channel funds to valuable investment opportunities via capital re-allocations. The results in Panel E and F of Table 8 support this view for small and young firms. They imply that small and young firms suffer particularly from the credit supply reductions in the recent financial crisis and reduce innovation due to funding shortages in result. Surprisingly, older firms show no changes in current innovation activities, but react to decreases in credit supply by reducing the likelihood of the initiation of new innovation projects.

Table 8: Instrumental variable estimation results for subsamples of constraint and unconstraint firms

	(1)	(2)	(3)
	Innovation reduction	Product innovation	Process innovation
Panel A: Sensitivity to decrease in sales			
ΔCredit_Supply × Low sensitivity	-0.129	0.390	0.061
	(0.160)	(0.252)	(0.251)
ΔCredit_Supply × High sensitivity	-0.716***	0.535**	0.474*
	(0.239)	(0.265)	(0.266)
Panel B: Sensitivity to decrease in profits			
ΔCredit_Supply × Low sensitivity	-0.253	0.393	0.222
	(0.161)	(0.254)	(0.253)
ΔCredit_Supply × High sensitivity	-0.619**	0.535**	0.344
	(0.242)	(0.265)	(0.269)
Panel C: Sensitivity to changes in internal means			
ΔCredit_Supply × Low sensitivity	-0.238	0.106	0.180
	(0.161)	(0.249)	(0.247)
ΔCredit_Supply × High sensitivity	-0.662**	0.827***	0.394
	(0.259)	(0.283)	(0.290)
Panel D: Being part of a firm group or not			
ΔCredit_Supply × No group	-0.628***	0.699***	0.494**
	(0.208)	(0.248)	(0.251)
ΔCredit_Supply × Group	-0.197	0.138	-0.010
	(0.235)	(0.304)	(0.298)
Panel E: Small and large firms			
ΔCredit_Supply × Small	-0.478**	0.409	0.627**
	(0.223)	(0.275)	(0.285)
ΔCredit_Supply × Large	-0.413	0.562	-0.220
	(0.295)	(0.367)	(0.382)
Panel F: Young and old firms			
ΔCredit_Supply × Young	-0.695***	0.388	0.015
	(0.243)	(0.293)	(0.296)
ΔCredit_Supply × Old	-0.238	0.542**	0.530**
	(0.197)	(0.253)	(0.255)

Notes: The dependent variables are indicator variables concerning the changes in the firm's innovation behavior as of 2009. 'Innovation reduction' takes unit value if the firm has reduced its innovation activities due to funding shortages in 2009. 'Product innovation' marks the initiation of an additional product innovation. 'Process innovation' is similarly constructed for process innovation. The variable of interest**,** ΔCredit_Supply is constructed as the change in credit supply by banks from 2008 to 2009. Each regression includes the following firm controls as described in Section 3.1: Log of firm size and its square, log of firm age, a dummy for being part of a firm group, the firms credit rating and three dummies each for the perception (Low, Medium, High) of the profit reduction and decrease in sales in the crisis. Each regression includes industry times federal state fixed effects. Coefficients are reflecting the estimates for ΔCredit_Supply for each subgroup. Firms are defined as small if they have less than 50 employees in accordance with usual definition of small and medium-sized enterprises. Companies are characterized as young if they are younger than the median age. Heteroscedasticity-consistent standard errors are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

5.4. Labor reallocation

It is clear that capital can be quickly and flexibly allocated to other tasks within the company (e.g. Lamont 1997; Shin and Stulz 1998; Stein 1997). In addition, it has already been shown that employees are also reallocated within the firm (e.g. Giroud and Mueller 2015). We are investigating in particular whether, under the assumption of existing innovation opportunities, unused human resources[27] might be shifted to the innovation department. One the one hand, such a reallocation is e.g. possible if production departments are overstaffed during a crisis and the human resources are temporarily of higher use in innovation departments (if their skills fit). This would especially take place if firms are facing a fall in demand for specific products such that human resources are allocated away from these. On the other hand, the shift of unused human resources to innovation might result from the termination of other innovation processes. Both options (reallocation from production and reallocation from terminated innovation projects) take place under the assumption that the firm has sufficient financial resources at its disposal.[28] Empirical studies show that firms associated with banks hit hard by the crisis reduced employment to a particularly high degree (e.g. Chodorow-Reich 2014; Huber 2018). Thus, it could be expected that firms would rather reduce labor than reallocate it to innovation in case of a negative shock to financing in the recent financial crisis. The corresponding estimation results concerning the behavior of firms with respect to the alternative allocation of labor in relation to their main bank's loan growth are shown in Table 9. Our hypothesis gets empirical support as a ten percent lower bank loan growth induces a 5.7 percentage point decrease in the likelihood of reallocating human resources to innovation in the crisis.

Table 9: Instrumental variable estimation results for the immediate innovation adjustments

	(1)
Dependent variable	Labor reallocation
ΔCredit_Supply	0.570***
	(0.187)
Log of employees	0.049
	(0.031)
Log of employees squared	-0.005
	(0.003)
Log of age	-0.057***
	(0.018)
Part of firm group	-0.029
	(0.031)
Low influence of sales reduction	0.102*
	(0.058)
Med influence of sales reduction	0.120**
	(0.061)
High influence of sales reduction	0.148**
	(0.066)
Low influence of profit reduction	-0.005
	(0.058)
Med influence of profit reduction	0.004
	(0.060)
High influence of profit reduction	0.034
	(0.065)
Firm rating	-0.001**
	(0.000)
R-squared	0.115
Obs.	1465

Notes: The dependent variable is an indicator variable concerning the change in the firm's innovation behavior as of 2009. 'Labor reallocation' takes unit value if the firm reallocated free human resources to the innovation department. The variable of interest, ΔCredit_Supply is constructed as the change in credit supply by banks from 2008 to 2009. Each regression includes industry times federal state fixed effects. Heteroscedasticity-consistent standard errors are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

6. Conclusion

We provide evidence for the existence of a relationship between the credit supply shocks to banks during the recent financial crisis and firm innovation activities. For this purpose, we combine data on German firms with information about their main banks. We exploit the exogenous variation in bank loan supply by applying the interbank market borrowing to assets ratio as an instrument for bank loan growth. Results of instrumental variable estimations show that firms indeed reduce their actual innovation activity during the financial crisis due to funding shortages

if they are related to a bank with a lower loan growth. Moreover, we are able to show that firms with weaker banks in terms of lower bank loan growth are less likely to initiate product and process innovation as well as to reallocate human resources to innovation in the crisis period. Determining the impact on firm strategy, we find that strategic decisions to cope with the crisis are made independently of firms' access to external financing. Moreover, we find that the impact of external financing depends on the availability of internal funds. Thus, for firms with enough internal financing at hand, bank financing was less relevant for innovation than for firms which suffered from scarce financial means. We also find that small and young firms reduce their innovation activities due to funding shortages in the recent financial crisis when credit supply is reduced. Older firms instead are found to only react with respect to the initiation of new innovation to changes in credit supply.

The determined effects coincide with the predictions made in the literature on the negative effect of credit constraints on innovation expenditures during economic downturns (e.g. Aghion et al. 2012). Our finding of a decline in innovation activity caused by a reduction in bank lending is consistent with the view that credit constraints lead to pro-cyclical behavior. Additionally, our evidence adds largely to the understanding of how changes in the innovation department are made, when (external) financing is scarce. As highlighted by works like Nanda and Nicholas (2014), firms tend to pursue more conservative innovation projects when they face shocks to external financing. Our study adds to these findings by showing that these changes in the innovation mode did not only occur in the Great Depression but also in the recent financial crisis as firms only change their immediate innovation behavior but do not adopt a specific strategy to cope with the crisis. Our results are also related to the findings by Huber (2018) who estimates a patent reduction for Commerzbank-related firms. Assuming that reduced patents are the

consequence of reduced innovation efforts, our estimates are well suited to explain the estimates by Huber (2018).[29]

The result of the analysis has several policy implications. Firstly, in global economic downturns innovative firms are more likely to need support in times of hampered access to external financing. This is mainly rooted in the fact that innovation is important for growth, but also for the recovery of an economy after a crisis (Storm and Naastepad 2015). We propose subsidies as analyzed by Brautzsch et al. (2015) and Hud and Hussinger (2015). Aside of subsidizing firms, financial support for banks might be an option, but most helpful would be to establish a possibility to avoid credit crunches altogether through appropriate precautionary measures. Regulatory interventions like the Basel II and III frameworks were indeed helpful in covering the financial problems of banks in the aftermath of the financial crisis. One – perhaps until now little recognized – justification for such regulation is the securing of external financing for innovation and the continuance of the associated growth opportunities for economies.

CRediT author statement

Marek Giebel: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project Administration

Kornelius Kraft: Conceptualization, Methodology, Investigation, Resources, Writing – Review & Editing, Supervision, Project Administration, Funding acquisition

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Appendix A – Descriptive statistics

Table A1: Distribution of firms over industries

Name	NACE Rev. 2.0 code	Firms	Percentage share
Mining	5-9, 19, 35	29	1.980
Food/Tobacco	10-12	50	3.413
Textiles	13-15	60	4.096
Wood/Paper	16-17	48	3.276
Chemicals	20-21	92	6.280
Plastics	22	64	4.369
Glass/Ceramics	23	47	3.208
Metals	24-25	141	9.625
Electrical equipment	26-27	210	14.334
Machinery	28	135	9.215
Retail/Automobile	29-30	58	3.959
Furniture /Toys/Medical technology/Maintenance	31-33	125	8.532
Energy / Water	36-39	41	2.799
Media services	18, 58-60	53	3.618
IT/Telecommunications	61-63	104	7.099
Technical services/R&D services	71-72	162	11.058
Consulting/Advertising	69, 70.2, 73	46	3.140
Total		1465	100.000

Table A2: Distribution of firms over federal states

Name	Firms	Percentage share
Baden-Wuerttemberg	224	15.290
Bavaria	180	12.287
Berlin	52	3.549
Brandenburg	56	3.823
Bremen	20	1.365
Hamburg	23	1.570
Hesse	99	6.758
Lower Saxony	90	6.143
Mecklenburg-Vorpommern	27	1.843
North Rhine-Westphalia	237	16.177
Rhineland-Palatinate	39	2.662
Saarland	14	0.956
Saxony	194	13.242
Saxony-Anhalt	72	4.915
Schleswig-Holstein	30	2.048
Thuringia	108	7.372
Total	1465	100.000

Appendix B – The effect of interbank market reliance and innovation

Next, we test whether the shock to the interbank market affects the innovation behavior of firms directly. Thus, we shed light on the reduced form estimates (Table 3), which are obtained by regressing the innovation outcome variables on the interbank market measure. The coefficient is positive and significant at the 1 percent level in column (1). This indicates that a 10 percent increase in the interbank borrowing ratio increases the probability of reducing innovation activities due to funding shortages by about 3.1 percent. For the remainder of the outcome variables, we observe expected, negative effects of the interbank borrowing ratio. Although, the coefficient is not significant at conventional levels for the initiation of process innovation in column (3), the other coefficients are highly significant at the 1 percent level.[30]

Table B1: Linear regression for the effect of interbank market borrowing on immediate innovation adjustments

	(1)	(2)	(3)
Dependent variable	Innovation reduction	Product innovation	Process innovation
Interbank	0.305***	-0.317**	-0.195
	(0.099)	(0.125)	(0.126)
R-squared	0.258	0.229	0.199
Obs.	1465	1465	1465

Notes: The dependent variables are indicator variables concerning the changes in the firm's innovation behavior as of 2009. 'Innovation reduction' takes unit value if the firm has reduced its innovation activities due to funding shortages in 2009. 'Product innovation' marks the initiation of an additional product innovation. 'Process innovation' is similarly constructed for process innovation. The variable Interbank is calculated as the value of interbank borrowing to total assets of the firm's main bank as of 2006. Each regression includes the following firm controls as described in Section 3.1: Log of firm size and its square, log of firm age, a dummy for being part of a firm group, the firms credit rating and three dummies each for the perception (Low, Medium, High) of the profit reduction and decrease in sales in the crisis. Each regression includes industry times federal state fixed effects. Heteroscedasticity-consistent standard errors are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

We use the reduced form estimates to determine the aggregate effect of the interbank market shock on the innovation outcomes in our sample.[31] Firstly, we calculate the predicted probability of each firm to adjust the related outcome and assume that the counterfactual state is that a zero interbank market borrowing to asset ratio exerts no effect on innovation. Consequently, we

simply multiply the coefficient of interbank with the average interbank market borrowing to asset ratio of the firms. For the reduction in innovation expenditures due to funding shortages in column (1) which serves as our benchmark result, this calculation exercise (0.305×0.255) results in 0.078. Thus, a firm associated with the average bank is 7.8% more likely to reduce its innovation behavior due to funding shortages in the crisis than a firm related to a bank with zero interbank market usage. In the next step, we divide this predicted probability by the sample mean of the dependent variable to evaluate the economic impact. The result implies that the interbank market shock explains about 38.8% of the reduction in innovation due to funding shortages.

Similarly, we can calculate the aggregate impact of the bank credit supply shock on the initiation of product innovation. For this purpose, we took the counter probability of this event to evaluate the foregone efforts. We find that about 31.75% of the reduction in product innovation are observed due to the interbank market shock. Consequently, the shock to the bank system significantly explains the innovation behavior of firms in the crisis.

Appendix C – Additional tables – Linear instrumental variable regressions

C1 – Reduced form regression utilizing a probit estimation approach

Table C1: Probit estimations for the effect of interbank market borrowing on immediate innovation adjustments

	(1)	(2)	(3)
Dependent variable	Innovation reduction	Product innovation	Process innovation
Interbank	0.281***	-0.285**	-0.170
	(0.089)	(0.120)	(0.120)
Pseudo R-squared	0.146	0.052	0.036
Obs.	1465	1465	1465

Notes: The dependent variables are indicator variables concerning the changes in the firm's innovation behavior as of 2009. 'Innovation reduction' takes unit value if the firm has reduced its innovation activities due to funding shortages in 2009. 'Product innovation' marks the initiation of an additional product innovation. 'Process innovation' is similarly constructed for process innovation. The variable Interbank is calculated as the value of interbank borrowing to total assets of the firm's main bank as of 2006. Coefficients are reflecting the marginal effects of the Interbank estimate calculated at the mean of the explanatory variables. Each regression includes the following firm controls as described in Section 3.1: Log of firm size and its square, log of firm age, a dummy for being part of a firm group, the firms credit rating and three dummies each for the perception (Low, Medium, High) of the profit reduction and decrease in sales in the crisis. Each regression includes industry and federal state fixed effects. Heteroscedasticity-consistent standard errors are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

C2 – Instrumental variable estimator for a binary dependent variable

Next, we apply the two-stage conditional maximum likelihood estimator (2SCML) as proposed by Rivers and Vuong (1988). The estimation strategy is related to the usual two-step approach described in section 3.2. Firstly, we run a first-stage OLS regression of ΔCredit_Supply on all instruments (Interbank market ratio). In the second stage, we plug the residuals of the first-stage regression (2) into the Probit equation (1). Standard errors are obtained by 200 bootstrap replications. This approach has two advantages: Firstly, we are able to test for the exogeneity of the ΔCredit_Supply variable by inspecting the significance of the coefficient of the residuals as suggested by Wooldridge (2002, p. 474). Secondly, we avoid inconsistent estimates which are produced by the usual two-stage approach with a nonlinear estimator in the second stage (Terza et al. 2008).

Table C2: Estimation results using the 2SCML estimation approach

	(1)	(2)	(3)
Dependent variable	Innovation reduction	Product innovation	Process innovation
	2SCML	2SCML	2SCML
ΔCredit_Supply	-0.430***	0.439**	0.262
	(0.138)	(0.197)	(0.193)
First stage residuals	0.540***	-0.446**	-0.348*
	(0.159)	(0.226)	(0.206)
Pseudo R-squared	0.148	0.052	0.037
Obs.	1465	1465	1465

Notes: The dependent variables are indicator variables concerning the changes in the firm's innovation behavior as of 2009. 'Innovation reduction' takes unit value if the firm has reduced its innovation activities due to funding shortages in 2009. 'Product innovation' marks the initiation of an additional product innovation. 'Process innovation' is similarly constructed for process innovation. The variable of interest, ΔCredit_Supply is constructed as the change in credit supply by banks from 2008 to 2009. Coefficients are reflecting the marginal effects of the **Δ**Credit_supply coefficient calculated at the mean of the explanatory variables. Each regression includes the following firm controls as described in Section 3.1: Log of firm size and its square, log of firm age, a dummy for being part of a firm group, the firms credit rating and three dummies each for the perception (Low, Medium, High) of the profit reduction and decrease in sales in the crisis. Each regression includes industry and federal state fixed effects separately. Bootstrapped standard errors obtained by 200 replications are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

Appendix D – Additional tables – Possible endogenous matching

Table D1: Matching results to obtain the propensity score for the construction of the inverse probability weights

	(1)
Dependent variable	Treated bank
Log of employees	0.557***
	(0.110)
Log of employees squared	-0.044***
	(0.011)
Log of age	-0.112**
	(0.050)
Part of firm group	0.125
	(0.086)
Low influence of sales reduction	0.035
	(0.157)
Med influence of sales reduction	0.062
	(0.167)
High influence of sales reduction	0.080
	(0.182)
Low influence of profit reduction	0.093
	(0.157)
Med influence of profit reduction	0.032
	(0.162)
High influence of profit reduction	0.011
	(0.179)
Firm rating	0.000
	(0.001)
Constant	-2.070***
	(0.485)
Pseudo R-squared	0.075
Obs.	1465

Notes: Standard errors in parentheses. Treatment status is defined as being related to a bank in the upper quartile of the interbank distribution. Each regression includes industry times federal state fixed effects. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

Table D2: Mean comparison before matching. Means calculated using inverse probability weights

	Mean		Difference	p-value
Variable	Control	Treated		
Log of employees	3.870	3.798	-0.073	0.586
Log of employees squared	17.470	16.901	-0.569	0.580
Log of age	2.995	3.008	0.012	0.821
Part of firm group	0.449	0.437	-0.012	0.732
Low influence of sales reduction	0.188	0.186	-0.002	0.953
Med influence of sales reduction	0.235	0.236	0.000	0.988
High influence of sales reduction	0.361	0.346	-0.015	0.651
Low influence of profit reduction	0.182	0.174	-0.007	0.783
Med influence of profit reduction	0.256	0.257	0.001	0.966
High influence of profit reduction	0.340	0.317	-0.023	0.486
Firm rating	226.893	225.132	-1.760	0.562

Appendix E – Additional tables – Demand effects

Table E1: Matching results to obtain the propensity score for the construction of the inverse probability weights

Dependent variable	(1) Treated bank
Panel A: Group 1 (N=85)	
Log of employees	0.179
	(0.123)
Firm rating	-0.002
	(0.004)
Panel B: Group 2 (N=39)	
Log of employees	0.996***
	(0.348)
Firm rating	0.001
	(0.006)
Panel C: Group 3 (N=59)	
Log of employees	0.042
	(0.108)
Firm rating	0.004
	(0.004)
Panel D: Group 4 (N=74)	
Log of employees	0.138
	(0.103)
Firm rating	-0.006
	(0.004)
Panel E: Group 5 (N=56)	
Log of employees	-0.048
	(0.180)
Firm rating	-0.023***
	(0.007)

(continued)

Table E1: Continued

Panel F: Group 6 (N=24)	
Log of employees	0.228
	(0.217)
Firm rating	0.003
	(0.004)
Panel G: Group 7 (N=64)	
Log of employees	0.459***
	(0.145)
Firm rating	0.005
	(0.005)
Panel H: Group 8 (N=66)	
Log of employees	0.475***
	(0.141)
Firm rating	0.002
	(0.005)
Panel J: Group 9 (N=85)	
Log of employees	0.577***
	(0.167)
Firm rating	0.007*
	(0.004)
Panel K: Group 10 (N=32)	
Log of employees	0.559**
	(0.266)
Firm rating	0.012
	(0.009)
Panel L: Group 11 (N=73)	
Log of employees	0.404***
	(0.123)
Firm rating	-0.001
	(0.003)
Panel M: Group 12 (N=74)	
Log of employees	0.249*
	(0.132)
Firm rating	0.005
	(0.004)

Notes: Treatment status is defined as being related to a bank in the upper quartile of the interbank distribution. Standard errors in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

Table E2: Mean comparison before matching. Means calculated using inverse probability weights

	Mean		Difference	p-value
Variable	Control	Treated		
Panel A: Group 1 (N=85)				
Log of employees	3.912	3.947	0.021	0.894
Firm rating	220.805	221.610	0.017	0.912
Panel B: Group 2 (N=39)				
Log of employees	2.912	2.898	-0.014	0.963
Firm rating	253.636	242.455	-0.205	0.505
Panel C: Group 3 (N=59)				
Log of employees	4.361	4.173	-0.074	0.718
Firm rating	231.458	233.875	0.045	0.828
Panel D: Group 4 (N=74)				
Log of employees	4.566	4.793	0.110	0.479
Firm rating	205.738	208.500	0.057	0.712
Panel E: Group 5 (N=56)				
Log of employees	3.387	3.196	-0.124	0.575
Firm rating	211.333	211.571	0.008	0.972
Panel F: Group 6 (N=24)				
Log of employees	2.694	2.905	0.248	0.444
Firm rating	264.400	253.800	-0.186	0.564
Panel G: Group 7 (N=64)				
Log of employees	3.992	3.996	0.002	0.991
Firm rating	225.625	227.167	0.032	0.876
Panel H: Group 8(N=66)				
Log of employees	3.398	3.400	0.001	0.996
Firm rating	235.821	242.393	0.121	0.525
Panel I: Group 9 (N=85)				
Log of employees	4.106	4.072	-0.026	0.871
Firm rating	227.526	228.579	0.019	0.908
Panel J: Group 10 (N=32)				
Log of employees	3.847	4.116	0.171	0.499
Firm rating	231.750	220.688	-0.258	0.311
Panel K: Group 11 (N=73)				
Log of employees	5.195	5.198	0.002	0.995
Firm rating	206.667	208.611	0.023	0.924
Panel L: Group 12 (N=74)				
Log of employees	4.331	4.197	-0.071	0.669
Firm rating	215.162	220.865	0.080	0.628

Appendix F – Additional tables – Estimator for an ordered dependent variable

Table F1: Estimation results and marginal effects for an ordered dependent variable

	(1)	(2)	(3)	(4)	(5)
	Ordered probit	Marginal effect			
		No impact	Low impact	Medium impact	High impact
Panel A: Product / service cost reduction					
ΔCredit_Supply	0.122	-0.013	-0.021	-0.015	0.048
	(0.427)	(0.042)	(0.075)	(0.052)	(0.169)
Panel B: Production and offer renewal					
ΔCredit_Supply	0.314	-0.070	-0.050	0.025	0.095
	(0.408)	(0.089)	(0.067)	(0.034)	(0.122)
Panel C: Extension of supply to new markets					
ΔCredit_Supply	0.702*	-0.118*	-0.112	-0.031	0.262*
	(0.425)	(0.069)	(0.070)	(0.021)	(0.158)

Notes: The dependent variables are indicator variables concerning the changes in the firm's innovation behavior as of 2009. 'Cost reduction' is a four point scale variable which indicates the impact (None, Low, Average, High) of pursuing a production/service cost reduction strategy to cope with the changing economic conditions during the crisis. 'Offer renewal' and 'Extension of supply to new markets' are constructed similarly for the questions of the impact of the renewal of existing production and service offers and the extension of supply to new market segments/ customer groups. The variable of interest**,** ΔCredit_Supply is constructed as the change in credit supply by banks from 2008 to 2009. Coefficients reflect the estimates for ΔCredit_Supply for each subgroup. Each regression includes the following firm controls as described in Section 3.1: Log of firm size and its square, log of firm age, a dummy for being part of a firm group, the firms credit rating and three dummies each for the perception (Low, Medium, High) of the profit reduction and decrease in sales in the crisis. Each regression includes industry and federal state fixed effects separately. Bootstrapped standard errors obtained by 200 replications are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

[1] See for example works like Aghion et al. (2005), Romer (1990) and Solow (1957) which show that innovations are important drivers for economic growth, development and competitiveness.

[2] A frequently mentioned problem related with survey responses is the non-response (see e.g. Vandenplas et al. 2015) and the social desirability bias (see e.g. Krumpal 2013). Thus, perhaps some managers do not want to admit economic problems in general and also with respect to the consequences of the financial crisis. On the other hand, in an anonymous survey they can express their dissatisfaction with problems in the economy such as insufficient access to credit.

[3] See e.g. Archibugi et al. (2013a); Archibugi et al. (2013b); Campello et al. (2010); Filippetti and Archibugi (2011); Hud and Hussinger (2015); Paunov (2012).

[4] Empirical studies from different angles include, for example, firm-bank relationships (e.g. Cosci et al. 2016; Giannetti 2012; Herrera and Minetti 2007), effects of bank de-regulation (e.g. Amore et al. 2013; Chava et al. 2013; Cornaggia et al. 2015), impacts of regional bank characteristics (e.g. Alessandrini et al. 2010; Benfratello et al. 2008; Hsu et al. 2014) or effects of regional bank distress (e.g. Nanda and Nicholas 2014).

[5] For different outcomes like investment or employment see e.g. Balduzzi et al. (2018); Bentolila et al. (2017); Chodorow-Reich (2014); Cingano et al. (2016); Dwenger et al. (2018); Giebel and Kraft (2019); Huber (2018); Iyer et al. (2014); Popov and Rocholl (2018).

[6] Our results might help to explain the finding in Huber (2018) that a patenting reduction between 2009 and 2012 is driven by the years 2011 onwards as a patent is the outcome of the innovation process in the firm.

[7] Empirical studies show that significant problems for innovative firms attempting to access external capital exist (e.g. Mina et al. 2013). These are seriously hampering innovation activities (e.g. Ayyagari et al. 2011; Mohnen et al. 2008) or lead to an underinvestment in R&D (e.g. Czarnitzki and Hottenrott 2011a and 2011b).

[8] It has to be noted that recent studies show that patents could be used as a collateral for bank financing or the reduction of information asymmetry between borrowers and lenders (e.g. Mann 2018; Saidi and Zaldokas 2019).

[9] Empirical evidence indicates that access to external finance also influences innovation activities. Studies show that characteristics of the firm-bank relationship (e.g. Cosci et al. 2016; Giannetti 2012; Herrera and Minetti 2007) and

regional bank characteristics (i.e. deregulation) impact firm innovation (e.g. Alessandrini et al. 2010; Amore et al. 2013; Benfratello et al. 2008; Chava et al. 2013; Cornaggia et al. 2015; Hsu et al. 2014; Nanda and Nicholas 2014).

[10] The bank lending channel in Germany is investigated by e.g. Ehrmann and Worms (2004); Upper and Worms (2004), Worms (2003).

[11] For Europe and Germany it is shown that the financial crisis of 2008/09 led to a credit supply reduction to the real sector (Bundesbank 2009; Cingano et al. 2016; Dwenger et al. 2018; Iyer et al. 2014; Meriläinen 2016; Puri et al. 2011).

[12] This is also observed in the recent financial crisis for Europe and Germany (e.g. de Bondt et al. 2010; Gilchrist and Mojon 2018). Additionally, financing is hampered even if firms try to substitute away from bank funding to other sources such as equity, since these financing sources are also affected (Kahle and Stulz 2013).

[13] Capital reallocation within firms led to a mitigation of financial frictions in the recent financial crisis (Matvos and Seru 2014).

[14] This is also evident in the empirical literature (e.g. Alessandrini et al. 2010; Benfratello et al. 2008). Investigating the impact of bank development on innovation, Benfretello et al. (2008) find a strong effect on process innovation as well as a weak and not robust effect on product innovation. Alessandrini et al. (2010) on the one hand find that functionally distance between the banking system and the local economy impacts both product and process innovation. Additionally, their results imply that the market share of large banks is only weakly correlated with the introduction of product innovation.

[15] See e.g. Rammer (2012) for a technical summary of the MIP wave 2010.

[16] For private banks, headquarter balance sheet information is applied.

[17] Table A1 of Appendix A shows the distribution of firms over the industries.

[18] We impute missing rating observations by lagged rating values. See e.g. Czarnitzki and Toole (2011) for a similar approach.

[19] In 2009, the Dresdner Bank and Commerzbank merged. Since we do not want to create a selection problem by dropping those observations, we deal with their merger by aggregating the pre-merger balance sheet positions of both banks for continuous variables. See e.g. Huber (2018) for a similar approach.

[20] We present additional definitions of the change in credit supply in the robustness test section 5.2. These cover the change from the year 2007 to 2008 as well as the change from 2007 to 2009.

[21] Results for an estimation method, which accounts for the binary nature of the dependent variable are shown in Appendix C, Table C2. The results are comparable.

[22] We conduct additional tests, which reinforce the results in Table 4. We find that there is no impact of the bank credit supply shock on the innovation strategy choice (i) conditional on being affected by the crisis (or not), (ii) conditional on taking any short-term innovation adjustment. Results for these tests are available upon request. Using a two-stage ordered probit estimation approach does not alter the results (Appendix F, Table F1). Additional tests with dummy variables indicating at least medium importance to any mere leads to similar results.

[23] The results are similar when defining firms as treated when they are related to a bank in the upper 10% or 50% of the interbank distribution. Results are available upon request.

[24] Appendix D covers results of the propensity score estimation (Table D1) and mean comparison after the re-weighting (Table D3). Restricting the sample to common support leads to a loss of 3 observations.

[25] We allow for a maximum acceptable difference between treatment and control observations (Caliper) of 0.05. Our caliper choice is below the caliper of 0.25 times the standard deviation of the propensity score as suggested by Rosenbaum and Rubin (1985).

[26] Results of the probit estimation to determine the propensity score are shown in Appendix E, Table E1. The comparison of means between treatment and control group before and after the re-weighting are given in Appendix E, Tables E2 and E3.

[27] Following Teece (1980), firms are able to shift inputs like capital and labor between production processes.

[28] See e.g. Nohria and Gulati (1996) for a discussion and analysis of the impact of slack resources on innovation.

[29] It has to be noted that the patent reduction could also be a strategic choice.

[30] Reduced form estimates without industry times state fixed effects and/or without controls have a similar magnitude and significance. They are available upon request. See Appendix C, Table C1 for the estimation of the reduced form relationship using a Probit model.

[31] Our approach to determine the aggregate impact follows Denk and Finkel (1992).