The Limits of Open Innovation: Openness and (quasi-)markets in the organization of innovation

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RP 0713

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April 2007

ISBN No: 978-1-85449-703-1

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Abstract:
Recent studies have stressed the importance of open innovation, a market-based approach to the governance of internal knowledge sharing through cross-functional teams alongside boundary-spanning knowledge linkages. To date, however, evidence on the complementarity *between* these two aspects of the organization of firms' innovation activities has been limited. Positive evidence does exist, however, on the benefits of each individual aspect of the open innovation approach. Our evidence, based on large samples of UK and German manufacturing plants, also suggests positive complementarities between the use of cross-functional teams in multiple innovation activities. It also suggests a similar result for boundary-spanning knowledge linkages. When these aspects of the open innovation approach are combined in more than one innovation activity, however, negative complementarities result. Our results therefore suggest that in practice the benefits envisaged in the open innovation approach are not generally achievable by the majority of plants, and that instead the adoption of open innovation across the whole innovation process – comprising a number of innovation activities - is likely to reduce innovation outputs. We argue, following Nickerson and Zenger (2004), that this may be the result of the potential for knowledge formation hazards in the innovation process, with the implication that more hierarchical forms of governance of the innovation process may be more generally effective.

JEL classification: O15, O31, O32

Keywords: Open innovation, (quasi-)markets, complementarities, UK, Germany

Acknowledgements: The research reported in this paper was supported by the ESRC under award RES-000-22-0813. We are grateful for the constructive comments of Keld Laursen.

1. Introduction

Recent studies have stressed the importance of 'open innovation' as a means of enhancing innovation performance (e.g. Chesbrough, 2003). As it is frequently described, the essence of the open innovation approach is to take advantage of external as well as internal knowledge sources in developing and commercialising innovation, so avoiding an excessively narrow internal focus in a key area of corporate activity. Although this boundary-spanning aspect of open innovation is often stressed, another key aspect of the open innovation approach involves maximising the sharing of ideas and knowledge *within* the firm through, for example, the use of cross-functional teams. A comprehensive implementation of the open innovation approach would therefore combine both aspects, i.e. cross-functional teams and boundary-spanning knowledge linkages.

To date, however, evidence on the complementarity *between* these two aspects of the organization of firms' innovation activity has been limited, although positive evidence does exist on the benefits of each individual aspect of the open innovation approach. In terms of internal knowledge sharing through cross-functional teams, for example, it has been argued that team-working may facilitate knowledge integration and information exchange (e.g. Grabher, 2001) and the development of trust and mutual learning (Creed and Miles, 1996). Positive empirical evidence also exists, however, suggesting the benefits of cross-functional teams on firms' innovation outputs. Cooper and Kleinschmidt (1995), for example, identify firms' use of cross-functional teams as one of the key success factors in new product development projects, while Gupta and Wilemon (1996) emphasise the importance attached to the development of cross-functional teams by R&D and technology managers. Similarly positive evidence exists of the benefits of boundary-spanning knowledge linkages for firms' innovation activity (e.g. Veugelers and Cassiman, 1999; Love and Roper, 2001, 2002; Cassiman and Veugelers, 2006). These studies also provide some evidence of complementarities between firms' internal activities – generally the firm's intra-mural R&D – and boundary-spanning knowledge linkages (e.g. Cassiman and Veugelers, 2006).

Our aim here – enabled by detailed information on the organization of firms' innovation activities – is to examine directly the pattern of complementarities between firms' internal knowledge sharing (i.e. their use of cross functional teams) and their boundary-spanning linkages. Open innovation suggests that we would expect to observe positive complementarities with the innovation benefits of each activity being mutually enhancing. In other words, in terms of Milgrom and Roberts (1990, 1995), we expect to observe Edgeworth complementarities between firms' internal and external knowledge sharing activities.

More fundamentally, however, our analysis may be seen as providing evidence on the extent to which market control can replace hierarchy in the organization of innovation. Historically, the analysis of boundary-spanning linkages has focussed extensively on the market ('buy') or hierarchy ('make') choice in terms of R&D and innovation (e.g. Veugelers and Cassiman, 1999; Love and Roper, 2001; Cassiman and Veugelers, 2006), while the adoption of cross-functional teams may be seen as the internal replacement of hierarchical with market controls, viz. "…teams function under market control, much like an external subcontractor. Similar to an external contractor, the autonomous work teams possess the capacity to deliver complete outputs (often complete intermediate outputs) and are measured and rewarded based on delivery of these outputs" (Zenger, 2002, p. 83). In other words, both the internal knowledge sharing and boundary-spanning linkages idealised in the open innovation approach represent the substitution of market control for hierarchy in terms of the organization of innovation. Our analysis examines whether the properties of market control envisaged by Zenger (2002) do actually produce the complementarities anticipated by the open innovation approach.

The remainder of the paper is organized as follows. In Section 2 we set out the conceptual framework for our research and derive hypotheses. We also review previous conceptual and empirical studies relating to complementarities in the innovation process, in particular those related to either cross-functional teams or firms' boundary-spanning linkages. This emphasises the positive, if partial, evidence on the individual benefits of cross-functional teams and boundary-spanning linkages for innovation, but also emphasises the potential limitations of market control mechanisms in the context of the uncertainties of the innovation process. Section 3 outlines our data sources, which relate to UK and German manufacturing plants, and our empirical approach which draws on Milgrom and Roberts (1990, 1995) and Mohnen and Röller (2005). Section 4 presents our empirical results which suggest the limits of market control in the context of innovation. Section 5 discusses the implications of our empirical results for the open innovation approach, and relates this to the theoretical analysis of Nickerson and Zenger (2004). The final section broadens the discussion to the implications of the research for innovation strategy.

2. Conceptual Framework and Hypotheses

Our primary concern here is to establish the way in which firms' internal knowledge sharing and boundary-spanning linkages interact to influence innovation outputs. Conventionally, the relationship between the inputs to firms' innovation activities and innovation outputs are modelled using the innovation or knowledge production function (e.g. Griliches, 1979; Love and Roper, 2001). The nature of firms' internal knowledge sharing and boundary-spanning may then increase innovation outputs for any given set of resource inputs. In particular, if I_i is a measure of the innovation outputs of firm i, n is the number of different 'activities' which comprise the innovation process, oin_i is an indicator variable indicating whether a firm is adopting an open innovation approach in activity i, and Z_i is a vector of control variables, we can write:

$$I_i = \sum_i^n \gamma_i oin_i + \beta Z_i + \varepsilon_i \qquad (1)$$

In terms of firms' internal knowledge sharing relationships and boundary-spanning linkages, two extreme situations might be envisaged. At one extreme, and reminiscent of

Rothwell's (1994) first generation innovation model, would be a situation where innovation is organized in a manner entirely internal to the firm, that is with no boundary-spanning relationships, and with internal functional demarcation of all of the different activities in the innovation process. This 'closed' innovation model (i.e. $oin_i = 0$ for all i) would represent 'traditional hierarchy' in the terms suggested by Zenger (2002). At the other extreme would be an open innovation approach (Chesbrough, 2003) with boundary-spanning linkages and cross-functional teams in all of the different activities comprising the innovation process (i.e. $oin_i = 1$ for all i). This 'open' approach to innovation equates to the replacement of hierarchy with market or quasi-market structures throughout all aspects of the innovation process, and the replacement of authority-based structures with the high-powered incentives implicit in market organization. Intermediate strategies could also be envisaged, of course, with either boundary-spanning and cross-functional teams used together in a sub-set of innovation activities, or used individually in different innovation activities. Such strategies can be conceived as discrete choices, with the potential for different strategy choices to yield different patterns of complementarities[1]. One important implication is that the potential gains for innovation from implementing cross-functional teams, say, may be undermined without an understanding the complementarities involved elsewhere : "Such violations of complementarity encourage further change initiatives which unravel the bundle of elements that support traditional hierarchy and push the organization towards a fundamental transformation. The clear trajectory of this transformation is toward quite radically, disaggregated organizations structured around teams. Complementary pressures, thus, push organizations toward either of two rather discrete and somewhat extreme organizational choices". (Zenger, 2002, p. 80). In earlier work, for example, we have shown that the complementarities stemming from cross-functional teams are strongest in the product identification and engineering elements of the product innovation process; and, that extending cross-functional working to marketing and the development of market strategy can have a negative impact on innovation success (Love et al., 2006).

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[1] Conceptual support for this view can be found in the literatures on punctuated equilibrium models (e.g. Gersick, 1991; Tushman and Romanelli, 1985).

Other studies have also suggested the potential contribution of cross-functional team working to the innovation process. Zeller (2002), for example, describes the introduction of cross-functional teams as part of the restructuring of R&D activities within pharmaceutical companies in response to the increasing globalisation of R&D:"Implementing new organizational structures such as cross-functional project teams, the pharmaceuticals pursued the goals of accelerating all relevant processes, in particular the development times, maintaining or improving innovative capabilities and integrating R&D operations located at different places." (Zeller, 2002, p. 279). Zeller also stresses the importance of project teams in developing stronger interconnectedness between discovery, development and marketing activities enabling firms to exploit potential complementarities (see also, Bonnett, 1986; Gupta *et al.*, 1987; Souder and Moenaert, 1992). More recently, Michie and Sheehan (2003) consider firms with high levels of participation in team-work as part of their examination of impact of alternative HRM systems on innovation in larger UK firms. Their findings are positive in that the HRM systems which include cross-functional teams have strongest positive impact on innovation outputs.

A particular focus in studies of cross-functional teams in innovation has been their potential to integrate firms' R&D and marketing functions (Robertson and Langlois, 1995). Hise et al. (1990), for example, from their analysis of the new product development procedures of 252 large manufacturing companies, conclude that collaborative efforts between marketing and R&D are a key factor in explaining the success levels of new products. Similarly, in their review of evidence, Robertson and Langlois, 1995, p.553 conclude that: "Independent of the degree of ownership integration, cross-functional and inter-firm project teams organizationally integrate parts of the production system in a selective way. This selective vertical integration contributes to speeding up innovation and development processes. The information flow and mutual understanding can be improved if researchers in discovery and development departments and even marketing people are unified at least temporarily in the same organization". The strategic, organizational and institutional context within which cross-functional teams are implemented has also received significant attention in the literature. Zenger

(2002) and others, for example, have argued that the range of effective organizational forms for innovation is not continuous but discrete, with choices defined by patterns of complementarity between system components. Empirical evidence is also available, however, which emphasizes the complementarity between cross-functional teams and other HRM strategies (Laursen, 2002; Laursen and Foss, 2003) and elements of industrial organization (Lhuillery, 2000)[2].

Similar organizational and institutional considerations have also shaped recent empirical studies of the benefits of boundary-spanning linkages for firms' innovation activity. For example, the role of R&D in shaping firms' absorptive capacity is now widely recognized (Cohen and Levinthal, 1989; Zahra and George, 2002; Roper et al., 2006) suggesting that some internal R&D capacity is needed for three reasons: first, to permit scanning for the best available external knowledge; secondly, to enable the efficient absorption and use of this knowledge; and thirdly, to help in the appropriation of the returns from new innovations (e.g. Griffith et al.,2003). Internal R&D may, for example, help firms to minimise asymmetric information with technology suppliers and so reduce uncertainty and the transaction costs and other strategic issues associated with extramural R&D (Teece, 1988; Audretsch et al, 1996). In the specific context of open innovation, Laursen and Salter (2006) find that increasing both the breadth and depth of external search[3] enhances innovation performance, but does so at a decreasing rate, so that beyond some limit the returns to increased breadth and depth of search become negative. In this study of UK manufacturing enterprises, Laursen and Salter also find that R&D enhances innovation, but at the margin there may be some substitution between internal and external knowledge sources in the innovation process.

This discussion of the relevant conceptual and empirical literature leads to two testable hypotheses. The first of these derives directly from the concept of open innovation, and

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[2] Team performance may also depend, however, on leadership (e.g. Stoker et al, 2001), external threat or support (West, 2002) or teamwork quality (Hoegl and Gemuenden, 2001).

[3] In this study 'breadth' is defined as the number of external sources used in innovation, while 'depth' relates to the extent to which firms draw heavily on these external sources.

relates to the *existence* of openness and its impact on innovation. This simply tests the proposition that some degree of openness is superior to a closed innovation approach:

H1: Complementarities exist between the use of cross-functional teams and boundary-spanning linkages, resulting in higher levels of innovation performance where they are used together relative to a closed innovation model.

The second hypothesis relates to the *extent* of openness in the organization of innovation, testing the hypothesis that a greater degree of openness leads to more innovation. Acknowledging the contribution of Zenger (2002) and Zeller (2002) on the discrete nature of organizational choice in innovation, and consistent with the model implied by equation (1), this relates to complementarities in different stages of the innovation process to innovation performance:

H2: The more phases of the innovation process in which cross-functional teams and boundary-spanning linkages are used together, the higher is the level of innovation performance.

Institutional factors may also influence patterns of complementarity between internal knowledge sharing and boundary-spanning links. Here, the UK and Germany – the two countries covered by our data – provide an interesting contrast because of differences in the nature of innovation activity in the two countries (Herrigel, 1996), and because of their marked institutional and organizational contrasts[4]. Love and Roper (2004), for example, suggest that institutional factors have a significant effect on the overall pattern of boundary-spanning linkages in the innovation process in the UK and Germany. German plants were found to be significantly more likely than their UK counterparts to have boundary-spanning linkages in each innovation activity, and to emphasise the risk and cost-sharing benefits of these linkages. UK plants, on the other hand, tended to have fewer boundary-spanning linkages and emphasised increased speed to market as their key benefits. Cross-functional teams, however, were more common in UK plants, particularly

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[4] A detailed analysis of the institutional and structural differences between the organization of innovation in the two countries is provided in Love and Roper (2004), and so only an overview is provided here.

in the early stages of the product innovation process. This too may reflect institutional differences between the UK and Germany such as training systems, industrial relations etc. (Finegold and Wagner, 1998). These marked differences in the use and extent of internal knowledge sharing and boundary-spanning links indicates that the impact of using an open innovation approach should vary substantially between the two countries[5], leading to the final hypothesis:

H3: The pattern of complementarities between cross-functional teams and boundary-spanning linkages, and the impact of these complementarities on innovation performance, will differ between the UK and Germany.

3. Data and Empirical Methodology

Our study is based on data from the Product Development Survey (PDS) which was a postal survey covering UK and German manufacturing plants' innovation activity during the 1991 to 1993 period. We choose to use this particular dataset here because it is particularly well suited to examining potential complementarities between cross-functional teamworking and boundary-spanning linkages as it provides detailed information both on innovation outputs as well as the internal organization of plants' innovation activities (see, for example, Love and Roper, 2004). This type of data on the internal organization of firms' innovation activities is not part of other innovation surveys – for example the European Community Innovation Survey – although these surveys do provide some information on firms' boundary-spanning linkages.

The period to which the PDS relates was at the beginning of the German recession of the mid-1990s, and a time when the UK economy was also experiencing a mild recession

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[5] Note, however, that there is nothing in the differences between the UK and German firms which suggests *a priori* **how** open innovation might affect innovation performance differently: this is an empirical question.

(Roper et al., 1996, pp 8-9)[6]. The survey was conducted jointly with the ifo-institut in Munich, with a UK sample derived from the 'Business Database' maintained by British Telecom and the German sample derived from the very large test panel maintained by the ifo-institute as part of its monitoring of investment behaviour in Germany. The target population in both countries were manufacturing plants with more than 20 employees, and samples in both countries were structured to allow size-band, regional and industry comparisons with higher sampling fractions for larger plants. Overall sampling fractions were 17.2 per cent in the UK and 6.1 per cent in Germany. A substantially higher sampling fraction (14.8 per cent) was used in the former East German Lander. Questionnaire design drew on the previous experience of the research team in conducting innovation surveys in both the UK and Germany (e.g. Ashcroft et al., 1994) with pilot surveys conducted in both countries. Final response rates were 20.6 per cent in the UK (1722 responses) and 25.1 per cent in Germany (1374 responses).

As the PDS was a structured survey, weighting is necessary to given nationally representative results. The representativeness of the survey can be assessed by comparing figures for R&D employment derived from the survey and those from comparable national statistics. In the UK the PDS estimate of national. R&D employment in manufacturing in 1993 was 117,000 compared to 119,000 from comparable national statistics. In Germany the PDS estimate was 248,000 R&D employees, an underestimate of the comparable figure of 278,000 from national statistics (Roper et al., 1996, p.66). This underestimation may reflect, at least in part, the exclusion of smaller firms from the PDS but is likely to suggest that German survey results slightly under-estimate overall levels of innovation activity.

In terms of the details it provides of the organization of plants' innovation activity, the PDS records the participation of staff from five major skill groups (i.e. scientists/technologists, engineers, designers, marketing and sales staff and skilled production workers) in four different activities in the product innovation process: new

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[6] Fieldwork for this study pre-dates that reported in Finegold and Wagner (1998) by 18-24 months. The intervening period was one of continuing weakness in the German economy with total employment falling by 10 per cent between 1989 and 1995 (Finegold and Wagner, 1998, p. 473)

product identification, product design and development, product engineering, product marketing[7]. Here, these data are used to create four dichotomous strategy choice variables, cft_i, i=1,4, which take value 1 if the firm uses cross-functional working (i.e. involves more than one skill group) in each innovation activity, and 0 otherwise. Similarly, for each of the four innovation activities the PDS provides information on whether plants had boundary-spanning linkages. Again, these data are used to create four dichotomous choice variables, net_i, i=1,4, which take value 1 if the firm had boundary-spanning linkages, and 0 otherwise. Open innovation in any innovation activity (i.e. $oin_i = 1$) requires that $net_i = 1$ and $cft_i = 1$, i.e. the plant is combining cross-functional teams and boundary-spanning links in innovation activity i. Table 1 summarises the proportion of innovating plants in the UK and Germany employing cross functional-teams (29-78 per cent) and having boundary-spanning linkages as part of their innovation activities. Both in the UK and Germany, cross-functional teams are more common in the design and development activities of the innovation process and less common in product marketing. Boundary-spanning linkages are generally less common, being used by 18-34 per cent of plants. The proportion of plants embracing both aspects of open innovation, i.e. combining cross functional teams and boundary-spanning links varies from 22 per cent in product design and development in Germany to around 10 per cent in German product marketing.

To test for complementarities between the four strategy choice variables – i.e. the oin_i – we use the framework proposed by Mohnen and Röller (2005).[8] To illustrate this approach, consider a situation where there are only two innovation activities and therefore two strategy choice variables oin_1 and oin_2 such that the vectors (00), (01), (10) and (11) define all possible combinations of strategy options. (11) would here represent

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[7] The PDS actually identifies the participation of each skill group in seven activities in the product innovation process. For some of these activities, however, the profile of cross-functional working was very similar (e.g. Love and Roper, 2004). For the current analysis, therefore, the original seven activities were grouped into four broader categories using cluster analysis. Specifically, 'prototyping' and 'final product development' were combined into 'product design and development'; 'product testing' and 'production engineering' were combined into 'product engineering'; and, 'market research' and 'sales strategy development' were grouped into 'product marketing'. The original activity 'identifying new products' was retained. Details of the cluster analysis are available from the authors.

[8] Athey and Stern (1998) provide a detailed overview of this approach to assessing complementarity and a range of other possible approaches.

open innovation, i.e. the adoption of cross-functional teams and boundary-spanning linkages in both activities in the innovation process, while (00) would represent the opposite extreme. Complementarity between the two strategy choices, or here the equivalent notion of supermodularity, in the innovation production function then requires that:

$$I(10,Z)+I(01,Z)\leq I(00,Z)+I(11,Z) \qquad (2)$$

That is adopting open innovation in both activities produces more positive effects on innovation outputs than the sum of the results produced by the adoption of open innovation in each activity individually. Equivalently, equation (2) can be expressed as:

$$I(10,Z)-I(00,Z)\leq I(11,Z)-I(01,Z). \qquad (3)$$

In other words, complementarity or supermodularity requires that adopting open innovation in one innovation activity has a more positive effect on innovation outputs when open innovation is also implemented in the other innovation activity.

In our empirical model we consider a situation with four open innovation strategy choice variables. Here, the situation is more complex, however, with each pairing of strategy choices either exhibiting complementarity or substitutability. Supermodularity is then said to exist where there is complementarity between all possible pairings of strategy choices. Complementarity between the first two open innovation choices requires that:

$$I(10XX,Z)+I(01XX,Z)\leq I(00XX,Z)+I(11XX,Z), \qquad (4)$$

where $XX = \{00, 01, 10, 11\}$. This suggests a set of four inequality constraints, one for each value of the set XX.[9] For example, complementarity between open innovation in the first (prototype development) and third (product engineering) activities of the innovation process requires that the following four inequalities hold:

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[9] Here we use the same notation as in Mohnen and Röller (2005).

$$I(1X0X,Z)+I(0X1X,Z)\le I(0X0X,Z)+I(1X1X,Z)\,. \qquad (5)$$

The set of inequalities for the remaining combinations of strategy choice variables can be derived analogously.

In operational terms, the key result is due to Topkis (1978), and establishes that complementarity over all pairs within a set of strategic choices implies supermodularity within that set of choices. This allows us to test for supermodularity for the set of four open innovation variables using a set of six pairwise tests for complementarity, each independent pairwise test considering the validity of four simultaneous inequality constraints (i.e. equation (5)). Operationalising these hypothesis tests requires the inclusion in the innovation production function of mutually exclusive state dummies for all of the 16 possible combinations of the four open innovation strategic choice variables. Conventionally, we label these state dummies (0000), (0001), … , (1111) following the rules of binary algebra. The state dummy labelled (0000), for example, the ‘closed innovation’ extreme, indicates no cross-functional teamworking or boundary-spanning linkages in any innovation activity, while (1111) corresponds to open innovation in each activity. Intermediate states are defined by binary values (0010) to (1110) and indicate the use of cross-functional teamworking and boundary-spanning linkages in different combinations of innovation activities.

To operationalise the tests the estimated innovation production function (1) is therefore:

$$I_i=\sum_{l=0}^{15}\gamma_l s_l+\beta Z_i+\varepsilon_i \qquad (6)$$

Where, as before, I_i is innovation activity for firm *i*, measured as the percentage of sales coming from new products, a standard measure of innovation ‘success’; the s_l represent the set of 16 state variables defining plants’ universe of possible strategic choices between open and closed innovation; and *Z* is a set of plant level factors which have previously been shown to be relevant determinants of innovative activity at the plant level (Love and Roper, 1999, 2001).[10] Descriptives and variable definitions are given in the Annex.

Two statistical issues arise in operationalising the test procedure suggested by Mohnen and Röller (2005) for our innovation survey data. First, a key requirement of the Mohnen and Röller (2005) testing procedure is that coefficient estimates of the state dummies are consistent. As our dependent variable in the innovation production function – the percentage of sales derived from innovative products – is bounded by 0 and 100 we use the fractional response estimation method suggested by Papke and Wooldridge (1996).[11] The second issue relates more directly to the minority status of the open innovation model in our UK and German data (Table 1), and the implication that the number of sample plants adopting cross-functional teams and boundary-spanning linkages in some combination of innovation activities is relatively small. This of course reflects the relative importance of the particular strategic choices of UK and German plants within the sample and gives an indication of the importance of these strategic choices in influencing the innovation performance of the overall population of UK and German firms. Also of interest, however, is to assess the impact on innovation of these alternative strategic choices abstracting from the specific priorities of our sample of UK and German firms. We address this by re-weighting the sample observations to give those observations adopting each strategic choice equal weight in the estimation. The intention is to provide a less context-specific indication of the potential complementarities of each strategy choice.

4. Empirical Results

Table 2 reports estimates of the innovation production function for UK and German plants with weighting designed to give nationally representative results, and Table 3

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[10] In common with other cross-sectional studies of complementarities using the supermodularity approach (e.g. Mohnen and Röller, 2005; Galia and Legros, 2005) our limited ability to address fully the issues of endogeneity in organizational design must be acknowledged in interpreting the results of the analysis.

[11] See Wagner (2001) for a discussion of the econometric issues arising in the estimation of model with fractional response variable applied to the export/sales ratio.

reports the implied marginal effects for the state dummies and for the control variables for each country.[12] For the UK, significantly positive effects on innovation outputs are evident from adopting cross-functional teams and boundary-spanning linkages in four different combinations of innovation activities: identifying new products alone or as a combination with either product design and development, product engineering, or product marketing (i.e. state variables 1100, 1010, 1001). The marginal effects of these strategic choices suggest increases of innovative sales by 9.4 per cent, 18.9 per cent, 11.7 per cent and 15.9 per cent respectively (Table 3). Interestingly, where cross-functional teams and boundary-spanning linkages are adopted in three or more innovation activities the UK state dummies tend to be negative, suggesting a negative effect where these more complex strategic choices are adopted. In particular, adopting cross-functional teams and boundary-spanning linkages in product design and development, product engineering and product marketing, or all four innovation activities (i.e. state variables 0111 and 1111) have negative effects in the UK reducing innovative sales by 6.3 per cent and 7.7 per cent respectively (Table 3). For Germany too, significant positive effects on innovative products from the adoption of cross-functional teams and boundary-spanning links are also restricted to two or fewer innovation activities (Table 2). Adopting open innovation in product marketing alone (i.e. 0001), or in combination with product design and development (0101); or a combination of product design and development with identifying new products (1100) or product engineering (0110), all have positive effects increasing innovative sales by 7.9 per cent , 9.4 per cent, 6.9 per cent and 7.4 per cent respectively (Table 3).

Initially, this pattern of results may appear to lend support for H3 (differences in the pattern of joint use of cross-functional teams and boundary-spanning linkages between the two countries), and directly contradict H2 (innovation performance is *lower* where cross-functional teams and boundary-spanning linkages are used jointly in more than two phases of the innovation process). However, this conclusion is premature. As indicated

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[12] The estimated model includes a constant term, which is also retained in calculating the associated marginal effects. The omitted category for the state dummies is 0000 to allow comparison with the situation where no cross-functional teams or external linkages are present. However, for the purpose of the complementarity test, the model is estimated without a constant as implied by Equation 1.

earlier, testing for complementarity between the adoption of cross-functional teams and boundary-spanning links in the different innovation activities involves testing sets of linear inequality restrictions (Mohnen and Röller, 2005; Leiponen, 2005)[13]. Table 4 reports the relevant Wald tests based on the fractional response models in Table 2. In each pairwise comparison, separate tests are required for the null hypotheses of complementarity and substitutability. Test values below the lower bound (1.642 at the 10 per cent level) suggest that the null hypothesis of complementarity or substitutability cannot be rejected; values above the upper bound (7.094 at the 10 per cent level) suggest rejection of the null; and, intermediate values below the upper and lower bounds of the test suggest indeterminacy (see Kodde and Palm, 1986). For the UK, for example, the test for complementarity between the adoption of cross-functional teams and boundary-spanning linkages in identifying new products and product engineering rejects the null hypothesis; while the test for substitutability is unable to reject the null. For this pairing the tests therefore suggest substitutability. Test results are summarised in symbolic form in Table 5, part A. In all but two cases for the UK (denoted 'I'), the test results give an unambiguous indication of either complementarity (denoted 'C') or substitutability (denoted 'S') between the adoption of cross-functional teams and boundary-spanning linkages in different innovation activities, and in several cases acceptance of one is accompanied by rejection of the other (signified by an asterisk in Table 5). The two exceptional cases for the UK are identifying new products and product marketing, as well as product design and development and product marketing, where both test statistics cannot reject the null hypothesis (Table 4). For Germany, more indeterminacy exists with four of the six pair-wise comparisons proving unclear (Tables 4 and 5). Where the German tests do suggest determinacy, however, they point to a substitute rather than complement relationship between the adoption of cross-functional teams and boundary-spanning linkages in different innovation activities.

In part, the indeterminacy in the German and UK test results might be due to the relatively small number of adopters of cross-functional teams and boundary-spanning

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[13] For this reason the significance or otherwise of any or all the individual dummies' coefficients is irrelevant in deciding whether the joint hypothesis of supermodularity is accepted or rejected.

linkages in some combinations of innovation activities. Table 5, part B, therefore reports the test results derived from the re-weighted results in which each of the sixteen alternative combinations of choice variables are given equal weighting[14]. For the UK, changes are relatively minor with four of the six paired comparisons giving the same result as those in Table 5, part A; one test – relating to potential complementarities between identifying new products and product design and development - moving from 'S' to 'I'; and, one moving from 'I' to 'C'. For Germany, the re-weighted results are more satisfying reducing to one (from four) the number of indeterminate tests. Again the results are disappointing in open innovation terms, however, suggesting a clearer pattern of substitutability between the adoption of cross-functional teams and boundary-spanning linkages between innovation activities.

In summary, both our nationally representative and re-weighted results suggest a general pattern for both the UK and Germany of either substitutability or (at best) indeterminacy between the adoption of open innovation in different innovation activities. The implication is that the gains from extending the open innovation model – i.e. the adoption of cross-functional teams and boundary spanning links – beyond a single initial innovation activity are generally subject to diminishing returns. Or, more specifically, the return to implementing open innovation in one innovation activity is reduced if open innovation is already in place in another innovation activity.

This suggests little support for the hypotheses developed earlier. Hypothesis 1 simply states that complementarities exist between the use of cross-functional teams and boundary spanning linkages in at least some phases of innovation. The results of Table 3 overwhelmingly indicate that this is not the case. Hypothesis 2 states that the more phases of the innovation process in which cross-functional teams and boundary spanning linkages are used together, the higher is the level of innovation performance. By definition, since pairwise complementarity/substitutability over any subset implies supermodularity/submodularity within that subset (Topkis, 1978), the results of Table 6

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[14] We do not report estimation results for these models here. These are available from the authors on request.

imply that there is no support for Hypothesis 2[15]. Finally, despite minor differences, this pattern of diminishing returns to open innovation is remarkably consistent between the UK and German samples. There is therefore little support for Hypothesis 3, which suggests significant differences in the pattern of complementarities between the UK and Germany.

At first sight, this result is surprising as in earlier papers we have considered the components of open innovation – i.e. cross-functional teams and boundary-spanning networks – in isolation and identified relatively consistent complementarities between their adoption in different innovation activities (Love et al., 2006a and 2006b). In Table 6, for example, we summarise the results of separate tests for complementarity between the adoption of cross-functional teams and boundary-spanning linkages for both the naturally and re-weighted samples alongside those for open innovation from Table 5. In more than half of the pairings of innovation activities (e.g. UK identifying new products/ product design and development) we observe situations where the extension of either cross-functional teams or boundary-spanning networks to the second innovation activity generates positive complementarities but the extension of open innovation to the second activity generates either indeterminate or decreasing returns.

5. Discussion: problem solving and the limits of open innovation

Our empirical results suggest that the gains from extending the open innovation model beyond a single initial innovation activity are generally subject to diminishing returns. In this section we consider why this result is so consistent for a relatively large sample of firms operating in separate institutional environments which we know lead to different patterns of innovation organization (Love and Roper, 2004). Drawing on the theoretical work of Nickerson and Zenger (2004) we hypothesise that the open innovation model is

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[15] In the UK, for example, Table 6 indicates that there is substitutability between the first and second, second and third, and first and third elements of the innovation process, which in turn indicates *joint* substitutability between all three elements.

ultimately limited because it advocates using an organizational form which has severe limitations in a complex problem-solving environment such as innovation.

Our starting point here is Nickerson and Zenger's (2004) (henceforth N&Z) knowledge-based theory of the firm, which focuses on the efficiency of alternative institutional forms in *generating* knowledge. This is based around the types of problems potentially faced by managers, and their different solution landscapes. For example, low interaction or 'decomposable' problems faced by managers may require little interaction among those with different knowledge sets allowing different groups within a firm to pursue their own independent design choice decisions without being unduly concerned about the decisions being taken by other groups possessing different knowledge sets. By contrast, high-interaction or 'non-decomposable' problems may have solution landscapes in which the returns of different solutions depend crucially on interactions between the design choices of groups with different knowledge sets. N&Z argue that these different types of problems map in turn on to alternative forms of efficient solution searches. Directional search, guided solely by feedback from prior trials, is well suited to low-interaction problems; whereas heuristic search, which as the name suggests requires shared mental models or overlapping knowledge stets, may be more suited to non-decomposable problems requiring a high degree of interaction among different groups within a firm.

So far the argument is essentially rooted in Simon's (1962) analysis of complex systems. The key contribution of N&Z, however, is how this maps in turn onto efficient governance choices reflected here in firms' decisions on whether or not to adopt an open innovation model. In particular, N&Z argue that the knowledge sharing on which heuristic search depends is subject to two 'knowledge formation hazards', both of which arise from the possibility of individual actors acting in a self-interested or opportunistic manner[16]. First, individuals may hoard usefully shareable knowledge rather than share it in a socially optimal manner. Second, individual actors may seek to shape the search process itself in a way that optimizes the value of knowledge which they personally hold,

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[16] For a discussion of the difference between opportunism and mere self-interest in the theory of the firm, see Love (2006).

and which may not be optimal to the shared search process as a whole. Neither is a problem for decomposable problems and directional search, but where problems are non-decomposable and require high levels of interaction, knowledge transfer is required to enable heuristic search and so "efficient search demands mechanisms that mitigate knowledge-exchange hazards" (p. 622).

Governance forms based on market mechanisms can provide high-powered incentives to individuals and are well suited to directional search; however, they provide only weak incentives for knowledge sharing and therefore little protection against knowledge-exchange hazards. Indeed, market-based governance mechanisms may actually discourage knowledge sharing and encourage knowledge hoarding because of their high-powered incentives. By contrast, hierarchy-based structures may be more efficient at resolving the knowledge formation and exchange hazards where problems are complex and knowledge sharing is paramount. For moderate complexity problems, authority-based hierarchy is useful because of the ability of managers to exercise 'direction', that is deriving economic value by permitting one set of actors to direct the activities of another (Demsetz, 1997)[17]. Here, direction substitutes for knowledge transfer and, and the hazards of knowledge formation and exchange are bypassed. However, direction is only efficient where managers have valuable knowledge with which to direct their subordinates. As problems become increasingly complex and non-decomposable, the limitations of authority-based hierarchy, premised on direction, are quickly reached, and another form of hierarchy – consensus-based hierarchy – comes to the fore. While authority-based hierarchy emphasises direction as a *substitute* for knowledge transfer, consensus-based hierarchies stress the use of a common, shared language and value the use of low-powered incentives which encourage knowledge sharing[18].

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[17] See Love (2005) for a detailed discussion of Demsetz's and Coases's concepts of direction in the theory of the firm.

[18] Wernerfelt (1997) also points out that authority exists even in circumstances where there is little room for the kind of incentive conflicts which give rise to the firm in e.g. property rights analysis, such as members of volunteer organizations or the crew of a racing yacht. Unlike Nickerson and Zenger, however, Wernerfelt does not distinguish between authority-based and consensus-based hierarchies.

N&Z therefore emphasise the trade-off between governance forms that powerfully motivate search effort (i.e. the market) and those that support heuristic forms of search (i.e. hierarchies), and this trade-off determines efficient governance modes. "As problems become increasingly complex, the costs of markets accelerates rapidly, reflecting their inability to cope with knowledge-exchange hazards. By contrast, the costs of authority-based hierarchy accelerates less quickly, leaving authority as the efficient governance choice for problems with moderate levels of interactions…" (p. 628). The costs of consensus-based hierarchy, although higher than the other two forms at low levels of problem complexity, rise less steeply as complexity rises, and thus hierarchy becomes the most efficient governance structure at high levels of complexity with correspondingly low decomposability.

In terms of open innovation the value of N&Z is that, within the framework of a knowledge-based theory of the firm[19], they show how managerial problems with different characteristics are best approached with different search solutions, and – crucially – how these search solutions map on to efficient organizational forms. We argue that this approach is well suited to the consideration of the organization of innovation, and can help to explain the limitations of the open innovation approach experienced by our sample of firms.

Innovation is an activity which involves employing search solutions to the problems of identifying, developing, producing and marketing new products (Roper et al., 2006). Almost by definition the issues of knowledge formation and exchange identified by Nickerson and Zenger are paramount in the innovation process, and inevitably the innovation process will involve some degree of heuristic search. However, both elements of the open innovation model, cross-functional teams and boundary-spanning linkages, are (quasi-)market mechanisms; the former involving an internal market with moderated high-powered incentive systems replacing those of the conventional hierarchy, and the latter an explicit market mechanism. In terms of the N&Z framework, both are

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[19] Ironically for an analysis which stresses the value-enhancing perspective of the knowledge-based approach to the firm, Nickerson and Zenger's analysis of the choice between alternative governance structures employs and entirely cost-minimising approach.

therefore best suited to directional search, with relatively low requirements for knowledge transfer. Within certain limits, this may not be a problem: some aspects of the innovation process may be more amenable to routinization than others, with a relatively decomposable form of search process proving relatively efficient. Up to some limit, therefore, the knowledge-transfer hazards induced by the use of market mechanisms in the innovation process can be contained, generating complementarities in the use of both cross-functional teams and boundary-spanning linkages *individually* in both the UK and Germany (Table 6). The same argument is supported by the stronger complementarity evident in the case of the quasi-market cross-functional teams than in the 'pure' market boundary-spanning linkages in both countries (Table 6).

The problem arises for those firms attempting to adopt open innovation throughout the innovation process, or in terms of our empirical analysis where firms opt to use both cross-functional teams and boundary-spanning linkages together in multiple activities of the innovation process. Our results suggest that in this situation, where market mechanisms best suited to directional search are used in combination, they prove to be inefficient, with firms experiencing the strong and rapid trade-off between different governance structures outlined by N&Z, and a resulting decline in innovation performance. In other words, our results suggest that the simultaneous use of market-based mechanisms of governance for cross-functional teams and boundary-spanning linkages in multiple innovation activities takes firms beyond the point at which hierarchy-based governance mechanism become more efficient, because they are able to deal more effectively with the problems of knowledge formation and exchange. And, this is the ultimate paradox of the open innovation approach: it involves using quasi-market organizational forms which, beyond some limit, are actually inappropriate for the form of heuristic problem-solving that is frequently needed in the non-decomposable world of product innovation.

6. Conclusions

Our aim in this paper is to examine the way in which firms' internal knowledge sharing through cross-functional teams and their boundary-spanning linkages interact to influence innovation outputs. The open innovation approach suggests the potential for positive complementarities between such internal and external knowledge sharing, with the innovation benefits of each being mutually enhancing. Our results suggest that in practice these benefits are not generally achievable by the majority of plants, and that instead the adoption of open innovation across the whole innovation process is likely to reduce innovation outputs. We test for the existence of Edgeworth complementarities in the innovation activities of an extensive sample of UK and German manufacturing plants and find that the gains from extending the open innovation model – i.e. the adoption of cross-functional teams and boundary-spanning links – beyond a single initial innovation activity are generally subject to diminishing returns. Or, more specifically, that the returns to implementing open innovation in one innovation activity is reduced if open innovation is already in place in another innovation activity.

The consistency and robustness of this negative result across our sample of UK and German plants is striking. We know from previous work that the institutional differences between the two countries lead to quite different ways of organizing the process of innovation, with German plants significantly more likely to have boundary-spanning linkages in each innovation activity, and to emphasise the risk and cost-sharing benefits of these linkages (Love and Roper, 2004). UK plants, on the other hand, tend to emphasise increased speed to market as the key benefits they derive from boundary-spanning linkages and to make much greater use of cross-functional teams. Despite these differences, and despite the fact that the pattern of complementarities exhibited by the two countries *separately* for cross-functional teams and boundary-spanning linkages are different, plants in both countries overwhelmingly experience decreasing returns to the adoption of open innovation in more than one stage of the innovation process. The suggestion is that those plants attempting to use both internal and external knowledge-sharing mechanisms together quickly come up against the limited efficiency of market-based knowledge-sharing mechanisms outlined by Nickerson and Zenger (2004) and so reach the practical limits of an open innovation approach, limits which are independent of the institutional setting in which the firms are located.

Although quite different in approach, our results appear consistent with those of Laursen and Salter (2006) and their analysis of the effect of openness on innovation performance among UK manufacturing firms. While our analysis concentrates on combinations of openness in different phases of the innovation process, Laursen and Salter are concerned with breadth and depth of external knowledge links in the innovation process as a whole. While both breadth and depth enhance innovation, beyond some limit the returns to increased breadth and depth of search become negative. Thus Laursen and Salter's results provide evidence on the dangers of over-searching, while our results warn against the dangers of over-openness.

Our results have implications for innovation strategy. The experience of UK and German plants suggests that extending an open innovation approach across the whole of the innovation process may be counterproductive and have negative effects on innovation outputs. In single innovation activities there are, however, positive complementarities from both cross-functional teams and boundary-spanning linkages. In strategic terms this suggests adopting a combination of open and closed innovation modes in different innovation activities. Our results – supported by the conceptual analysis of N&Z – also provide some guidance on the type of activities where the adoption of a market-based governance structure such as open innovation may be most valuable. This is likely to be in innovation activities where search is more deterministic, activities are separable, and where the required level of knowledge sharing is correspondingly moderate – in other words those activities which are more routinized. For this type of activity market-based governance mechanisms may well be more efficient than hierarchical governance structures. For other innovation activities where outcomes are more uncertain and unpredictable and the risks of knowledge exchange hazards are greater, quasi-market based governance structures such as open innovation are likely to be subject to rapidly diminishing returns in terms of innovation outputs. In these activities hierarchy-based structures may be more efficient at resolving the knowledge formation and exchange hazards where problems are complex and knowledge sharing is paramount. From a strategic perspective, therefore, the key decision is not simply a choice between open versus closed innovation, but rather selecting the appropriate combination of open and closed innovation modes in different activities that will optimize innovation outputs.

Limitations and scope for future research

The use of any large-scale survey instrument inevitably involves trading off breadth and depth of data. In the case of the PDS, we are able to obtain data on *whether* cross-functional teams and boundary-spanning linkages are used in several phases of the innovation process, but not the *extent* of this teamworking or boundary-spanning. While this binary approach is consistent both with the supermodularity approach and with the conceptual and empirical literature on complementarities in organizational design (Milgrom and Roberts; 1990, 1995; Zenger, 2002), it could be usefully complemented with analysis that is able more fully to explore how the extent of openness at different stages of the innovation cycle influences innovation outcomes. This is likely to involve a different methodological approach to that used above, and may require the use of in-depth case studies to develop a more nuanced understanding of the link between openness and innovation performance.

There are two other obvious limitation of the present research. The first is its cross-sectional nature: we can say nothing about the process by which the use of cross-functional teams or boundary-spanning linkages changes through time, and what impact this may have on innovation. The second is the timing of the data, which refer to a period in the mid-1990s. Rapid changes in, for example, the use of information technology may have helped to reduce the knowledge formation and sharing problems induced by the quasi-market, open innovation approach since our data were collected. Two potential areas for future research therefore present themselves. The first is the development of panel data, involving the repeated survey of a target population. This would clearly be a useful (if expensive) addition, but given the point raised above on the extent of openness, a second and complementary approach might be detailed longitudinal case studies. This latter approach would provide much more detailed information on how moves towards – or away from – an open innovation system impact on innovation, and in particular might shed further light on which phases of the innovation process are most (and least) amenable to open innovation.

Another area in which more research is needed is in terms of the countries studied. Much of the research on open innovation relates to a relatively few large US corporations such as Proctor & Gamble. It is unclear from this research whether the potential benefits of open innovation are in some way restricted to large corporations and/or corporations from the US managerial system. The results above indicate that, despite their institutional differences, both UK and German manufacturers find that the gains from extending the open innovation model beyond a single initial innovation activity are generally subject to diminishing returns. It would be very interesting to contrast these results from countries with quite different institutional and cultural backgrounds, especially those in which knowledge-sharing and cooperation are more highly prized than the Anglo-Saxon environment of much management research.

The final limitation and research opportunity concerns services versus manufacturing. Both the research described above and that of Laursen and Salter (2006) involves only manufacturing enterprises. Recent research has pointed to important differences in the nature of the innovation process between manufacturers and service providers. For example, manufacturers tend to emphasise 'hard' strengths such as R&D competence and flexibility of production methods while service providers more frequently stress 'soft' skill such as workforce skills and the importance of collaborative interactions (Tether, 2005; Kanerva et al, 2006). These finding might provide suggestive evidence of a more positive role for open innovation in service innovation, and future research could usefully establish whether the rapid trade-offs between openness and innovation outputs identified above are also a feature of the service sector.

Table 1: Percentage of Innovating Firms Engaging in cross functional team-working, networking and open innovation

	UK	Germany
	N=493	N=461
A. Cross-functional teams (cft_i)		
Identifying new products (%)	71.6	54.9
Product design and development (%)	78.9	63.2
Product engineering (%)	71.4	48.2
Product marketing (%)	44.6	28.7
.		
B. Networking (net_i)		
Identifying new products (%)	18.2	29.1
Product design and development (%)	27.0	37.8
Product engineering (%)	26.9	21.1
Product marketing (%)	23.3	34.3
.		
C. Open Innovation (oin_i)		
Identifying new products (%)	13.5	14.0
Product design and development (%)	21.0	22.3
Product engineering (%)	18.6	9.4
Product marketing (%)	11.8	9.8

Notes and Sources: See text for variable definitions. Percentages relate to innovating firms only and survey responses are weighted to give representative results. Source: Product Development Survey

Table 2: Innovation Production Function Estimates - Fractional Response
Dependent Variable: Percentage of Innovative Products in Sales

	UK			Germany		
	Coeff		Std Err	Coeff		Std Err
Strategy Choice Variables						
0001	0.328		(0.26)	0.484	**	(0.24)
0010	0.383		(0.28)	-0.125		(0.38)
0011	-0.216		(0.34)	-0.056		(0.38)
0100	-0.175		(0.26)	0.189		(0.16)
0101	0.383		(0.48)	0.564	*	(0.30)
0110	0.247		(0.32)	0.456	*	(0.24)
0111	-0.411	**	(0.21)	-0.314		(0.40)
1000	0.482	*	(0.25)	0.024		(0.25)
1001	0.893	**	(0.37)	0.034		(0.40)
1010	0.585	*	(0.30)	0.547		(0.34)
1011	0.368		(0.28)	-0.228		(0.21)
1100	0.768	**	(0.34)	0.380	**	(0.19)
1101	0.817		(0.60)	0.295		(0.39)
1110	-0.249		(0.26)	-0.147		(0.30)
1111	-0.520	**	(0.20)	-0.000		(0.89)
All state dummies 0001-1111 (Wald	chi2(15)= 41.47(0.00)			chi2(15)=17.28(0.30)		
Control Variables						
R&D intensity	0.015		(0.00)	0.00982	*	(0.01)
Employment (Thousands)	0.136		(0.24)	0.278	*	(0.16)
Employment squared	-0.0169		(0.01)	-0.0183		(0.03)
Part of group	-0.025		(0.14)	-0.324	**	(0.13)
External ownership dummy	-0.103		(0.16)	0.200		(0.50)
Degrees (percent)	0.008		(0.00)	0.0167	**	(0.01)
No qualifications	0.000		(0.00)	0.001		(0.00)
Small batch production	-0.149		(0.15)	0.133		(0.12)
Large batch production	-0.100		(0.14)	0.053		(0.14)
One-off production	-0.324	*	(0.17)	-0.105		(0.13)
Continuous production	0.061		(0.17)	0.293	**	(0.15)
East German Firm				1.384	**	(0.14)
Industry Dummies						
Textiles and clothing	0.519		(0.35)	0.713	**	(0.24)
Metals and metal fabrication	-0.204		(0.33)	0.185		(0.22)
Mechanical engineering	0.181		(0.30)	0.443	*	(0.26)
Electrical and optical equipment	0.519		(0.32)	0.445	*	(0.23)
Transport equipment	0.958	**	(0.36)	0.160		(0.28)
Other sectors	0.365		(0.30)	0.239		(0.20)
Constant	-1.537***		(0.36)	-2.364	**	(0.27)

Observations	493	461
Wald test of overall significance	chi2(32)=112.31(0.0000	chi2(33)=256.26(0.0000)

Note: Robust standard errors in parentheses; ***/**/* indicates p<0.01/0.05/0.1.

Table 3: Marginal effects calculated based on Fractional Response Model

	UK			Germany		
	dy/dx		Std. Err.	dy/dx		Std. Err.
0001#	0.062		(0.052)	0.079	*	(0.043)
0010#	0.073		(0.056)	-0.017		(0.049)
0011#	-0.035		(0.052)	-0.008		(0.052)
0100#	-0.029		(0.040)	0.028		(0.025)
0101#	0.073		(0.099)	0.094	*	(0.057)
0110#	0.045		(0.063)	0.074	*	(0.044)
0111#	-0.063	**	(0.029)	-0.040		(0.046)
1000#	0.094	*	(0.053)	0.003		(0.036)
1001#	0.189	**	(0.087)	0.005		(0.057)
1010#	0.117	*	(0.067)	0.091		(0.065)
1011#	0.070		(0.057)	-0.030		(0.026)
1100#	0.159	**	(0.080)	0.060	*	(0.033)
1101#	0.170		(0.143)	0.046		(0.066)
1110#	-0.040		(0.039)	-0.020		(0.039)
1111#	-0.077		(0.027)	0.000		(0.126)
R&D intensity	0.003		(0.002)	0.001	*	(0.001)
Employment (thousand)	0.023		(0.042)	0.039	*	(0.023)
Employment squared	-0.003		(0.003)	-0.003		(0.004)
Part of group#	-0.004		(0.024)	-0.042	***	(0.016)
External ownership#	-0.017		(0.026)	0.030		(0.080)
Workforce with degree	0.001		(0.001)	0.002	*	(0.001)
Workforce with no qualification	0.000		(0.000)	0.000		(0.000)
Small batch production#	-0.026		(0.026)	0.019		(0.016)
Large batch production#	-0.017		(0.023)	0.008		(0.020)
One-off production#	-0.053	**	(0.026)	-0.015		(0.018)
Continuous production#	0.011		(0.030)	0.043	*	(0.023)
Former DDR	-		-	0.265	***	(0.032)
Textiles and clothing	0.099		(0.073)	0.121	**	(0.048)
Metals and metal fabrication	-0.034		(0.052)	0.027		(0.034)
Mechanical engineering	0.032		(0.055)	0.069		(0.045)
Electrical and optical equipment	0.099		(0.066)	0.068	*	(0.038)
Transport equipment	0.200	**	(0.084)	0.024		(0.043)
Other sector	0.065		(0.055)	0.035		(0.029)

Note 1: (#) Marginal effects for each state dummy are calculated setting all other state dummies at zero and all other variables at their mean values. Marginal effects for variables other than state dummies are calculated setting all variables at their mean value.

Note 2: Robust standard errors in parentheses; ***/**/* indicates p<0.01/0.05/0.1.

Table 4: Complementarity and substitutability in open innovation. Wald test of inequality restrictions based on fractional response model

	Combinations of networking activities					
	1-2	**1-3**	**1-4**	**2–3**	**2– 4**	**3– 4**
Complementarity Test						
UK	3.506	7.102	0.367	5.414	0.235	8.710
Germany	0.092	2.111	0.559	0.547	0.042	4.668
Subtitutability Test						
UK	0.860	0.001	1.107	0.007	0.159	0.000
Germany	0.234	0.043	0.318	0.052	1.137	0.000

Note: Wald test of inequality restrictions based on fractional response model. Critical values for $\alpha = 0.10$ are 1.642 for lower bound and 7.094 for upper bound. See Kodde and Palm (1986). If the Wald statistic is below the lower bound, the null hypothesis of complementarity or substitutability cannot be rejected. If the Wald statistic is above the upper bound, the null hypothesis is rejected. The test is inconclusive for intermediate values.

Table 5: Summary of the Patterns of Complementarities and Substitutablitity in open innovation in the UK and Germany

A: Initial results

UK

	Identifying new products	Product design and development	Product engineering	Product marketing
Identifying new products				
Product design and development	S			
Product engineering	S*	S		
Product marketing	I	I	S*	

Germany

	Identifying new products	Product design and development	Product engineering	Product marketing
Identifying new products				
Product design and development	I			
Product engineering	S	I		
Product marketing	I	I	S	

B: Re-weighted results

UK

	Identifying new products	Product design and development	Product engineering	Product marketing
Identifying new products				
Product design and development	I			
Product engineering	S*	S		
Product marketing	I	C	S*	

Germany

	Identifying new products	Product design and development	Product engineering	Product marketing
Identifying new products				
Product design and development	I			
Product engineering	C	S		
Product marketing	S	S	S*	

Note 1: C: complementarity; S: substitutability; I : test inconclusive at 10% level *: failure to reject the null is also accompanied by rejection of the alternative.
Note 2: Conclusions about complementarity or substitutability have to be drawn form the Wald test reported in and summarize the results, indicating complementarity with C and substitutability with S. The * indicates that failure to reject the null hypothesis is also accompanied by rejection of the alternative, making the result particularly robust.

Table 6: Summary of the Patterns of Complementarities and Substitutability in innovation organization in the UK and Germany

UK														
Cross-functioning team					**External Networking**					**Open Innovation**				
	I	II	III	IV		I	II	III	IV		I	II	III	IV
I					I					I				
II	C				II	C				II	S			
III	C	C			III	S	S*			III	S*	S		
IV	S*	I	S		IV	I	S	S*		IV	I	I	S*	
Germany														
Cross-functioning team					**External Networking**					**Open Innovation**				
	I	II	III	IV		I	II	III	IV		I	II	III	IV
I					I					I				
II	S*				II	C				II	I			
III	C*	C			III	S	S			III	S	I		
IV	S	C	S		IV	C	C	S		IV	I	I	S	

Note: C: complementarity; S: substitutability; I: inconclusive; *: failure to reject the null is also accompanied by rejection of the alternative

Version 2: re-weighted sample

UK														
Cross-functioning team					**External Networking**					**Open Innovation**				
	I	II	III	IV		I	II	III	IV		I	II	III	IV
I					I					I				
II	C				II	C				II	I			
III	I	C			III	S*	S			III	S*	S		
IV	S	C	S		IV	C	S	S*		IV	I	C	S*	
Germany														
Cross-functioning team					**External Networking**					**Open Innovation**				
	I	II	III	IV		I	II	III	IV		I	II	III	IV
I					I					I				
II	S*				II	I				II	I			
III	C	C			III	S	S			III	C	S		
IV	S	C	S		IV	C	C	S*		IV	S	S	S*	

Annex: Variable Definitions and Summary Statistics

	UK		Germany	
	Mean	SD	Mean	SD
R&D intensity of the plant – percentage of the work	4.091	5.678	4.524	6.840
Plant Employment (Thousands)	0.133	0.302	0.245	0.489
Plant is member of multi-plant group[*]	0.521	0.500	0.156	0.363
Plant is foreign-owned[*]	0.152	0.359	0.023	0.149
Percentage of the workforce with degree level	7.545	9.178	6.971	6.945
Percentage of the workforce with no post-school	49.373	28.542	34.092	26.260
Plant is predominantly engaged in small batch	0.544	0.499	0.485	0.500
Plant is predominantly engaged in large batch	0.304	0.460	0.212	0.409
Plant is predominantly engaged in one-off production[*]	0.207	0.405	0.249	0.433
Plant is predominantly engaged in continuous	0.211	0.410	0.297	0.457
Plant is located in former DDR[*]	-	-	0.097	0.296

Note: Sample observations were weighted to allow for sample structuring.

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