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Dynamic complementarities in innovation strategies

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ABSTRACT

Using a panel of Irish manufacturing plants over the period 1991–2008 we test for dynamic complementarities in the joint use of internal R&D and external knowledge sources. We find little evidence, either from considering successive cross-sectional waves of comparable surveys, or in terms of the strategy switch choices of specific plants, that there has been a systematic move towards the joint use of internal and external knowledge in innovation. We then test formally for the presence of complementarities in the joint use of internal R&D and external innovation linkages. In static terms we find no evidence of complementarity, but in dynamic terms find evidence that strategy switches by individual plants towards a more 'open' strategy are accompanied by increased innovation outputs.

1. Introduction

The strategic innovation literature increasingly recognizes that a combination of internal and external knowledge sources is a key element of a successful innovation strategy (Arora and Gambardella, 1990, 1994; Veugelers and Cassiman, 1999). More broadly, 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, one key aspect of the open innovation approach is to take advantage of external as well as internal knowledge sources in developing and commercializing innovation, so avoiding an excessively narrow internal focus in a key area of corporate activity. In this context, effective boundary spanning between the internal and external aspects of innovation becomes central to a successful innovation strategy. Several studies also provide direct 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; Love and Roper, 2009).

If there are indeed widespread complementarities between internal and external knowledge sources in innovation, one would expect this to be reflected in firm behaviour through time. We examine two aspects of this. First, is there any evidence of a systematic shift of firms towards more joint use of internal R&D and external innovation linkages? And second, where individual firms do move towards an innovation strategy involving both internal and external sources, is this accompanied by increased innovative activity? In order to consider these issues it is helpful to use panel data, preferably involving a lengthy time period. By contrast, the majority of work on internal/external complementarity uses cross-sectional data, which cannot identify how innovation strategies change through time, nor what the effects of these changes are on firm performance.[1]

In assessing the value of adding external knowledge sources to existing internal knowledge we make use of the concept of dynamic complementarities. Two discrete activities are (Edgeworth) complementary if adding one activity increases the returns from doing the other. This implies that the benefit of adding a new activity depends not simply on what the firm currently does, but on what it did in the past: it concerns adding something to an existing strategy. This can therefore only be determined by considering the effects of a specific change in strategy by a given enterprise relative to the option of sticking with the existing strategy. This is an intrinsically dynamic analysis, and so needs information on strategy choice decisions through time. In order to examine these questions in a dynamic context we use a unique dataset which comprises an unbalanced panel of Irish manufacturing plants which covers six successive three-year periods spanning the years 1991–2008. By analysing the strategy choices and innovation performance of these

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[1] Exceptions to this are discussed in the sections which follow.

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plants through time we are able to shed light on the two key issues identified above.

We therefore make two contributions to the literature. First, we are able to examine, over an extended period of time, whether there is any evidence of a change in the tendency for firms in Ireland to jointly use internal and external knowledge in innovation. We do this both on average by comparing representative cross-sectional samples of establishments at different points in time, and secondly by examining how manufacturing plants change their innovation strategies through time. No other dataset we are aware of is able to examine these changes over such a long time period using comparable data. Second, we are able to investigate the relationship between strategy choices and innovation performance using the concept of dynamic complementarities. This represents a significant advance over the static complementarity analysis usually employed in innovation studies (Cassiman and Veugelers, 2006; Schmiedeberg, 2008; Love and Roper, 2009) which typically infer the complementarity between internal and external knowledge sources from cross-sectional comparison of strategy choices across different firms, rather than the same firms through time.

We find little evidence of a systematic shift towards a more 'open' innovation strategy in Irish manufacturing, at least in terms of the joint use of internal R&D with external innovation linkages. Further, our analysis of static complementarities suggests that there is no evidence of (strict) complementarity between internal R&D and external innovation linkages. However, when dynamic complementarities are considered, there is systematic evidence that switching to the joint use of internal and external knowledge sources is accompanied by increased innovation outputs. We end by considering the implications of these findings for the literature on innovation strategies and for policy.

2. Complementarity in theory and practice: a simple typology of innovation strategies

Innovation depends crucially on firms' ability to absorb external knowledge, combine it with their own proprietorial knowledge and develop new market offerings (Chesbrough, 2003; Roper et al., 2008). The strategic challenge is how firms can best organize the sourcing, codification and exploitation of the internal and external knowledge and informational resources to maximize and sustain innovation (e.g. Zahra and George, 2002; Davila et al., 2005). An important element in this process is the identification and effective harnessing of knowledge complementarities between different activities inside and outside the boundaries of the firm.

Achieving the optimal mix between internal knowledge generation and external knowledge sourcing for innovation suggests a strategic choice. However, the major theoretical approaches do not provide unequivocal guidance on the issue of the optimal internal/external mix. In the transactions cost literature, for example, the firm's minimand is cost, although issues of appropriability, contract compliance and the potential for opportunism and hold-up need also to be considered (Love and Roper, 2002). Because of its emphasis on the relative costs of performing operations in-house or externally, almost inevitably the transaction cost approach tends to regard these alternative scenarios as substitutes; the emphasis is on deciding which of two alternative governance structures is least costly in transaction cost terms.

It has been argued that the TCE approach is relatively poorly equipped to deal with innovation, because of its inability to deal adequately with processes which involve learning (Foss and Klein, 2010; Barge-Gil, 2013). However, the other major conceptual approach in the management literature, the resource-based view (RBV) or competences approach is somewhat ambivalent on the merits of internal versus external organization. The emphasis of the RBV on heterogeneous and inimitable assets, resources and attributes appears to imply an emphasis on in-house development and the avoidance of the potentially risky external route, where competitors might learn to copy at least some of the basis of the firm's competitive advantage. On the other hand, the same approach acknowledges the possible benefits from firms sharing technological or other capabilities via strategic alliances, joint ventures and knowledge sharing agreements (Barge-Gil, 2013). Theory does not necessarily provide unambiguous hypotheses, therefore providing a clear role for empirical research.

Schmiedeberg (2008) suggests several practical reasons why internal and external R&D activity might be expected to be complementary. First, the absorptive capacity dimension of internal R&D described by Cohen and Levinthal (1989) facilitates the search for external innovation partners by providing the basis on which to assess their input quality. Second, high absorptive capacity facilitates coordination and communication between internal and external partners, making joint projects more likely to be successful. In addition, the presence of internal R&D makes a particular firm not only more visible as a potential innovation collaboration partner, but also more likely to be perceived as an attractive partner by other firms. Some internal R&D capacity is therefore useful 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 (Griffith et al., 2003).

Empirical studies of complementarities in internal and external innovation activity yield mixed results. An early study, Arora and Gambardella (1990), finds that the strategies of linkages with external parties are complementary among large firms in the biotechnology industry, a finding echoed for patterns of external networking in German (but not UK) manufacturing by Love and Roper (2009). Using German CIS data, Schmiedeberg (2008) tests explicitly for complementarities between internal R&D and externally contracted R&D, but finds little evidence to support the hypothesis of complementarity. In a study of 269 Belgian manufacturing firms, Cassiman and Veugelers (2006) test for complementarities in 'make and buy' strategies for R&D with respect to subsequent innovation performance. They conclude that internal R&D and external knowledge acquisition are complementary innovation activities, but that the degree of complementarity is sensitive to other elements of the firm's strategic environment, such as the use of 'basic' R&D. Other recent studies explore in more detail different aspects of contingencies between internal and external innovation inputs. For example, in a study of 83 pharmaceutical firms, Hagedoorn and Wang (2012) find that the level of in-house R&D investment matters critically: internal and external R&D are complementary where in-house R&D investment is high, and substitutes where it is low. Lokshin et al. (2008) find similar results in their study of Dutch manufacturing firms. They also find evidence of complementarity of internal and external R&D, but with a positive effect for external R&D only where firms have sufficient absorptive capacity in terms of internal R&D investment. Finally, Grimpe and Kaiser (2010) conclude that outsourcing R&D is made more effective by the presence of both internal R&D and formal R&D collaborations.

2.1. A typology of strategies

In order to explore the existence or otherwise of complementarities between internal R&D and external collaborative linkages in innovation, we can identify four 'states' or strategies employing different combinations of internal R&D and external linkages:

1. No R&D or external linkages (NEITHER)

2. No R&D but with external linkages (EXTERNAL)
3. R&D but no external linkages (INTERNAL)
4. Both R&D and external linkages (BOTH)

By design these four categories are mutually exclusive strategies which do not allow for nuances of the extent of R&D or the nature of external interaction with innovation partners.[2] This is appropriate, as our objective is to examine the potential dynamic complementarities between internal and external knowledge sources; this requires the use of mutually exclusive and categorical states which cover all permutations of internal/external combination (Cassiman and Veugelers, 2006).

Despite their simple and categorical nature, each of the categories is a legitimate innovation strategy in reality. Although firms in the NEITHER category appear to have no conventional inputs into innovation – indeed this category might at first sight be regarded as the absence of an innovation strategy[3] – this may be rational behaviour for some firms. They may still be able to introduce new products either from knowledge resources built up previously, or by making new or improved products which require relatively little technological or other knowledge inputs. In addition, the external relationships above relate to formal links with external collaborators: firms may still scan the external environment through the use of trade journal, exhibitions, etc., and so capture sources in more indirect ways (Laursen and Salter, 2006), or use non-R&D inputs which assist product innovation such as design, training and technological forecasting (Barge-Gil et al., 2011). EXTERNAL companies have no internal R&D capacity, and rely on ideas and knowledge generated from contact with customers, suppliers and other external agencies.[4] This strategy is relatively common among SMEs (Kleinknecht, 1987); indeed recent research suggests that small firms have more to gain from the use of formal external collaborations linkages than their larger counterparts (Vahter et al., 2012). INTERNAL firms engage in 'closed' innovation, in which internal R&D is the only source of (formal) innovation inputs, a coherent strategy where leakage of commercially sensitive knowledge might compromise competitive advantage. Firms in the BOTH category employ a strategy in which both internal R&D and external sources are used. They therefore engage in one (limited) aspect of 'open' innovation.[5]

If the complementarities argument has any empirical validity, two dimensions should be apparent. First, there should be a systematic trend through time towards firms adopting BOTH as a strategy. Second, we should be able to detect some benefit to firms resulting from any systematic move towards using BOTH. The first of these can be examined in two mutually exclusive but complementary ways. First, for a given country, region or sector, is there any evidence that, collectively, firms are more likely to adopt BOTH as an innovation strategy than in the past? Second, is there any evidence that a given sample of firms shows a tendency to *shift* towards the use of BOTH through time? The first question can be examined by comparing representative cross-sectional samples of business units at different points in time, and we do this for Irish manufacturing. Answering the second question requires longitudinal establishment data, ideally a cohort study. We make use of the panel element of the Irish plant-level data described below to explore this dimension of changes in open innovation practice.

To identify any benefits from moving towards BOTH there should be evidence of dynamic complementarities in the use of internal R&D and external linkages. This involves more than testing whether BOTH firms are more innovative than those in the other categories: rather we have to demonstrate formally that firms which move towards BOTH from either INTERNAL or EXTERNAL (i.e. which add R&D to existing external linkages or vice versa) experience larger increases in innovation performance than those which add either R&D or external linkages to having NEITHER, after allowing for other determinants of innovation. This is formally tested in the empirical analysis below. In the next section we describe the dataset used to perform this analysis.

3. Data and descriptives

3.1. Dataset

Our empirical analysis is based on data from the Irish Innovation Panel (IIP) covering the period 1991–2008. The IIP provides information on the innovation activities of manufacturing plants in Ireland and Northern Ireland and comprises six plant-level surveys.[6] These were conducted every three years using similar survey questionnaires with common questions, and capture the same indicators of open innovation during this period. Each survey was designed to be representative of Irish manufacturing in terms of sector and sizebands (measured by employment). The initial IIP survey used here covered the period 1991–93, and had a response rate of 32% (Roper et al., 1996). The second survey covered plants' innovation indicators for the 1994–96 period, and had a response rate of 32.9 per cent (Roper and Hewitt-Dundas, 1998). The next IIP survey covered the 1997–99 period and reached a response rate of 32.8 per cent. The survey covering the 2000–2002 period achieved an overall response rate of 34.1 per cent. Subsequent surveys covering the 2003–2005 and 2006–2008 periods achieved response rates of 28.7 per cent and 38 per cent respectively. The resulting panel is unbalanced, due both to entry and exit of plants and varying survey samples. The total number of observations is 4795, of which 4611 can be allocated to one of the four identified strategies.

In terms of external linkages, our focus here is on responses to a question asked in each of the different waves of the IIP: Over the last three years did you have links with other companies or organizations as part of your product or process development? Plants responding in the affirmative were then allocated to either the EXTERNAL or BOTH categories, depending on whether or not they also reported having in-house R&D. This measure of external involvement makes no allowance for the extent (i.e. breadth) of external involvement in innovation. However, this may be less of an issue than might be thought. Plants that confirmed having linkages were subsequently asked to indicate which types of external partners they had during the 3-year period covered by the survey. Eight partner types of external linkages were outlined in the survey questionnaire: linkages to customers, suppliers, competitors, joint ventures, consultants, universities, industry operated laboratories, and government operated laboratories. The mean number of different types of innovation linkage over the period is just 1.1 with a standard deviation of 1.7, suggesting that the dichotomous variable catches the essence of the EXTERNAL strategy.

[2] For example, working with different external partners may have different effects on innovation outputs (see e.g. Roper et al., 2008).

[3] We are grateful to an external referee for this observation.

[4] They may, of course, benefit from internal knowledge generation which is not supported by any formal in-house R&D.

[5] In terms of the aspects of open innovation highlighted by Dahlander and Gann (2010), the BOTH strategy can be regarded as one configuration of inbound innovation; we do not consider openness in the outbound aspects of innovation.

[6] The IIP dataset is at plant level. However, most of the observations are single plant firms. Overall, 58 per cent of all observations in the IIP are from single plant firms: among small plants this figure is significantly higher at 77 per cent.

Table 1
Proportions of sample in each strategy by time period.

Strategy	1991–2008% (No.)	1991–93	1994–96	1997–99	2000–02	2003–05	2006–08
NEITHER	35.8 (1653)	37.1	35.3	33.2	39.5	38.0	29.8
EXTERNAL	14.6 (673)	11.9	14.5	16.4	17.1	13.1	13.1
INTERNAL	21.0 (967)	24.8	21.8	20.2	18.4	19.0	22.7
BOTH	28.6 (1318)	26.2	28.4	30.2	25.0	29.9	34.4
Total	100.0 (4611)						

NEITHER, no R&D and no linkages; EXTERNAL, no R&D and has linkages; INTERNAL, R&D and no linkages; BOTH, R&D and linkages.

3.2. Has the joint use of R&D and external linkages become more common?

We examine the evidence for any shift towards the joint use of R&D and external linkages in two ways. First, since each IIP survey is designed to be representative of Irish manufacturing, we can compare the distribution of responding plants across each survey and determine if, for example, there are more plants in the BOTH category through time. This could happen for several reasons, which are not mutually exclusive. First, plants adopting BOTH as a strategy might be more likely to survive, and so such plants will form a larger proportion of the population of plants as time passes, ceteris paribus This may or may not involve an element of self-selection, i.e. better performing plants may choose to become more 'open' as well as BOTH conferring performance benefits. Second, 'births' may be more likely to use internal and external sources jointly than 'deaths', leading to a higher proportion of plants in the BOTH category through time. Again, this may or may not indicate performance benefits. Finally, existing plants may switch their strategies towards BOTH through time, because of anticipated or actual performance benefits from doing so. Comparing the proportion of plants in each wave of the IIP therefore includes the net results of all three effects (i.e. both interplant and intra-plant effects), and should be interpreted in this way. However, because of the panel nature of the dataset, we are able to deal specifically with the final mechanism, the tendency to switch innovation strategy: we are therefore able to consider whether plants in the IIP show any systematic *movement* towards BOTH through time by concentrating exclusively on intra-plant movements.

We first consider the cross-sectional characteristics of the dataset. Descriptive data for observations in each category are shown in Table 1. Overall, plants with no R&D or external innovation linkages (NEITHER) account for just over one third of observations; those with only external linkages (EXTERNAL) account for approximately 15% of observations, R&D only (INTERNAL) for 21%, and joint users (BOTH) for approximately 29% of observations. Table 1 also shows how the distribution of plants among strategic categories has changed through time.[7] Overall, there is a remarkable degree of stability among the categories through time, with slight evidence of an increase in BOTH evident in the final time period. Since each wave of the IIP is designed to be representative of Irish manufacturing at the time of survey, this suggests that innovation in Irish manufacturing has not shown any systematic tendency to greater joint use of internal and external knowledge in innovation during the period, at least in terms of selected strategies.

Table 2 shows the innovation performance of plants using each strategy, measured in two standard ways. The first simply indicates the proportion of plants which indicated they had introduced a new product during the period in question; the second is the proportion of sales arising from new products. All strategies include both innovators and non-innovators, and as might be anticipated, there is a clear hierarchy in terms of the proportion of plants of different types which are product innovators; less than one third of NEITHER plants innovate, compared with over 90% of BOTH plants, with the two remaining categories lying between these figures. A broadly similar hierarchy is evident with respect to the proportion of new and improved products for each category of plant. Interestingly, this hierarchy is still to some extent evident even when considering the proportion of new and improved products among innovators in each category: in other words, plants using BOTH tend not only to be more likely to innovate, but also have some tendency to be more innovation intensive even than innovators which lack any conventional innovation inputs. We should also note that the NEITHER category is more likely than other categories to include plants which do not even attempt to innovate, which may partly explain the much lower incidence of innovation in this category.

For reasons discussed earlier, we cannot infer from these data that BOTH *results* in improved innovation performance. Nevertheless, it is instructive to see whether the relative innovation performance of plants in the four strategic groups has changed; in other words, has the 'premium' associated with BOTH increased through time? If so, this might be an indication that the joint use of internal and external resources has been associated with increased aggregate innovative performance in Irish manufacturing, even though the proportion of BOTH plants has changed little through time. Fig. 1 shows the relative innovation performance of the four groups through time. With the exception of the first survey there is clear evidence of the hierarchy described above persisting through time, and it appears that the relative innovation performance of each group has changed little over the period of the IIP. There is little evidence that BOTH plants have increased their output performance relative to the other groups.

3.3. Has there been systematic switching towards BOTH as a strategy?

We now consider whether individual plants have shown any tendency to move systematically towards BOTH as a strategy. To do this we restrict the analysis to those plants for which we have at least two observations in the IIP, reducing the empirical analysis to 2096 observations. This allows us to examining whether there is any systematic strategy movement among an identifiable group of (surviving) manufacturing plants in Ireland.

Table 2
Innovation performance by strategy.

Strategy	Product innovators (%)	Average innovation intensity*	Average innovation intensity[a] (innovators only)
NEITHER	31.5	9.4	32.4
EXTERNAL	69.8	29.0	42.8
INTERNAL	79.9	31.0	38.6
BOTH	92.4	41.2	44.9

*Proportion of new and improved products in total sales.

[7] Because the panel is unbalanced the proportions of plants in each category includes a combination of strategy switches and entries and exits to/from the panel.

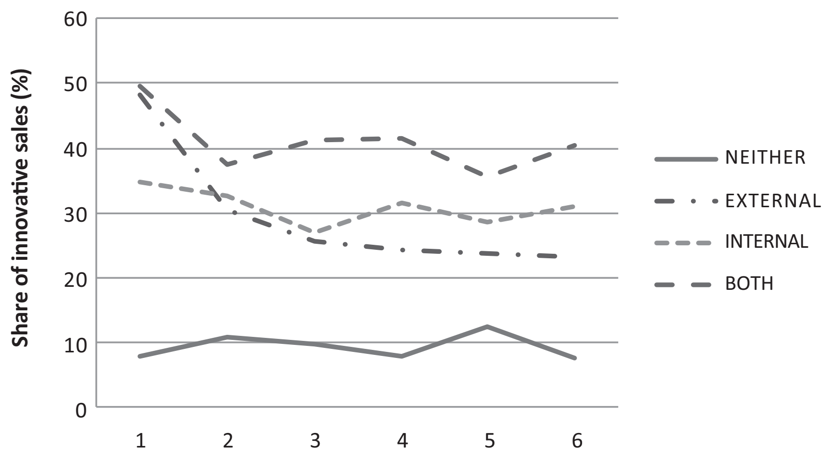

Fig. 1. Innovation performance by strategy by 'wave' of IIP.

Table 3 shows the transition matrix for plants with more than one observation in the IIP. The proportion of plants falling into each category in the reduced sample is almost identical to that for the IIP as a whole (c.f. Table 1), suggesting that the smaller sample is representative of the IIP at least in terms of strategy choices. The transition matrix shows that switching between categories of innovation strategy is relatively commonplace; of the 2096 observation, 1037 (49.5%) show at least one movement of strategy during the period of the panel. It should, of course, be borne in mind that the IIP covers a relatively long time period, and so alterations to innovation strategy might be expected to occur. In addition, all cells of the transition matrix are populated, suggesting that all strategy switch choices were enacted in practice, and so do not represent merely theoretical possibilities.

The interpretation of the transition matrix can be shown by example. Take the case of plants in the NEITHER category. Of the 789 plants which were first observed in this category, 484 (61.3%) remained in that category, 122 (15.5%) switched to EXTERNAL; 103 (13%) switched to INTERNAL, and 80 (10.1%) travelled to whole distance to BOTH. For both NEITHER and BOTH a majority of plant stayed within their original category. However for the intermediate strategies there is more evidence of switching. This is most notable for the EXTERNAL category, where only 32% of firms remained within that category, with approximately as many either dropping their external connections and adopting a NEITHER strategy, or incorporating R&D and moving towards BOTH. Despite the incidence of switching, there is little overall evidence of a systematic movement towards BOTH, or indeed towards any other specific strategy. Overall, the outcome of the observed switches during the course of the IIP leaves the proportions of surviving plants in each category little changed, with a slight increase in the proportion of BOTH plants (from 26.4% to 29.5%) and a very slight fall in the NEITHER category (from 37.6% to 35.6%).

These descriptive data appear to suggest two things. First, there has been little systematic shift in the overall composition of innovation strategies through time, whether one considers both inter- and intra-plant movement or exclusively in terms of intra-plant 'switching'. Elsewhere we have also noted there is no systematic tendency towards increased 'breadth' of innovation linkages in the IIP over the same time period (Love et al., 2014; Vahter et al., 2012). Within the limitations of the available data, this does not appear to support the suggestion of a major shift towards (inbound) openness in innovation, at least in Irish manufacturing.

Second, the data give some support for the contention that BOTH is associated with a greater probability and intensity of innovation. However, in order to explore this further we need to take into account other possible influences on innovation activity, and to test formally for the existence of complementarities between internal R&D and external knowledge sourcing. We do this in two stages. First, we test for complementarity in the standard (static) sense, then we explore the possibility of dynamic complementarities in innovation strategies.

4. Estimating static complementarities

Two discrete activities are (Edgeworth) complementary if adding one activity increases the returns from doing the other. Two approaches are commonly used to determine the existence of complementarities. The 'adoption' approach simply regresses a set of exogenous variables on the strategy choice variables, and interprets (positive) pair-wise correlation between the error terms of the regressions implying a complementary relationship. However, this cannot be regarded as definitive: common unobserved variable or measurement error may result in correlation of error terms where complementarity is absent (Athey and Stern, 1998).

In order to determine the existence of complementarity empirically, we adopt the production function or 'direct' approach (Athey and Stern, 1998; Cassiman and Veugelers, 2006; Schmiedeberg, 2008). This has the advantage over the simpler adoption or correlation approach of not relying merely on conditional correlations

Table 3
Transition matrix of the four innovation strategies (number of observations in parentheses).

Starting category	End category				Total
	1	2	3	4	
1	61.34% (484)	15.46% (122)	13.05% (103)	10.14% (80)	*100% (789)*
2	33.01% (102)	31.72% (98)	9.71% (30)	25.57% (79)	*100% (309)*
3	22.7% (101)	6.74% (30)	37.3% (166)	33.26% (148)	*100% (445)*
4	10.85% (60)	9.76% (54)	23.15% (128)	56.24% (311)	*100% (553)*

Source: IIP. Period 1991–2008.
Note: Each transition represent a switch between one wave and the preceding wave.
1, NEITHER (no R&D and no linkages); 2, EXTERNAL (no R&D and has linkages); 3, INTERNAL (R&D and no linkages); 4, BOTH (R&D and linkages).

between the residuals of reduced-form estimations of the relevant strategies, and therefore allows a direct test for complementarity (Carree et al., 2011). The production function approach operates by regressing a measure of innovation performance on mutually exclusive strategy choices and other suitable exogenous variables, then applying the formal tests of complementarity outlined below. Note that this involves more than simply estimating the determinants of innovation with each of the four mutually exclusive strategies as dependent variables, and comparing the relative sizes of the coefficients in each strategy variable. Such an approach would amount to little more than a pairwise comparison between two possible modes of innovating (i.e. internal R&D and external linkages). Our concern is not simply whether open innovation leads to a higher level of innovation activity than other strategies, but specifically whether there is complementarity between R&D and external linkages.

If I_i is a measure of the innovation outputs of firm i, C_i is an indicator variable indicating whether a firm combines R&D and external linkages in activity i, and Z_i is a vector of control variables, we can write:

$$I_i = \gamma_i C_i + \beta Z_i + \varepsilon_i \tag{1}$$

Here the C_i can indicate the four discrete innovation strategies outlined earlier. Such strategies can be conceived as discrete choices, with the potential for different strategy choices to yield different patterns of complementarities.

To test for complementarities between the strategy choice variables – i.e. the C_i in Eq. (1) – we use the framework proposed by Mohnen and Röller (2005) and Cassiman and Veugelers (2006).[8] Although there are four strategies, there are only two innovation activities (R&D and external linkages) and therefore two strategy choice variables C_1 and C_2 such that the vectors (00), (01), (10) and (11) define all possible combinations of strategy options.[9] Thus (11) would here represent the adoption of both R&D and external linkages in the innovation process (i.e. BOTH), while (00) would represent the opposite extreme (i.e. NEITHER). Complementarity between the two strategy choices, or here the equivalent notion of supermodularity, in the innovation production function then requires that:

$$I(10, Z) + I(01, Z) \leq I(00, Z) + I(11, Z) \tag{2}$$

That is adopting R&D and external linkages produces more positive effects on innovation outputs than the sum of the results produced by the adoption of R&D and external linkages individually. Equivalently, Eq. (2) can be expressed as:

$$I(10, Z) - I(00, Z) \leq I(11, Z) - I(01, Z). \tag{3}$$

In estimating Eq. (1) I_i is an innovation output indicator, defined as the percentage of plant i's sales derived from innovative products (i.e. those products improved or newly introduced over the previous three years) and Z is the set of plant level, industry and regional controls. Although the elements of vector Z are principally designed to control for plant-level heterogeneity, they are also variables which have previously been shown to be relevant determinants of innovative activity at the plant level (Love and Roper, 1999, 2001; Roper et al., 2008), including plant size, access to group resources, workforce qualifications, exporting, and the presence of government support for innovation. Since the dependent variable measures the percentage of plants' sales due to innovative products a tobit estimator is employed. Descriptive statistics for the main variables are shown in Table 4.

Table 4
Descriptive statistics.

Variable	Observations	Mean	Std. dev.
Share of new products in sales (%)	4408	25.428	30.720
Exporter dummy (0/1)	4329	0.592	0.492
Log of employees	4629	3.876	1.133
Log of employees squared	4629	16.303	9.611
Age (years)	4594	29.574	30.454
External ownership (0/1)	4795	0.310	0.463
Share of employees with degrees (%)	4493	9.764	12.974
Government support for product innovation	4722	0.191	0.393
Northern Ireland dummy	4795	0.396	0.489

Note: Figures relate to pooled data from six waves of the IIP relating to the periods 1991–1993, 1994–1996, 1997–1999, 2000–2002, 2003–2005, 2006–2008.

As noted inter alia by Athey and Stern (1998), an empirical issue in estimation of this form is that unobserved heterogeneity between observations in the sample of plants can cause bias in the estimation results. This can occur if heterogeneity in the determinants of the choice of strategy is correlated with the error term of the innovation production function estimating the effects of the strategies. While the use of panel data mitigates to some extent the issue of firm heterogeneity, the issue of endogeneity may still occur. One possible solution, applied by Athey and Stern (1998) and Cassiman and Veugelers (2006), is to jointly estimate both the adoption process[10] and the innovation production function in a two-step estimator or a simultaneous system. Two conditions must be satisfied for such a procedure to generate reliable results. One is that there must be independent variables that can identify the adoption process, and the other is that the two-step estimator or the simultaneous estimator should have sufficient predictive power. As discussed previously elsewhere (e.g. Cassiman and Veugelers, 2006) it is difficult empirically to satisfy these conditions.

The second way, perhaps more pragmatically, of dealing with such potential endogeneity is to apply some form of instrumental variable approach (e.g. Mohnen and Röller, 2005). However, this approach has generally proved unsuccessful. In the case when highly specific microeconomic datasets are used, and when the observations cannot be merged with other datasets which might provide suitable instruments for, say, variations in managerial expertise, suitable instruments become quite unobtainable. This has led both Mohnen and Röller (2005) and Cassiman and Veugelers (2006) to conclude that attempts at instrumentation, or even joint estimation as suggested by Athey and Stern (1998), are unlikely to lead to improved estimation and may actually be counterproductive unless much better – i.e. truly exogenous – instruments can be found.[11]

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

9 An alternative is to use variables for internal R&D, external linkages and an interaction term. Clearly this is econometrically equivalent to the use of four dichotomous strategy choices (Schmiedeberg, 2008, p. 1495), but the latter approach allows the complementarity/supermodularity test to be more easily performed.

10 These are the choice of organizational form in Athey and Stern (1998), and make/buy choices in Cassiman and Veugelers (2006).

11 In the case of panel data analysis, Leiponen (2005) deals with this issue by assuming that unobserved heterogeneity does not change over time, so that the GMM systems estimation controls for unobserved firm fixed effects. Miravete and Pernías (2006) attempt an econometric model which separately identifies the unobserved heterogeneity in their panel of Spanish ceramics firms. However, they admit that many of the regressors used in their estimation are actually themselves endogenous and that they too lack suitable instruments (p. 19, footnote 9).

By way of experimentation, we applied an estimation approach similar to the robustness test in Cassiman and Veugelers (2006). Like them, we do not find strong instrumental variables that are at the same time both valid and strong instruments for choices between the innovation strategies. In this robustness test we have modelled the choice of the four innovation strategies (NEITHER, EXTERNAL, INTERNAL, BOTH) as dependent variables on sector- and plant-level variables, using a multinomial logit model. Then, in order to try to account for the potential endogeneity of these category dummies, we included the predicted probabilities of each strategy from this adoption equation to the knowledge production function (Eq. (1)), instead of the standard strategy dummies.

The plant-level predictors of choice of each category included the standard inputs in knowledge production function (skill intensity, ownership size, age, export orientation, government support for product innovation, productivity). The sector-level predictor variables in the multinomial logit of choice between the four categories include trade openness, trade growth, foreign direct investment (FDI) presence in a sector and Herfindahl index. Unfortunately, these sector-level variables were relatively poor predictors of the choice between the different innovations strategies: they are largely not significant as determinants of the choice of innovation strategies. This leaves us with the adoption equation of different innovation strategies that is identified by largely the same plant-level variables that need to be included as standard controls in the second stage of the IV model, i.e. the knowledge production function itself. As could be expected, this produces implausible coefficients for some of the key explanatory variables in the knowledge production function.[12] Due to the lack of suitable instruments we rely here on the standard Tobit based estimation results. We nevertheless acknowledge the potential for endogeneity and recognize that our results must be interpreted in this light.

Results of estimating Eq. (1) are shown in Table 5: estimations are carried out without a constant to show the contribution of all four strategy options. As might be anticipated, the hierarchy of innovation described in the basic data (c.f. Table 2) is again evident. Thus after allowing for other plant- and industry-level conditioning variables there is a monotonic increase in the size of the coefficients for the four strategy variables.

By itself this does not indicate that BOTH is a superior strategy to the others in terms of innovation outputs. To determine this we must test for complementarity between internal R&D and external innovation linkages as suggested by Eq. (3), i.e.

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

The null hypothesis of no complementarity cannot be rejected using the direct test (Table 5, final row). Thus even though 'open' innovators appear to be more innovative than other types of plants, there is no statistical evidence that BOTH is a superior strategy choice. The reasons for this are immediately clear by examining the coefficients for each strategy in Table 5. Compared to NEITHER, having either R&D (INTERNAL) *or* external linkages (EXTERNAL) involves a much larger level of innovative sales – in the region of 30–46 percentage points higher. By contrast, the added advantage of being BOTH is more modest, adding around 11–17 percentage points to innovative sales. Thus, in static terms, the additional benefit of moving from either INTERNAL or EXTERNAL to BOTH is less than that of moving from NEITHER to either of the intermediate strategies, which is what the complementarity test formally establishes.[13]

Table 5
Testing for static complementarities.

	Dependent variable: Sales from new or improved products (%)	
	Full sample	Restricted sample
NEITHER	-23.347^{***}	-20.420^{***}
	(3.214)	(4.872)
EXTERNAL	7.790^{**}	1.894
	(3.281)	(4.995)
INTERNAL	13.959^{***}	12.048^{*}
	(3.278)	(5.078)
BOTH	24.672^{***}	22.730^{***}
	(3.282)	(5.049)
Exporter	4.153^{***}	5.280^{***}
	(0.735)	(1.025)
lnSize	2.612^{*}	2.623
	(1.493)	(2.347)
lnSize squared	0.007	0.032
	(0.184)	(0.283)
Establishment age (years)	-0.106^{***}	-0.160^{***}
	(0.012)	(0.016)
Externally owned	3.465^{***}	2.547^{*}
	(0.827)	(1.205)
Workforce with degree (%)	0.237^{***}	0.080^{*}
	(0.026)	(0.037)
Govt. support for product innov.	7.109^{***}	8.810^{***}
	(0.795)	(1.079)
Northern Ireland dummy	−1.042	0.176
	(0.750)	(1.012)
Sector dummies	Yes	Yes
Period dummies	Yes	Yes
Observations	3506	1515
Log-likelihood	−68,797.7	−28,921.0
Complementarity test (p-value of Chi^2-test):		
H0: $11-10 \leq 01-00$	$p = 1.000$	$p = 1.000$

Panel (RE) Tobit model. Coefficients are marginal effects. Standard errors in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

As a robustness check the same estimation is carried out for the restricted sample of plants for which we have at least two observations. The results are very similar as for the full sample (Table 5, second column): once again, the null hypothesis of no complementarity between internal R&D and external innovation linkages cannot be rejected.

5. Estimating dynamic complementarities

Even with the use of a panel structure, there is still a somewhat static quality to the analysis above. The concept of (Edgeworth) complementarity is implicitly dynamic: it involves the *addition* of something else to what the firm currently does. However, the testing of complementarities is typically comparative static, involving the comparison of the strategic options of *different* firms at a single point in time (Cassiman and Veugelers, 2006; Cozzarin and Percival, 2006; Love and Roper, 2009), rather than of individual firms through time.

Panel data has the obvious advantage that the actual strategy choices of individual plants can be observed through time. This means that we can make judgements on the existence or otherwise of complementarities between R&D and external linkages based on observations of plants which actually make such strategy choices. Econometrically, this involves a different underlying assumption from the static model. In the static framework differences across firms in what cannot be observed are assumed to be randomly distributed (conditional on the observed variables), allowing the inference of unbiased coefficients from estimations across firms. With the panel approach, the underlying assumption is that

[12] Results available on request.
[13] Bear in mind the point made earlier that the NEITHER category is more likely than other categories to include plants which do not even attempt to innovate, which will be reflected in the results of the complementarity test.

Table 6
Testing for dynamic complementarities.

Dependent variables	(1) Panel Tobit, all plants Share of sales of new or modified products (%)	(2) Panel Tobit, plants with innovative sales Share of sales of new or modified products (%)	(3) Panel probit, all plants (marginal effects reported) Product innovation dummy
Category dummies			
sw22	24.803***	11.570***	0.174***
	(2.284)	(2.176)	(0.021)
sw33	40.864***	6.515***	0.471***
	(1.840)	(1.578)	(0.02)
sw44	50.569***	15.757***	0.549***
	(1.644)	(1.425)	(0.019)
sw12	27.678***	10.075***	0.207***
	(1.980)	(1.882)	(0.017)
sw13	−8.200***	−9.770***	−0.022
	(2.722)	(2.229)	(0.029)
sw14	43.659***	16.183***	0.352***
	(2.304)	(1.984)	(0.023)
sw21	11.649***	15.056***	0.056***
	(2.151)	(2.312)	(0.018)
sw23	29.005***	5.631*	0.33***
	(3.591)	(3.112)	(0.035)
sw24	39.615***	9.380***	0.398***
	(2.392)	(2.003)	(0.025)
sw31	20.470***	6.821***	0.154***
	(2.079)	(1.982)	(0.019)
sw32	27.985***	0.135	0.295***
	(3.603)	(3.150)	(0.033)
sw34	52.803***	19.571***	0.474***
	(1.927)	(1.629)	(0.022)
sw41	2.665	3.001	0.027
	(2.920)	(3.122)	(0.024)
sw42	28.094***	11.385***	0.199***
	(2.745)	(2.491)	(0.026)
sw43	38.841***	6.316***	0.404***
	(1.927)	(1.647)	(0.019)
Exporter	4.823***	1.000	0.047***
	(1.015)	(0.882)	(0.01)
lnSize	−1.429	−10.270***	0.029
	(2.302)	(2.039)	(0.023)
lnSize_sqr	0.478*	1.260***	−0.001
	(0.277)	(0.239)	(0.003)
Establishment age (years)	−0.158***	−0.165***	0.0002
	(0.016)	(0.013)	(0.0002)
Externally owned	2.341**	−0.338	0.032**
	(1.189)	(1.001)	(0.013)
Workforce with degree (%)	0.069*	0.038	0.001***
	(0.037)	(0.031)	(0.0004)
Govt. support for product innov.	7.131***	2.306***	0.111***
	(1.079)	(0.858)	(0.013)
Northern Ireland dummy	0.585	−0.875	0.002
	(0.992)	(0.862)	(0.01)
Sector dummies	Yes	Yes	Yes
Period dummies	Yes	Yes	Yes
Constant	−16.395***	49.807***	–
	(4.773)	(4.329)	–
Observations	1539	946	1616
Log-likelihood	−29,268.6	−25,229.1	−4812.347
Test of inequality (p-values of Chi^2-test):			
H0: sw24 ≤ sw13	$p = 0.000$	$p = 0.000$	$p = 0.000$
H0: sw34 ≤ sw12	$p = 0.000$	$p = 0.001$	$p = 0.000$

Note: Panel (RE) Tobit model. Coefficients are marginal effects. Standard errors in parentheses.
Category dummies: the first number denotes the starting category, the second number denotes the next observed category:
no R&D and no linkages: 1.
no R&D and has linkages: 2.
R&D and no linkages: 3.
R&D and linkages: 4.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

intrafirm *dynamics* in unobservables are randomly distributed (conditional on the observed variables).

The dynamic approach also more easily allows decomposition of the final strategy choice into its constituent elements, thus providing more information on how plants arrive at a given strategy from different starting points. In order to understand precisely how the movement from a certain strategy towards BOTH affects innovation we need to map the actual movements of individual establishments, and trace the relationship of these moves with innovation output. While this can be done by inference in the static approach, for example by comparing the relative differences in the coefficients between BOTH and INTERNAL as opposed to between BOTH and EXTERNAL in Table 5, the dynamic approach permits a more direct comparison of the relative innovation implications of intra-plant strategy switches, simply by directly comparing the coefficients on different strategy switch choices.

To perform the dynamic complementarities analysis we once again restrict the analysis to those plants for which we have at least two observations in the IIP: we thus use at least two separate three-year observations for each plant. The nature of the switching process in the transition matrix described earlier (Table 3) might appear to indicate that there is little consistency or strategic intent among the plants in the sample. However, this would be a premature conclusion. It may be that, for individual plants, the process of switching has led to a superior choice of strategy: it is therefore conceivable that while the proportions of plants in each category remain similar, the distribution may have changed in such a way that plants are collectively more innovative than before as a result of having moved to a more productive innovation strategy. Thus although there may be little direct evidence of a 'paradigm shift' in terms of the *number* of plants moving towards the joint use of internal R&D and external innovation linkages, there may nevertheless be some advantage through time resulting from beneficial switches in innovation strategy.

Testing for evidence of dynamic complementarities in terms of R&D and external innovation linkages involves considering not simply static complementarity between R&D and external linkages (i.e. the four strategy choices) as before. We must now extend the analysis to consider the effects on innovation output of the decision to change strategy or remain with the original strategy. This involves not four strategy options as before, but sixteen strategy-switch possibilities, comprising twelve possible 'switch' decisions plus the decision to remain with each of the four original strategies. To do this we re-estimate Eq. (1), but replacing the original four strategy choices with sixteen 'strategy switch' dummy variables.

The results of estimating the revised innovation production function are shown in Table 6 (column 1). Each of the strategy variables is now either a move between strategies or a decision to remain with an existing strategy. Thus option SW22 involves remaining with the second (EXTERNAL) strategy, while SW34 involves switching from strategy 3 to strategy 4, i.e. from INTERNAL to BOTH, and so on.[14] The coefficients on each of the 15 strategy-switch options can be interpreted as being relative to the base option of remaining with the NEITHER strategy (i.e. SW11). In all cases except two the strategy-switch coefficients are positive and significant, indicating that most 'switch' options are superior to that of consistently doing neither R&D nor engaging in external linkages. The exceptions are SW41 and SW13. In the former case, the insignificant coefficient suggests that moving from BOTH to having no innovation inputs is equivalent in innovation terms to maintaining a NEITHER strategy. In the case of SW13 switching from NEITHER to INTERNAL has an apparently counterintuitive negative sign, indicating that firms setting up an in-house R&D facility where none existed previously tend to have a slightly reduced degree of innovation intensity. This may be a reflection of the disruption to the introduction of new products in the short run caused by establishing an in house R&D facility de novo.

As suggested earlier, the coefficients in Table 6 also provide information on the differential effects of achieving BOTH by different routes, and of the outcomes arising from remaining with existing strategies. For example, the first three coefficients show the premium on innovation performance (compared to sticking with NEITHER) of remaining with EXTERNAL (SW22), INTERNAL (SW33) and BOTH (SW44) respectively. Mirroring the results of Table 5 and Fig. 1, plants electing to continue with BOTH have a higher level of innovation intensity than those continuing with either of the other strategies, and all three are significantly more innovative than plants which consistently do NEITHER. There is also evidence that there is some asymmetry in achieving BOTH by different routes, as indicated by the different coefficients on switches SW34 and SW24 (INTERNAL to BOTH versus EXTERNAL to BOTH).

However, our principal interest is not just in the absolute value of the strategy-switch coefficients per se, but in whether certain strategy switches are more productive than others. As before, this involves testing for the inequality embodied in Eq. (3). Thus in order to test for dynamic complementarity we now want to test whether adding external linkages to an existing R&D capability has a stronger relationship with innovation performance than adding linkages where there is no R&D (i.e. that the coefficient on SW34 is greater than that on SW12), and whether adding R&D to existing linkages has a stronger relationship with innovation performance than adding R&D where no linkages exist (i.e. SW24 > SW13). In both cases the null hypothesis of no complementarity is rejected using the direct test (final row of Table 6), demonstrating the existence of dynamic complementarities in innovation strategies.

We perform two robustness checks. In the first case we perform the estimation only on innovating firms, and in the second we replace the dependent variable with a dummy product innovator variable. In both cases the results remain essentially unchanged (columns 2 and 3, Table 6), and in both cases the H0 of no complementarity is rejected. In dynamic terms, switching to BOTH is associated with higher innovation outputs.

6. Discussion and conclusions

The purpose of this paper was to examine the existence of complementarities between internal R&D and external linkages in innovation. We do this in a dynamic context, using a relatively long-term panel data set. If there are widespread complementarities we should be able to detect two regularities: first, there should be some evidence that firms are increasingly likely to use a combination of internal and external knowledge in their innovation activity: and second, there should be some evidence that firms derive a systematic advantage from so doing.

Using a panel dataset of Irish manufacturing plants covering the period 1991–2008 we find little evidence, either from considering successive cross-sectional 'waves' of comparable surveys, or in terms of the strategy switch choices of specific plants, that there has been a systematic move towards the use of a more 'open' innovation strategy. There is some suggestion that plants using the BOTH strategy are more innovative than other types of plant, but little evidence that the 'premium' on BOTH has changed through time. We then test for the presence of complementarities in the joint use of internal R&D and external innovation linkages, one key element of (inbound) open innovation. In static terms we find no evidence of complementarity, but in dynamic terms find evidence

[14] All option categories in the estimation have more than 30 observations except two (sw23 and sw32), both of which have 21 observations.

that strategy switches by individual plants towards BOTH are accompanied by increased innovation outputs.

The inherent difficulty of adequately allowing for endogeneity in a large number of possible strategy choice means that we must be circumspect in suggesting that there is strict complementarity between internal R&D and external innovation linkages, and therefore that switching to this strategy will necessarily make an establishment more innovative. What we can unambiguously say is that over the course of the IIP there has been a tendency for strategy switches to occur in such a way that BOTH tends to be associated with more innovation-intensive manufacturing plants. The extent to which this reflects self-selection rather than the beneficial effects of the strategy switches cannot be determined for certain, although it is difficult to imagine why the most innovative firms in a fairly large sample would systematically gravitate towards a specific strategy over an extended time period unless it conferred some advantage.

However, even if self selection were an important driver behind the observed strategy switches and performance results, this provides important information on the issue of strategy choices in innovation. As discussed earlier, the 'raw' data as shown in the transition matrix appears to suggest that there has been no coherent shift overall towards the joint use of internal and external innovation inputs among a given sample of firms over an extended timescale. Nevertheless, the fact that, through time, enterprises make conscious strategy choices which tend to result in BOTH being associated with high levels of innovation performance suggests that some systematic and subtle strategy switches have occurred, a movement which is masked by simply examining aggregate data on numbers of establishment in different strategic categories through time. One could therefore argue that there has been a movement towards a 'better' set of strategy choices in one specific sense: where plants make a switch to the BOTH strategy this has been accompanied by improved innovation performance. In other words, through time, those firms which are able to benefit most from employing BOTH are gravitating towards such a choice, and where this occurs it tends to be accompanied by improved innovation performance. Whether individual plants self-select to this strategy choice or not, the positive link between the strategy-switch choices they make and improved innovation performance is apparent.

This also raises the issue of why, if there is some beneficial link between BOTH and performance, there has not been a systematic trend towards its use. Barge-Gil (2013) makes some suggestions about why there may not be more of a move towards open innovation, including the possibility that firms may overestimate its costs. However, our results suggest that from a policy perspective we should perhaps be asking a slightly different question. The issue may not be why more firms do not move towards 'open' innovation, but how to encourage firms to move towards strategies which maximize their innovative potential. In some cases this may indeed mean encouraging greater openness, but there is no suggestion from our results that this need be optimal in *every* case: for some individual enterprises maintaining a closed strategy may still be optimal, for others it may even be the case that moving away from an open strategy may be beneficial. Thus, despite the evidence from our results that BOTH is associated with higher innovation performance, there is no a priori reason to suppose that simply having more firms in the BOTH category is necessarily beneficial for the economy as a whole.[15]

The present analysis has a number of limitations. By design, our strategy categories are starkly defined, and cannot reveal the subtleties of different degrees and types of external linkages, although this aspect has been widely studied elsewhere (e.g. Roper et al., 2008). In addition, enterprises may use a mix of different strategies in different innovation projects, something which cannot be detected in large-scale surveys of the present type. We also know little about the process which leads to switches in innovation strategies, and which is clearly central to the findings reported above: how do firms learn that switching to BOTH pays? There is some evidence that firms can learn from their openness to external sources, specifically related to external innovation linkages (Love et al., 2014), suggesting that a process of organizational learning may play a part in the process. Further detailed work here would be welcome. We can say little about how the relationship between using internal R&D and external linkages varies with the level of R&D commitment. Unlike, for example, Hagedoorn and Wang (2012) we do not have detailed information on the extent of internal and external R&D, and therefore cannot establish whether firms moving to BOTH as a strategy might also increase their overall level of R&D investment. We must also be aware that we have no information on the costs involved in different strategic choices, and therefore can say nothing about their impact on profitability. Finally, our findings are, of course, restricted to manufacturing firms in Ireland, a relatively small, open economy. Other countries may have different stories to tell, but our analysis does suggest the value for long-term panel data to consider issues of strategy choice in innovation.

[15] This applies only to the private benefits of openness. Increased levels of openness in innovation may be socially beneficial if there are positive externalities of openness (Roper et al., 2013).

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