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Openness and innovation performance: are small firms different?

Abstract

We explore whether and how the benefits of openness in innovation are different for small plants (less than 50 employees) compared to medium and large plants. Using panel data from Irish manufacturing we find that the contribution of the 'breadth' of openness (i.e. the variety of plants' innovation linkages) on innovation performance is stronger for small plants than for larger plants. Both small and larger plants face diminishing returns as the breadth of openness increases, but small plants experience negative returns at lower level of the breadth of openness than larger plants. Our results suggest that small plants can gain significantly from using wider set of innovation linkages, but for such plants appropriate partner choice is a particularly important issue. Small plants also gain significantly more than larger ones from investing in the linkages within the supply chain.

Keywords: external knowledge linkages; open innovation; SMEs; boundary-spanning linkages; learning effects

1. **Introduction**

External sources of knowledge have long been considered to be among key inputs in firms' innovation process (e.g. Cohen and Levinthal 1989, Powell 1998, Nelson and Winter 1977, Freeman 1991). Since the work of Chesbrough (2003) that summarizes many earlier ideas about the role of external partners into the widely popular concept of 'open innovation', the research literature on the benefits and determinants of external knowledge linkages has grown particularly rapidly. A central idea of the open innovation approach is to apply external as well as internal knowledge sources in developing and commercialising innovation, thus avoiding an excessively narrow focus on only internal knowledge creation. This is arguably not a new idea. Similar or related views are reflected, for example, in the seminal studies by Cohen and Levinthal (1989) and their concept of 'absorptive capacity' or in Freeman's (1991) analysis of the role of external networks in innovation.

Notwithstanding its origins, open innovation as a concept (Chesbrough 2003, Dahlander and Gann 2010) includes both the inbound (sourcing-in external knowledge for innovation) and outbound aspect (revealing internal knowledge resources to the external environment with or without immediate financial rewards; e.g. out-licensing own unused technologies). We concentrate in this paper specifically on the inbound aspect: in particular, the effects of sourcing of external knowledge[1] on innovation performance. In a recent review of the open innovation literature, Dahlander and Gann (2010) identify over 150 related papers with an emphasis on case-studies of multinationals such as Procter & Gamble (Dodgson et al., 2006), sectoral studies (e.g. Su et al. 2010 on biotechnology), and broadly-based national econometric studies (Laursen and Salter 2006, Leiponen and Helfat 2010, Love et al. 2014). Few of the studies reviewed by Dahlander and Gann (2010) consider the potential benefits of external knowledge linkages to small firms or SMEs, despite plausible reasons to expect the

[1] This includes both pecuniary and non-pecuniary interactions, as outlined in the Dahlander and Gann (2010) classification of varieties of 'open innovation'.

effects and role of external knowledge linkages to be different for smaller firms. It has long been acknowledged, for example, that there are marked differences in the scope and focus of the innovation strategies of smaller and larger firms (Acs and Audretsch 1990). Specifically, building and benefiting from external linkages poses particular challenges for SMEs because of their relative lack of capacity to seek and absorb external knowledge. Despite these difficulties, recent empirical evidence suggests that SMEs do purposively engage in external knowledge sourcing (Brunswicker and Vanhaverbeke 2011, Lee et al. 2010), and that the prevalence of external technology exploration and other 'open innovation' practices among SMEs has increased in recent years (van der Vrande et al. 2009).

Our contribution is to explore whether the benefits for innovation performance from wider openness to outside knowledge are different for smaller and larger firms, and what are the key reasons driving the differences in these effects between the size groups. Specifically, we concentrate on the benefits for firms' innovation performance from openness to external knowledge sources, and consider whether the breadth of firms' innovation linkages (number of different types of innovation linkages) and the nature of such linkages have different implications for innovation performance in smaller and larger firms. For example, do larger firms derive greater benefit from more extensive networks of innovation partners due to their greater absorptive capacity? Or are more extensive innovation networks actually a greater advantage to smaller firms, compensating for their weaker internal resources?

Our analysis extends the seminal study by Laursen and Salter (2006) that finds inverted U shaped relationship between the variety of different types of external knowledge linkages of firms and their innovation performance. Our study is also related to evidence presented in a recent empirical extension of Laursen and Salter (2006) by Garriga et al. (2013), suggesting that the search strategy for external knowledge and its impacts are likely to be affected by firm context, including constraints on available resources.

Understanding the potential benefits of external knowledge linkages specifically for small firms is important for three reasons. First, in most economies SMEs represent by far the largest cohort of firms, suggesting that it is important to know whether and to what extent is the involvement of external partners into own innovation process useful for such establishments. Second, if the benefits of openness are different for small and larger establishments, this may help policymakers to develop suitable industrial and innovation policies specifically for SMEs and avoid introducing policies which may have (unexpected) detrimental effects on some groups of firms. Thirdly, given the obvious heterogeneity among the group of 'small firms', it is of particular interest whether the size-related differences in the effects of external knowledge linkages can be explained by differences in firm's other key innovation-related characteristics such as absorptive capacity, skill intensity, availability of resources, and managerial experience, or whether such differences persist even after accounting for these observable aspects of firm heterogeneity.

Based on an unbalanced panel of Irish manufacturing plants from 1994 to 2008, we confirm the existence of an inverted U-shaped relationship between the 'breadth' of external innovation linkages and innovation performance for both larger and smaller plants (Laursen and Salter, 2006; Love et al., 2014). Significant differences emerge, however, in the profile of innovation benefits which small and larger plants derive from any given breadth of external innovation linkages, even if we account for various aspects of firm heterogeneity. In particular, as search breadth initially increases, each increment to breadth contributes more to innovation performance in smaller plants. At the same time, however, the maximum innovation benefit which small plants can derive from external linkages is lower, and occurs with fewer types of linkages than that for larger plants. In other words, small plants experience the limits to openness at lower levels of breadth than larger plants.

2. Literature Review and Hypotheses

Our key concern here is the relationship between openness in terms of external knowledge linkages and innovation performance. For example, Powell (1998) stresses the potential value of external knowledge linkages in stimulating creativity, reducing risk in the innovation process, accelerating or upgrading the quality of the innovations made, and signalling the quality of firms' innovation activities. External innovation linkages may also increase firms' access to technology developed elsewhere (Mowery, 1990; Niosi, 1999) and their ability to appropriate the returns from innovation (Gemser and Wijnberg, 1995). Moreover, having more extensive networks of linkages or more different types of linkages is likely to increase the probability of obtaining useful knowledge from outside of the firm (Leiponen and Helfat 2010). Empirical evidence also points to the conclusion that knowledge gained from alternative sources tends to be complementary, and also complementary with firms' internal knowledge in shaping innovation performance (Roper et al. 2008, Cassiman and Veugelers 2006)[2]. Having more or more different types of external linkages may therefore both increase the probability of obtaining valuable knowledge and maximise potential complementarities between internal and external knowledge.

Openness in innovation in the form of a larger number of different types of external knowledge linkages has also some potential disadvantages. There may be difficulties with managing and protecting intellectual property rights. Having a larger number or variety of types of innovation partner may also lead to problems with the management and monitoring of these relationships (Simon 1947, Audretsch et al., 1996; Sieg et al. 2007) and the simultaneous absorption of knowledge from a number of different sources. These disadvantages are likely to increase as firms' number of linkages increases with the potential

[2] R&D can be seen also as a proxy of absorptive capacity of firms (Cohen and Levinthal 1989). Own R&D may enhance firms ability to benefit from other knowledge sources. For example, in Rosenberg's (1990) view firm's own research capability is seen as indispensable for monitoring and evaluating research that is performed elsewhere.

for the firm to reach a 'saturation level' where the innovation benefits of external linkages are maximised. Beyond that level, the addition of another innovation linkage will result in a deterioration of the innovation performance of the firm as the attention of managers is diluted between large numbers of different knowledge sources. Koput (1997) and Laursen and Salter (2006) reflect this in their notion of 'over-searching', and some empirical analyses of innovation performance do find evidence of external and internal knowledge being substitutes rather than complements under certain circumstances (Love and Roper 1999, Audretsch et al. 2005).

The balance between the positive effects of firms' external innovation linkages and the potential for over-searching led Laursen and Salter (2006), Leiponen and Helfat (2010) and Love et al. (2014) to expect an inverted U-shaped relationship between the breadth or number of innovation linkages and innovation performance, an expectation confirmed by their empirical analyses.

This does not of course suggest that the shape of the relationship between the breadth of plants' innovation linkages and performance will be the same for small and larger establishments. Small establishments may, firstly, face particular difficulties in establishing and benefiting from external knowledge linkages due to their shortage of the abilities that are needed: i) to build organizational structures to enable the identification of useful external knowledge; and ii) to absorb externally developed ideas and technologies, even if these were already initially copied or transferred from outside the firm. Secondly, small establishments' lower level of knowledge resources (Narula 2004) means that they may be unattractive co-operation partners for other firms, further reducing the chances of building 'openness'. This is perhaps reflected in recent empirical evidence which suggests that small producers adopt open innovation practices significantly less often than medium sized firms (van de Vrande et al. 2009).

It is tempting to infer from these arguments that smaller firms will benefit less from wider breadth of external knowledge linkages. However, the relative benefits of increasing breadth of external linkages for small and large firms may be much more subtle than this and there are good reasons to think that the innovation benefits of openness may actually be stronger for small firms – at least up to some limit. Weaker internal knowledge resources and ability to invest in in-house knowledge creation may make external sourcing of knowledge especially important for small firms (Leiponen and Byma 2009, Edwards et al. 2005). As small firms start, on average, with lower overall levels of knowledge resources, adding more or new types of innovation linkages is likely to have a larger proportionate effect on small firms[3]. For small firms the search for knowledge created elsewhere may also be a more viable way of acquiring new knowledge than in-house generation due to the costs and risks involved in R&D activity. Developing linkages to customers or suppliers, for example, is unlikely to involve the same fixed costs as conducting in-house R&D. SMEs might also benefit more from external linkages because of behavioural advantages related to flexibility and speed of decision making (Vossen, 1998; Acs and Audretsch 1987). Due to this and their ability to specialize in narrow market segments that are unattractive to larger firms, SMEs may be better at quickly adopting the ideas and suggestions by lead users into the product development phase.

Thus, there are reasons why the benefits for innovation of each additional external linkage may be greater for smaller firms. However, the limits to openness also come into play here. As Laursen and Salter (2006) suggest, the returns to increased openness (breadth of linkages) are likely to become negative at some point as managerial cognitive limits are reached and the diseconomies of 'over-searching' are encountered (Koput 1997; Laursen and Salter

[3] Therefore external linkages (and knowledge) may act as a substitute for a *lack* of internal knowledge generation within SMEs, as well as being complementary with existing internal knowledge.

2006). Due to their smaller top management teams and therefore potentially lower capacity to organise and manage large sets of external linkages, one might expect this limit to be reached more quickly among small firms (Tether, 2000). In other words, while the innovation performance of smaller firms may benefit more from an additional type of external linkage, smaller firms could also reach the limits of any additional benefit earlier than larger firms.

Our discussion above leads to our two central hypotheses:

Hypothesis 1: The initial marginal benefit to innovation performance of each additional type of innovation linkage will be greater in small establishments.

Hypothesis 2: The maximum benefit to innovation performance of firms' external innovation linkages will be reached at a lower number of different types of innovation linkages by small establishments.

Firms' innovation linkages are diverse, however, involving a range of different partners: supply chain linkages with customers and suppliers, linkages with competitors, universities, labs, consultants, etc. The first naturally occurring innovation linkages typically form with firms' clients and suppliers. For example, Brunswick and Vanhaverbeke (2011) confirm in their recent study of circa 1500 European SMEs that customers are often an attractive source of innovation inputs for them. Some types of innovation linkages - for example, with universities and research centres – may, however, require larger expertise and absorptive capacity from the firm. As mentioned above, small firms are more likely to lack these resources. The benefits from having linkages with universities and research centres may also take a longer time to materialise, as new knowledge developed there is rarely easily adaptable to the circumstances at the firm. The adaptation process, again, will need investments from the firm. Thus, in the case of some types of linkages we can expect large (learning related) costs in the short run, and benefits only in the longer run. Linkages with universities and researchers are also fraught with risks due to the uncertainty of any commercial applicability of research outcomes (Roper et al, 2008). Larger firms may be better equipped for leveraging these risks. For these reasons, we may expect the most beneficial linkages for small firms to be with clients and suppliers rather than with universities etc. This leads us to the two last hypotheses to be tested based on Irish establishment level panel data.

Hypothesis 3. Among different types of innovation linkages, supply chain linkages will matter most for the innovation performance of small plants.

Hypothesis 4. Supply chain innovation linkages will matter more for the innovation performance of small compared to larger plants.

3. Data and Methods

Our empirical analysis is based on data from the Irish Innovation Panel (IIP) covering the period 1994 to 2008. The IIP provides information on the innovation activities of manufacturing plants in the Republic of Ireland and Northern Ireland and comprises five plant-level surveys[4]. These were conducted every three years using similar survey questionnaires with common questions, and capture the same indicators of open innovation during this period. The initial IIP survey used here was conducted between November 1996 and March 1997. It covered plants' innovation indicators for the 1994-96 period, and had a response rate of 32.9 per cent. The next IIP survey covered the 1997-99 period, with a response rate of 32.8 per cent. The survey of 2000 to 2002 period achieved a response rate of

[4] 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.

34.1 per cent. Subsequent surveys covering the 2003 to 2005 and 2006 to 2008 periods achieved response rates of 28.7 per cent and 38 per cent. We note that the resulting panel is significantly unbalanced, both due to the foundation and closure of plants and survey non-response. On average, a plant in the IIP (in waves 2-6) has 1.7 period-observations available, 52 per cent of plants have at least 2 periods and 30 per cent have at least 3 periods' data available[5].

Our focus here is on plants' 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 organisations as part of your product or process development?* Plants that confirmed having linkages were then 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. Figure 1 shows how the average number of different types of linkages or breadth of linkages has changed through time for small plants (with 10-49 employees) and larger plants. On average, over the whole sample period, small plants have an average of 0.82 different types of external linkages, half that of larger plants (1.64, Table 1)[6]. We note that most plants have up to 4 different types of linkages. The share of plants with more than 4 different types of linkages is rather small: depending on the wave of IIP between 4-10 per cent of all establishments. There is also little evidence in our Irish dataset supporting the idea of a 'paradigm shift' towards more open innovation among small or larger plants[7]. This is consistent with the

[5] Numbers of observations in each wave of the IIP are as follows: 1994-96, 751; 1997-99, 1047; 2000-02, 906; 2003-05, 799; 2006-08, 415.

[6] The difference between the mean value of linkage types for small and larger plants is highly significant (t=13.89, ρ=0.000).

[7] Each wave of the IIP is designed to be representative of Irish manufacturing at the time of survey in terms of sector and sizeband distribution.

analysis of Spanish data by Barge-Gil (2011), but contrary to that found in the Netherlands by van de Vrande et al. (2009).

Not surprisingly perhaps, the most common external partners in plants' innovation activity were customers and suppliers (Table 2). Links to universities, labs, competitors and other partners are much less common. This regularity holds for both small and larger plants. Small plants in particular, have significantly fewer supply chain linkages to customers and suppliers than larger plants. For example in the 2006 to 2008 period, 33 per cent of small plants and 53 per cent of larger plants had supply chain linkages. Notably, the gap between small and large plants is even larger in terms of links to universities and laboratories and linkages to competitors and others knowledge sources (Table 2).

Our econometric analysis is based on estimation of the innovation production function as a key stage of innovation value chain, with innovation linkages included among other standard explanatory variables (Crépon et al. 1998; Laursen and Salter, 2006; Love et al., 2014). Our econometric model is similar to the one used in Laursen and Salter (2006) based on UK data and Love et al. (2014) based on the full sample of the IIP dataset. As the dependent variable in the innovation production function we use a common innovation output indicator – the proportion of plants' sales (at the end of each three-year reference period) derived from products that were either newly introduced or improved during the previous three years. This variable reflects plant's ability to introduce new or improved products to the market and their subsequent commercial success. On average, 20 per cent of the sales of small plants were from newly introduced or improved products compared to 29 per cent for larger plants (Table 1).

We estimate the innovation production function separately for small and larger plants[8]. Let $INNOV_{it}$ be an innovation output indicator (for plant *i* at survey period *t*), and FCB_{it} a vector of plant level standard control variables and OI_{it} represent plants' breadth or number of different types of innovation linkages. The innovation production function with sector specific (λ_j) and time effects (τ_t) can then be written:

$$INNOV_{it} = \delta_0 + \delta_1 OI_{it} + \delta_2 OI_{it}^2 + \delta_3 FCB_{it} + \lambda_j + \tau_t + \varpi_{it}. \qquad (1)$$

Here, *i* denotes the plant, *t* period (IIP wave), and *j* sector, ϖ_{it} is an idiosyncratic error term.

Hypothesis 1 implies that the innovation benefits of external linkages will be greater for small plants. We can test this hypothesis based on a comparison of δ_1 and δ_2 in the innovation production functions for smaller and larger plants. It also proves helpful to plot these relationships highlighting contrasts in the shape and turning point of the relationship between the number of linkages and innovation performance as anticipated in Hypothesis 2.

Next, our analysis addresses Hypotheses 3 and 4 about the role of supply chain linkages. We define SCL_{it}, as a dummy variable (0,1) indicating presence of linkages within the supply chain, either with customers or suppliers of the plant. Variable $UNILAB_{it}$ is a dummy indicating the presence of linkages with universities or labs. Variable $OTHER_{it}$ is a dummy variable denoting the presence of linkages to plant's competitors, joint ventures or consultants. The model that investigates the role of different types of linkages is the following:

$$INNOV_{it} = \alpha_0 + \alpha_1 SCL_{it} + \alpha_2 UNILAB_{it} + \alpha_3 OTHER_{it} + \alpha_4 FCB_{it} + \lambda_j + \tau_t + \nu_{it}. \qquad (2)$$

Hypothesis 3 implies that $\alpha_1 > \alpha_2, \alpha_3$. Hypothesis 4 implies that the coefficient α_1 is significantly greater for small plants than for larger ones.

[8] As a robustness test we also estimate a version of the production function based on the full sample, with key explanatory variables interacted with firm size (see Annex 1).

Our choice of estimation approach for Equation (1) and (2) reflects the form of our dependent variable. The share of new or improved products in sales can take values between 0 and 100. Therefore we use a panel tobit model and in each equation a set of sector indicators at the 2- digit level and a series of time dummies. We also include in each model a standard set of controls for other plant characteristics which have been found in many previous studies to affect innovation outputs. One of the most important innovation inputs is an indicator of whether or not plants are under-taking in-house R&D (Crépon et al. 1998, Griliches 1995; Oerlemans et al. 1998). This is also an indicator of absorptive capacity (Cohen and Levinthal 1990). In our sample, in-house R&D was performed by 29 per cent of small plants and 60 per cent of larger plants (Table 1). We also include variables intended to reflect the strength of plants' internal knowledge base – multinationality and the age and scale of the plant (Klette and Johansen, 1998). A multinationality dummy is incorporated as a control variable because links between plants within a multinational are a potentially important channel for international knowledge transfer (Dunning 1988). Also, multinational firms may be more able to reap the benefits of open innovation than domestic firms due to access to knowledge resources within the firm. Additionally, we include the share of each plant's employees which have a degree level qualification, an indicator of labour quality (Freel 2005) and potentially also absorptive capacity. Models also include a dummy variable to indicate whether or not plants had received public support for their innovation activity (Hewitt-Dundas and Roper 2009). The Herfindahl index is included as a broad proxy for sectoral competition (at the 2-digit level), as this can affect innovation (e.g. Aghion et al. 2009).[9]

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[9] Finally, before turning to our empirical results it is important to acknowledge the potential for survey-based studies such as ours to suffer from common method variance or bias (CMB). Formally, we have checked for CMB using the Harmon's one factor test (Podsakoff et al. 2003) and the marker variable technique (e.g.

4. Results

The results of estimating Equations (1) and (2) are shown in Table 3. There is strong evidence of an inverted U-shaped relationship between our measure of breadth of external knowledge linkages and innovation outputs, for both small and larger firms (Laursen and Salter, 2006; Leiponen and Helfat, 2010; Love et al. 2014). The coefficients on the variables 'number of different types of linkages' and its squared term are significantly different in the sample of small plants and medium/large plants. The test statistics of differences in coefficients and the corresponding p-values are $\chi^2=8.31$, $p=0.004$ in the case of the number of different types of linkages and $\chi^2=5.55$, $p=0.018$ in the case of the number of different types of linkages squared. In Figure 2 the coefficients on the number of linkages and its square in Table 3 (Models 1 and 2) are used to plot the relationship between breadth of openness and innovation performance. It is evident that among small plants the innovation benefits of openness in terms of wider set of different linkages are greater than that for larger plants reflecting the larger coefficient on breadth in the estimated model for small plants. However, as almost all small plants have fewer than six types of external linkage the effect of breadth of open innovation on innovation performance is, in effect, stronger for almost all small plants. This provides strong support for Hypothesis 1.

Hypotheses 2 posited that the maximum innovation benefits of breadth of knowledge linkages would be reached earlier in the case of small plants. This is indeed the case, as shown in Figure 2. The turning point of this openness-innovation performance relationship for small plants occurs at about four types of external linkage: adding additional linkages

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Malhotra et al. 2006). Based on both standard techniques, there appears to be no reason to suspect significant CMB in our analysis.

beyond this point is associated with lower innovation output.[10] By contrast for larger plants increasing breadth of linkages continues to be associated with greater innovation output, albeit at a decreasing rate. This tends to support the view that governing many different types of linkages requires significant co-ordination capacity, precisely the kind of resources and co-ordination abilities which may be lacking in smaller establishments.

One issue with Figure 2 is that it does not account for the different 'starting point' in terms of level of innovation performance of small and larger plants which may reflect, for example, their different levels of internal knowledge resources. This is taken into account in Figure 3 where we combine equation coefficients (from Table 3) with average values of each explanatory variable other than breadth to define average predicted levels of innovation performance. Here the underlying relationships between breadth of linkages and innovation output remains unchanged, but we show the level of share of new or modified products in sales that is attained for an average plant in both groups (i.e. the level of innovation output attained given all the other regression coefficients and average values of explanatory variables). The results of our regression analysis, combined with information about mean values of the control variables in each group, show that the level of innovation output of the average small plant is lower than the level of the average large plants as long as the number of different types of innovation linkages is less than 3 or above 4. If small plants have 3 or 4 different types of linkages they attain, on average, the same level of innovation output as larger plants. This reinforces the message of Hypothesis 1 that – within limits – small firms can make up for a lack of other internal innovation resources by developing external linkages with innovation partners.

As another robustness check, we use the McDonald and Moffitt (1980) decomposition to divide the effects of the breadth of linkages in Column (1) and (2) of Table 3 into two

[10] Note that the downward sloping part affects only a small share of NEED TO FINISH THIS NOTE

components. First, the marginal effect on the probability of having larger than zero share of new and modified products in sales. Second, the marginal effect on the expected value of innovation output conditional on the plant having positive innovative sales. The results confirm that the marginal effects of the breadth of innovation linkages both on the probability that a plant will have new or modified products and on innovation intensity among innovators is higher among small plants (Table 4). This suggests that the benefit of adding an additional external linkage is greater for small plants both in terms of its effect on their propensity to innovate *and* in terms of increasing their level of innovation outputs once over the innovator hurdle. The effect on the uncensored part of the distribution of innovation performance (i.e. the 'intensity' effect) accounts for 32 per cent of the total effect on innovation performance of small plants. The corresponding figure for large and medium sized plants amounted to 42 per cent. This shows clearly that the effect on the propensity to have positive innovative sales is proportionally more important for small plants.

Columns 3 and 4 in Table 3 outline the results of estimating Equation (2), where we test Hypotheses 3 and 4 on the effects of different types of linkage. As expected, supply chain linkages matter most for small plants (Hypothesis 3). Small firms that have supply chain linkages have about 23 per cent higher share of new or modified products in sales than other small plants. At the same time, linkages with competitors, joint ventures and consultants add only about 5 per cent to this innovation output measure. There are thus large benefits for small plants from having supply chain linkages. Or, to put it another way, there are large penalties from not having this essential type of linkage. We also find support for Hypothesis 4: on average, supply chain linkages matter more for small plants' innovation performance than for that in large establishments. This is clear from a comparison and a formal test of the difference between the coefficients of the supply chain linkages variable in Columns 3 and 4 in Table 3. The contribution of supply chain linkages to innovation performance is more than four times higher among small plants than among larger plants, and the difference is statistically significant (χ^2=15.87, p=0.001)[11]. Among other results, it has to be pointed out that having linkages with universities and labs is not necessarily beneficial for small establishments. Indeed in our data such linkages are associated in the short term with a reduction in innovation performance. This could be explained by the large costs of establishing linkages with universities for small plants and the time period needed for the benefits of these types of linkages to materialise. Larger establishments may find it easier to absorb these costs of learning from universities and labs.

The control variables used in the tobit models largely take the expected signs but also suggest some significant differences between the determinants of innovation performance in small and larger plants. For example, R&D is an important input in the innovation production function for both small and larger plants but has a significantly greater association with innovation performance in smaller plants[12]. Similarly, exposure to export markets (χ^2=3.06, ρ=0.002) and having a more highly qualified workforce (χ^2=2.43, ρ=0.015) both have a proportionately greater association with innovation performance in smaller rather than larger plants (Love et al; 2010; Freel, 2005). Other factors such as external ownership (χ^2=0.02, ρ=0.987) and receiving public support (χ^2=0.95, ρ=0.340) for innovation also have positive relationship with innovation performance, the relationships which are similar in scale for small and larger plants (Hewitt-Dundas and Roper, 2009). Interestingly, sectoral concentration as measured by the Herfindahl index is only significant for larger plants where it has a positive rather than negative sign.

[11] As a robustness check we again re-estimated these effects using interaction effects (Annex 1). This again suggests very similar general conclusions about the importance of supply chain linkages as the results based on comparing the different size-groups in Table 3.

[12] Comparing Models 1 and 2 in Table 3, for example, a test of the equality of the coefficients on in-house R&D in the two models suggests a significant difference (χ^2=5.80, ρ< 0.000.)

Extension: heterogeneity among small plants

Thus far we have treated 'small firms' as a homogeneous group. We now extend the analysis to consider some of the factors which might underlie both heterogeneity within the small firm sector, and which might also help explain the differences in external linkage effects between small and large plants.

The earlier conceptual overview suggested that certain aspect of small firms may explain their different effects of external linkages relative to large firms, Principal amongst these were issues relating to absorptive capacity, especially R&D and skills, as well as (lack of) managerial expertise and the generally greater resources of larger firms[13]. Given the heterogeneity of the small firm sector these issue may also in part explain intra-small firm heterogeneity in the linkage-innovation relationship: we allow for both possibilities here.

We investigate the heterogeneity of the effects of breadth of linkages within our main size-groups in Table 5. We show whether the results vary significantly by differences among plants in terms of : i) absorptive capacity (proxied by own R&D and by skilled labour availability), ii) managerial experience, iii) and external resources (proxied by foreign ownership). To test for the heterogeneity of effects within size groups, we include interaction terms of breadth of linkages and breadth of linkages squared with firm's own R&D (Columns 1 and 2), indicators of foreign ownership (Columns 3 and 4), skill intensity (Columns 5 and 6), and availability of managerial prior experience (Columns 7 and 8).

Dealing first with heterogeneity within the small firm sector, the results suggest that issues of absorptive capacity and managerial and general resources have little effect on the

[13] We note that some of these differences between size groups have been taken into account in our analysis presented so far. Inclusion of skill intensity, an indicator of foreign ownership and R&D enables to account to some extent for differences within the group of small firms. However, these controls do not enable us to determine whether the effects of knowledge linkages vary within the sub-groups of small plants.

relationship between linkage breadth and innovation. The inverted U-shaped effect still persists, and only in the case of R&D is there any significance in terms of an interaction effect, suggesting a strong substitute relationship between internal R&D and external linkages. The more general conclusion based on the results in Table 5 is that the inverted U-shaped statistically significant relationship between the breadth of linkages and innovation performance among both small plants or medium- and large plants persists even after inclusion of these interaction effects. Hence, we can conclude that our key result concerning the effect of breadth of linkages does not simply reflect differences in plants' absorptive capacity, availability of skilled labour, ownership or the extent of managerial experience.

5. Conclusions

Based on an econometric analysis of Irish plant-level panel data from 1994 to 2008 our results suggest that external knowledge linkages work very differently in small manufacturing plants compared to larger ones. First, small plants are consistently less open in terms of their number of external linkages than larger ones and this is consistent over the 1994 to 2008 period. Second, as expected, we find an inverted U-shaped relationship between the extent ('breadth') of openness and plants' innovation performance, both for small and larger plants (Figure 2). Third, small plants gain more from each additional linkage type than do larger plants. This effect seems to be not reflecting the differences in absorptive capacity, skill intensity or managerial experience (see Table 5), but more likely the lower starting level of external linkages of small establishments and the resulting larger marginal effect of investments in knowledge sourcing from external partners.

Fourth, small plants reach their limit to benefitting from openness earlier than larger plants. Taking the last two findings together suggest that larger establishments are able to continue benefitting from increased linkage breadth (albeit at a decreasing rate) beyond the limit at which increased breadth has started to have negative effects for small plants (Figures 2 and 3). Finally, the contrasts between small and large plants are especially strong in the case of effects of linkages within the supply chain. For small plants, such linkages are the most important, and supply-chain linkage smatter much more for them than for larger plants.

Perhaps our most important conclusion is that increasing the breadth of linkages is proportionately more important to innovation in smaller plants. On average, small plants have 0.8 different types of external innovation linkages (Table 1) which contribute around 8 percentage points to innovative sales (Figure 2). This accounts for around 40 per cent of the average level of innovative sales of smaller plants (20.4 per cent, Table 1). For larger plants, which have an average of around 1.6 different types of external innovation linkages (Table 1), those linkages account for around 7 percentage points or around a quarter of average innovative sales by larger plants. So, where they are able to take advantage of external linkages, small plants often have more to gain than their larger counterparts. Our findings therefore underline the importance of paying attention to the heterogeneity of effects of external knowledge sourcing across different types of plants. Average effects based on all plants in manufacturing industry clearly hide large variations across different groups of plants.

Some caution must be exercised in suggesting the benefits of external linkages for smaller firms. Partnering involves two parties and small firms may sometimes be unattractive (or unnoticed) co-operation partners for other enterprises, especially large ones. This may mean that the costs involved in seeking and finding a suitable partner may well be beyond the means of many small firms. We know little about the costs involved in developing such relationships, an area which provides a potentially valuable focus for future research. In addition, it should be borne in mind that developing such linkages is very much a minority activity among small firms: the average number of linkages for small firms in our sample is less than one, with only 21 per cent of small firms having three or more types of linkage. Nevertheless, the potential benefits of increased breadth are great: as indicated in Figure 3, for our sample an average small firm with no innovation linkages has a level of innovation intensity approximately 12 percentage points below that of an average firm with more than 50 employees. By the time both firms have reached three types of external linkage, this gap has completely closed, suggesting that external boundary-spanning linkages can be an effective strategy for small firms to boost markedly their level of innovativeness.

The findings also clearly underline the relative importance of innovation linkages in the supply chain for small firms. Although both small and larger establishments benefit from these, the effect is markedly greater for small firms. This may well be related to the relatively low entry costs of such linkages compared with links to universities, competitors and others, and suggests that an obvious route for small firms to start reaping the benefits of breadth of openness is through exploring innovation linkages with existing customers and suppliers.

In strategic terms our results suggests the value of openness in innovation for small firms involving, perhaps, up to four types of external partner. The limited resources available within small firms for managing and developing these external relationships, however, suggests the importance of the careful selection of the most appropriate or beneficial innovation partners. Criteria for partner selection will of course vary, reflecting the internal capabilities of each small firm and their innovation ambitions (Jeon et al., 2011). In policy terms, however, this suggests the potential importance of partnership brokering intermediaries which might encourage small firms to adopt more open innovation strategies and help to identify potential innovation partners (Cantner et al., 2011).

Two limitations of our analysis suggest the need for caution in drawing more specific policy implications. The first limitation of our analysis, which restricts its direct policy application, is the broad nature of our measure of the breadth of plants' portfolio of innovation linkages. This implicitly makes a number of assumptions: that each type of linkage is of equal innovation value, that this value remains the same through time, and that the relative innovation value of each type of linkage is the same for larger and smaller firms. Each of these assumptions suggests the value of further research to develop more realistic weighting structures for different types of linkages. A second limitation is the fact that we investigate a correlative relationship. Although our regression results can reflect the effects of external linkages on innovation performance, a clear identification of causal effects may be needed in future analysis of benefits of openness, for example, using natural experiment based approach.

Table 1: Descriptive statistics of variables used in regression analysis

	Small plants		Medium and large plants	
Variable	Mean	Std. Dev.	Mean	Std. Dev.
Sales from new or improved products (%)	20.43	28.49	29.39	30.78
R&D conducted in-house (dummy)	0.39	0.49	0.60	0.49
Number of linkages (0…8)	0.82	1.46	1.64	2.03
Linkages within supply chain (dummy)	0.28	0.45	0.46	0.50
Linkages with universities and labs (dummy)	0.13	0.33	0.30	0.46
Other linkages (dummy)	0.19	0.39	0.33	0.47
Employment (no.)	23.96	11.33	199.53	389.19
Age of the plant (years)	28.57	27.66	32.22	32.92
Foreign owned plant (dummy)	0.14	0.35	0.49	0.50
Export dummy	0.42	0.49	0.72	0.45
Workforce with degree (%)	9.63	14.15	10.57	12.54
Govt. support for product innov. (dummy)	0.18	0.39	0.30	0.46
Herfindahl index	0.26	0.13	0.28	0.11
Number of observations	2170		1672	

Source: IIP. Note: Dummy variable 'Other linkages' includes linkages to competitors, joint ventures and consultants.

Table 2: Percentage of plants with linkages to different types of partner

	Percentage of plants with linkages:		
Small plants:			
Period	Within supply chain %	To universities and labs %	Other linkages %
1994-1996	24.9	9.8	16.9
1997-1999	31.9	16.8	24.1
2000-2002	24.7	10.4	15.5
2003-2005	23.7	11.2	17.1
2006-2008	33.2	12.2	18.3
Medium and large plants:			
Period	Within supply chain %	To universities and labs %	Other linkages %
1994- 1996	43.2	26.5	30.8
1997-1999	51.2	30.7	34.9
2000-2002	41.1	26.5	32.1
2003-2005	43.8	29.2	26.6
2006-2008	53.1	43.3	38.8

Notes: Observations are weighted to give representative results.

Source: IIP. Other linkages are to competitors, joint ventures and consultants.

Table 3: Knowledge production function: the role of breadth and type of external innovation linkages

	Breadth of linkages		Type of linkages	
	(1)	(2)	(3)	(4)
Dep. var.: Sales from new or improved products (%)	Model 1, Small plants	Model 1, Medium and large plants	Model 2, Small plants	Model 2, Medium and large plants
R&D conducted in-house	32.843***	21.513***	32.057***	21.774***
	(1.009)	(1.134)	(1.007)	(1.140)
Number of different types of linkages	11.808***	4.488***		
	(0.733)	(0.655)		
Number of different types of linkages squared	-1.309***	-0.232**		
	(0.148)	(0.108)		
Supply chain linkages (dummy)			22.973***	5.292***
			(1.167)	(1.246)
University/lab linkages (dummy)			-5.900***	-0.990
			(1.482)	(1.282)
Other linkages (dummy)			4.722***	10.769***
			(1.344)	(1.262)
Employment (no.)	0.406**	0.010***	0.403**	0.011***
	(0.182)	(0.003)	(0.181)	(0.003)
Employment (no.) squared	-0.009***	-0.000*	-0.008**	-0.000*
	(0.003)	(0.000)	(0.003)	(0.000)
Establishment age (years)	-0.102***	-0.115***	-0.094***	-0.117***
	(0.018)	(0.017)	(0.017)	(0.017)
Foreign owned plant	5.892***	5.259***	5.488***	6.015***
	(1.324)	(1.127)	(1.315)	(1.133)
Export dummy	6.732***	1.929	6.161***	2.318*
	(0.991)	(1.267)	(0.992)	(1.272)
Workforce with degree (%)	0.284***	0.138***	0.315***	0.129***
	(0.036)	(0.044)	(0.036)	(0.044)
Govt. support for product innov.	7.717***	5.142***	10.148***	5.711***
	(1.178)	(1.131)	(1.183)	(1.142)
Herfindahl index	8.861	20.734**	6.230	20.210**
	(6.504)	(8.401)	(6.485)	(8.442)
Constant	-22.794***	-11.360***	-23.387***	-11.773***
	(3.400)	(3.297)	(3.393)	(3.329)
Industry dummies	Yes	Yes	Yes	Yes
Period dummies	Yes	Yes	Yes	Yes
Observations	1674	1348	1647	1331
Log-likelihood	-3.57e+04	-2.46e+04	-3.50e+04	-2.43e+04

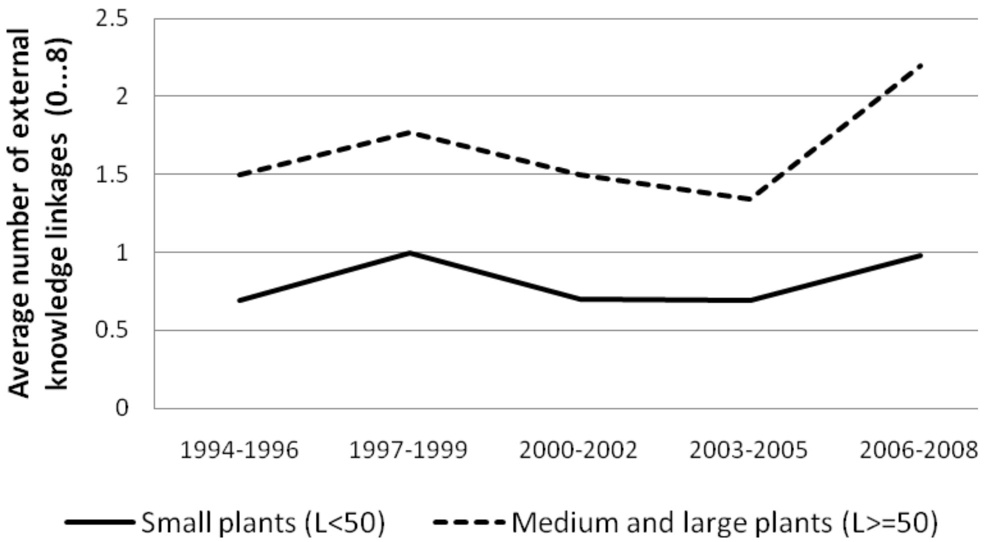
Source: Irish Innovation Panel, waves 2-6 of the survey are included. Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Random effects tobit models. Dummy variable 'Other linkages' includes linkages to competitors, joint ventures and consultants. Observations are weighted in regression analysis to give representative results.

Table 4: McDonald and Moffitt (1980) decomposition of the effects of breadth of linkages in tobit model in Table 3

	Marginal effects at sample means on innovation performance	
	Marginal effects on the probability of having innovation output (i.e. probability that the share of new or improved products in sales>0)	Marginal effects on the expected value of innovation performance conditional on having innovation output (i.e. conditional that the share of new or improved products in sales>0)
Small plants:		
Number of different types of linkages	0.082***	3.564***
Number of different types of linkages squared	-0.009***	-0.403***
Medium and Large plants:		
Number of different types of linkages	0.029***	1.806***
Number of different types of linkages squared	-0.001**	-0.086**

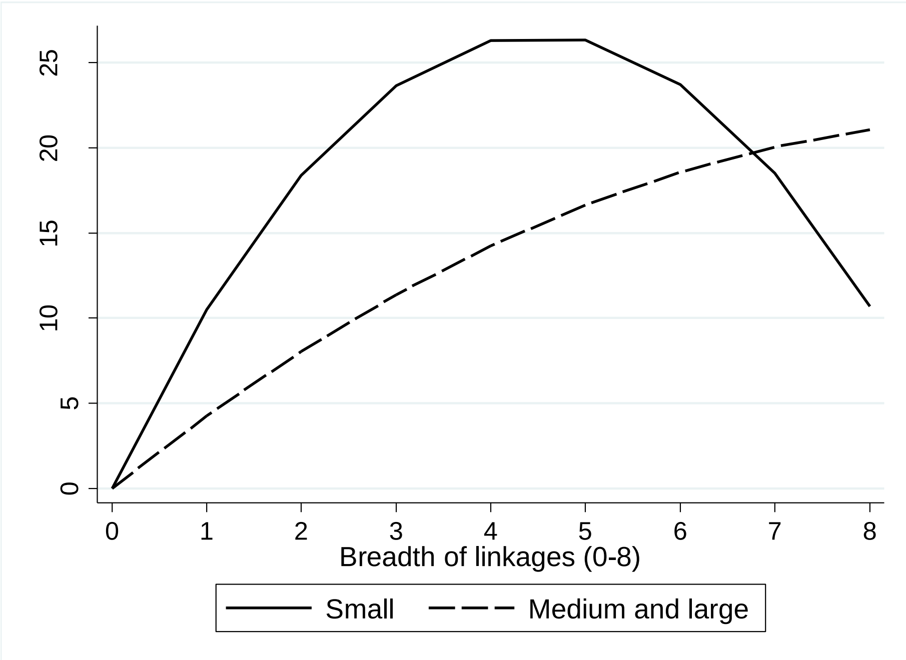
Source: Irish Innovation Panel, waves 2-6 of the survey are included. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Marginal effects are calculated based on model in Equation 1, as estimated with tobit model in Columns 1 and 2 of Table 3.

Figure 1: Average number of different types of innovation linkages



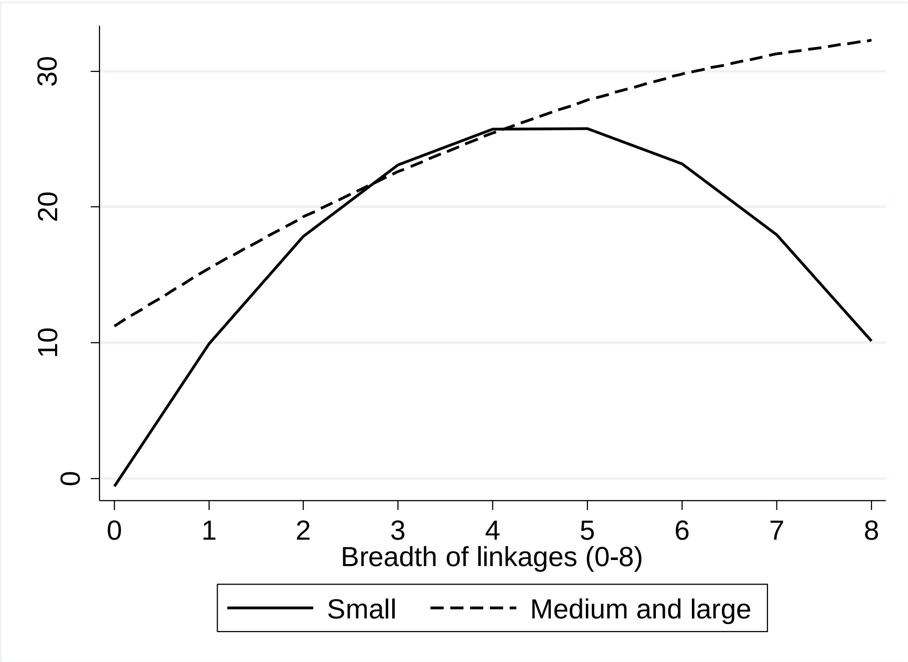
Notes: Observations are weighted to give representative results. Small plants are defined as plants with less than 50 employees. **Source**: IIP

Figure 2: Relationship between breadth of openness (number of different types of linkages) and innovation performance



Source: Regression results in Column 1 of Table 3.

Figure 3: Level of innovation performance reached on average for different levels of breadth of openness: accounting for different initial levels of innovation output.



Source: Regression results in Column 1 of Table 3. (Starting point for small plants: -0.56, for larger plants 11.22)

Table 5: Knowledge production function: interaction of breadth of linkages with plant characteristics

Dep. var.: Sales from new or improved products (%)	(1) Small plants	(2) Medium and large plants	(3) Small plants	(4) Medium and large plants	(5) Small plants	(6) Medium and large plants	(7) Small plants	(8) Medium and large plants
Number of different types of linkages	23.663***	8.584***	11.925***	5.742***	11.371***	6.158***	12.164***	4.788***
	(1.171)	(1.228)	(0.805)	(0.914)	(0.918)	(0.878)	(0.797)	(0.684)
Number of different types of linkages squared	-3.113***	-0.780***	-1.393***	-0.257*	-1.373***	-0.388***	-1.447***	-0.276**
	(0.260)	(0.215)	(0.164)	(0.156)	(0.188)	(0.143)	(0.164)	(0.113)
Number of different types of linkages*R&D	-20.599***	-5.773***						
	(1.483)	(1.426)						
Number of different types of linkages squared*R&D	3.104***	0.773***						
	(0.314)	(0.245)						
Number of different types of linkages*FDI			-0.308	-3.047**				
			(1.910)	(1.279)				
Number of different types of linkages squared*FDI			0.413	0.134				
			(0.380)	(0.213)				
Number of different types of linkages*Workforce with degree					0.040	-0.159***		
					(0.052)	(0.052)		
Number of different types of linkages squared* Workforce with degree					0.004	0.016**		
					(0.010)	(0.008)		
Number of different types of linkages*Shortage of managerial experience							-1.594	-2.538
							(1.577)	(1.589)
Number of different types of linkages squared*Shortage of managerial experience							0.626*	0.495
							(0.350)	(0.318)
Industry and period dummies, other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1674	1352	1674	1348	1674	1352	1674	1352
Log-likelihood	-3.6e+04	-2.5e+04	-3.6e+04	-2.5e+04	-3.6e+04	-2.5e+04	-3.6e+04	-2.5e+04

Source: Irish Innovation Panel, waves 2-6 of the survey are included. Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Random effects tobit models. Observations are weighted in regression analysis to give representative results.

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Annex 1: Robustness tests

Table A1: Knowledge production function: interaction of breadth and type of linkages with plant size

Dep. var.: Sales from new or improved products (%)	(1) Role of breadth of linkages	(2) Role of type of linkages
R&D conducted in-house	28.485***	28.294***
	(0.746)	(0.749)
Number of different types of linkages	10.358***	
	(0.552)	
Number of different types of linkages*Employment	-0.024***	
	(0.003)	
Number of different types of linkages squared	-1.005***	
	(0.101)	
Number of different types of linkages squared*Employment	0.003***	
	(0.0004)	
Supply chain linkages (dummy)		17.211***
		(0.978)
Supply chain linkages*Employment		-0.025***
		(0.006)
University/lab linkages (dummy)		-3.137***
		(1.133)
University/lab linkages *Employment		-0.008
		(0.006)
Other linkages (dummy)		8.469***
		(1.078)
Other linkages *Employment		-0.001
		(0.006)
Employment (no.)	0.029***	0.027***
	(0.004)	(0.004)
Employment (no.) squared	1.72e-06*	6.14e-06
	(9.86e-07)	(9.76e-07)
Establishment age (years)	-0.108***	-0.099***
	(0.126)	(0.126)
Foreign owned plant	5.999***	6.364***
	(0.862)	(0.863)
Export dummy	4.911***	4.865***
	(0.766)	(0.771)
Workforce with degree (%)	0.219***	0.244***
	(0.028)	(0.028)
Govt. support for product innov.	6.638***	7.957***
	(0.822)	(0.828)
Herfindahl index	14.563***	13.710***
	(5.026)	(5.036)
Constant	-18.952***	-19.625***
	(2.023)	(2.023)
Industry dummies	Yes	Yes
Period dummies	Yes	Yes
Observations	3022	2978
Log-likelihood	-6.0e+04	-5.9e+04

Source: Irish Innovation Panel, waves 2-6 of the survey are included. Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Random effects tobit models. Dummy variable 'Other linkages' includes linkages to competitors, joint ventures and consultants. Observations are weighted in regression analysis to give representative results.