Networks, Space and Organisational Performance: A Study of the Determinants of Industrial Research Income Generation by Universities

Abstract

This paper examines the extent to which both network structure and spatial factors impact on the organisational performance of universities as measured by the generation of industrial research income. Drawing on data concerning the interactions of universities in the UK with large R&D-intensive firms, the paper employs both social network analysis and regression analysis. The analysis finds that the structural position of a university within networks with large R&D-intensive firms is significantly associated with the level of research income gained from industry. Spatial factors, on the other hand, are not found to be clearly associated with performance, suggesting that universities operate on a level playing field across regional environments once other factors are controlled for.

Keywords: university-industry links; networks; large R&D-intensive firms; knowledge transfer; regions; social network analysis; centrality.

1. Introduction

The rise of the knowledge-based economy has brought major changes in the position that universities are expected to occupy in our economies and societies. Universities have come to be regarded as key sources of knowledge utilisable in the pursuit of economic growth, with knowledge commercialisation and transfer activities attaining a more important role within universities (Etzkowitz, 2003; Drucker and Goldstein, 2007; Huggins et al., 2008; Kitson et al., 2009; Howells et., 2012). Many governments and their agencies are turning their attention to the role of knowledge transfer activities in developing innovative, sustainable, and prosperous economies and industries (Lawton Smith, 2007; Goddard et al., 2012; Hewitt-Dundas, 2013; Hughes and Kitson, 2012). The growth of university-industry interactions and networks derives from the requirements of individual firms to source knowledge from external sources, which is increasingly recognised as a key factor within modern innovation processes (Chesbrough, 2003). This has led some to consider these networks to be a form of capital allowing firms access to economically beneficial knowledge (Huggins and Thompson,

2014) or a resource through which firms gain access to a range of intangible assets such as enhanced reputation (Lavie, 2006; Gulati, 2007)**.**

At the same time, universities have become compelled to pursue knowledge transfer activities for pecuniary reasons. Driven by reductions in government funding, as well as shrinking endowments and increased operating costs, university administrators and faculty have sought other sources of funding to cover their research costs in the form of third stream activities such as services and contracts undertaken for private commercial organisations, which increasingly sit alongside more traditional sources such as funding from research councils (Siegel et al, 2007; Geuna and Muscio, 2009; Hewitt-Dundas, 2013). Studies show that such external funding, particularly funding by industry, has favourable impacts on the scientific performance of universities. Although several scholars have expressed concern regarding the potentially adverse effect of the growth of industrial funding upon the autonomy of university researchers and the quality of scientific production (Dasgupta and David, 1994), there is a growing body of evidence indicating that university researchers funded by industry are more productive than colleagues who are not in receipt of such funding (Gulbrandsen and Smeby, 2005). These studies suggest that industrial funding provides university researchers not only with additional financial resources but also relevant knowledge, generating synergistic effects on their scientific productivity, resulting in improved organisational performance (Manjarrés-Henríquez et al., 2009).

In contrast, there is a dearth of evidence concerning the factors that facilitate universities in generating external income, particularly in the form of research grants and contracts. Although a growing body of work examining university knowledge transfer demonstrates that many institutions are developing initiatives designed to increase such activity (Abreu et al., 2008; Hewitt-Dundas, 2013), less is known about the nature and pattern of the interactions emerging from such knowledge transfer practices, and how such interactions influence organisational performance as measured by the generation of external research income.

The questions the paper addresses concern the nature of the network and spatial factors underlying the interactions that universities undertake with industry, and the subsequent influence of these factors on the generation of research income from industry. The paper explores whether or not a university's ability to raise research income is associated with (1) its structural position within a wider network pattern of university-industry interactions, (2) the spatial reach of its interactions with firms, as well as (3) the nature of the regional environment in which it is located. Through the use of both social network analysis and regression analysis, the paper explores whether the network and spatial structure of the interactions of universities with large industrial R&D players is associated with research income generation from industry. In essence, the paper seeks to examine whether or not interactions with large R&D firms provide universities with access to resources that enhance future prospects for industrial funding generation. In other words, it explores the extent to which universities are able to exploit the type of network resources that others have argued are beneficial to the performance of organisations (Lavie, 2006; Gulati, 2007; Huggins and Thompson, 2014; 2015).

The focus upon large industrial R&D performers as organisations with which universities interact is motivated by the fact that they are likely to be important sources of knowledge and other network resources for universities, as they constitute a large proportion of the knowledge and innovation capacity of many major economies such as the UK (Bercovitz and Feldman, 2007; D'Este and Patel, 2007; Hewitt-Dundas, 2011; Huggins et al., 2012). Given the strategic importance of externally generated income to both the scientific productivity and financial viability of universities, the paper contributes to the literature concerning the role of universities in the knowledge-based economy.

To achieve these aims, the analysis utilises data from a unique database containing information on the knowledge-based interactions universities in the UK have with external organisations in the forms of collaborative research, contract research, and consultancy projects. Coupled with data on the largest private sector R&D performers in the UK, the database facilitates the matching of universities with leading R&D-intensive firms. Following a review of the substantive literature and the methodology underlying the empirical analysis, the paper first presents a social network analysis of the key interactions taking place between universities and these leading firms. Regression analysis is used to examine, along with other related factors, the extent to which these interactions are related to the capability of universities to raise research income from industry. The paper concludes with a discussion of the findings and their implications.

2. Theoretical and Empirical Context

Building upon the research questions presented above, this section initially provides a review of the paper's three key analytical concepts: network position; regional environment; and spatial distance between interacting parties. Each concept is considered with regard to the literature concerning university-industry interactions and their potential capability to explain rates of industrial research income generation by universities. The last part of the section provides further contextual details of university funding in the UK.

An understanding of the performance of organisations, such as firms and universities, has made significant advances in recent years through studies of the networks in which those organisations are embedded. In particular, it has been argued that the network space occupied by actors, defined by the nature of the relationships, interactions, and ties, may be equally, if not more important, than the geographic space within which actors are located and interact (Huggins and Thompson, 2014). The network space of actors—be it firms or universities—

can be usefully analysed by studying their position within a particular network structure through the use of social network analysis techniques. Social network analysis, as developed by sociologists, maintains a key behavioural assumption that any actor typically participates in a social system involving other actors who are significant reference points in decision-making (Knoke and Kuklinski, 1982). The nature of the relationships a given actor has with other system members may, therefore, affect the focal actor's actions. In recent years, social network analysis has been increasingly applied to examinations of the flow of knowledge across organisations and the knowledge networks these organisations utilise to facilitate innovation (Fleming et al, 2007; Schilling and Phelps 2007; Varga and Parag, 2009).

Some scholarly research suggests that the nature of networks is related to underlying patterns of knowledge flow (van Wijik et al., 2008). The position of an actor within networks is found to be correlated with relative power, which refers to a set of resources that the actor (could) mobilise through its existing set of relationships, in this case: knowledge (Mizruchi and Galaskiewicz, 1994). At the individual level, these resources are usually considered to take the form of social capital, consisting of the benefits accruing from interpersonal networks (Coleman, 1988; Putnam, 2000). At the organisational level, however, such resources are considered to be a form of network capital, consisting of the benefits accruing from inter-organisational networks (Kramera and Revilla Diez, 2012; Huggins and Thompson, 2014; 2015). However, there are few studies that have applied the concept in an empirical manner with regard to examining links between universities and industry.

The nature of the relationships a given actor has with other network members is expressed by various measures in social network analysis, with centrality measures ranking actors in terms of their relevance due to their position in a network. As will be detailed later in the section of data and methods, the analysis focuses on two aspects of the centrality a focal university has within university-industry networks: 'degree centrality' and 'eigenvector centrality'. 'Degree centrality' refers to the number of actors a focal actor is directly connected to, and measures the rate of the involvement of the actor in the network (Freeman, 1978). 'Eigenvector centrality' assumes that a focal actor's status is a function of the status of those other actors to which the focal actor is connected, meaning that, in a communication network, the amount of information available to an actor is positively related to the amount of information available to those other actors with which it is connected (Bonacich, 1987). In the context of the analysis, the former—degree centrality—denotes the number of large R&D-intensive firms a university in question interacts with, whereas the latter—eigenvector centrality—measures the number of other universities to which each of the large R&D-intensive firms is linked. Employing a composite of the two complementary measures of network centrality, as well as the degree centrality measure as a baseline comparator, the analysis assesses a university's power to mobilise resources within university-industry networks (Bonacich, 1987).

Aside from the network positions, scholars have long been interested in the effect of location on a range of economic activities, specifically focusing on the factors that make a region 'competitive' (Kitson et al., 2004). Competitive regions generally have a higher number of knowledge-based firms as well as higher levels of R&D expenditures, and are typically populated by research intensive universities engaged in world leading research (Howells et al., 2012; Huggins et al., 2012). In contrast, uncompetitive regions tend to be organisationally and institutionally 'thin', with a lack of innovation-driven public or private sector entities (Ponds et al., 2007; Huggins and Thompson, 2014).

Universities in economically core regions may possess locational advantages related to the generation of research income based on their spatial proximity to a greater pool of large R&D players, as well as the additional effects stemming from more competitive environments. Spatial proximity is potentially an important factor in accessing knowledge from a source and forging links to it (Ponds et al., 2007; 2010). This may be especially important with respect to more tacit forms of knowledge where a shared 'codebook', or language and customs (Cowan et al., 2000), and the existence of a trusting relationship between parties (Wood and Parr, 2005) facilitate the transfer and absorption of knowledge from one source to another. Extant research on university-industry interaction has produced some evidence suggesting that the co-location of research intensive firms and universities in the same region facilitates the interactions leading to innovative collaboration (Bouba-Olga et al., 2012; D'Este et al., 2013). Given the current evidence base, it can be suggested that universities located in core regions with greater pools of large R&D-intensive firms may have better opportunities to forge links with large R&D players than their counterparts in more peripheral regions. Furthermore, universities located in core regions may benefit from additional regional effects, such as the greater availability of insider information due to environments conducive to spillovers, more intensive competition among local universities in winning research grants and contracts, and a greater accumulation of experience at 'winner' institutions.

A further geographical factor to consider is the spatial reach of knowledge sourcing activity (D'Este and Iammarino, 2010; Laursen et al., 2011; Huggins et al., 2012; Bouba-Olga et al., 2012; D'Este et al., 2013). Despite the role of spatial proximity, not all knowledge is acquired from geographically proximate areas. As non-proximate actors become better able to transfer complex knowledge across spatial boundaries, the constraining effect of distance on knowledge flow may be gradually diminishing (Tracey and Clark, 2003). Rising levels of national and transnational academic-industry partnerships demonstrate that neither firms nor universities consider knowledge flows to be necessarily spatially constrained (Huggins et al., 2008). Given this trend, universities interacting with large R&D players at longer distances may improve their reputation and earn big-ticket research contracts, compared with universities for which interactions with industry are spatially limited.

Returning to the issue of research income generation, income from industry represents a relatively small but potentially significant source of research grants and contracts. According to the 2010–11 Higher Education – Business and Community Interaction Survey, the research grants and contracts awarded by UK industry, commerce, and public corporations account for 8.3% of the total university research income from domestic sources. Although the amount may appear relatively low, the proportion increases if the public match-funding provided for many industrial projects are included, with Behrens and Gray (2001) estimating that industrial funding directly influences approximately 20–25 per cent of research funding at universities. Therefore, industrial funding has become a significant driver of university performance in the knowledge-based economy.

3. Data and Methods

The data collected and methods of analysis employed by the study are outlined below.

Data

To construct a sample dataset for this investigation, information was collected from the following three key sources: (1) a unique database of almost 10,000 firms and organisations interacting with UK universities between 2005 and 2008 via knowledge transfer activities; (2) the 2008 R&D Scoreboard published jointly by the Department for Innovation, Universities & Skills (DIUS) and the Department for Business, Enterprise & Regulatory Reform (BERR), which consists of two R&D rankings: the Top 850 UK companies; and the Top 1400 Global companies by R&D investment (both of which provide financial data on these R&D firms); and (3) HEFCE's (Higher Education Funding Council for England) HE-BCI (Higher

Education – Business and Community Interaction) survey data on UK universities and HESA's (Higher Education Statistics Agency) data covering university financial accounts for various years.

The database of interactions consists of information gathered from an analysis of research and annual reports published by universities (Appendix Table 1 in the supplemental file provides an indication of the initial data capture process based on an example of ten identified interactions). For each university in the UK, a review of these reports was undertaken for the 3-year period of 2005–08. For this period, the research team recorded the details of any active interactions with industry in the forms of collaborative research, contract research, or consultancy projects. The definitions for each type of interaction are those commonly utilised by the higher education sector, namely: (1) collaborative research referring to academic research undertaken in partnership with other organisations; (2) contract research denoting a transaction involving the provision of university research to an external partner; and (3) consultancy meaning application of existing knowledge in the form of advice or work to an outside party.

For each case of interaction, the name of an organisation interacting with a university was noted along with any other information about characteristics of the interacting organisation, distinguishing private-sector firms from other types of organisations. Following this, the research team mined a number of business databases to obtain further details of each private-sector firm such as business size, location, and sector of activity. This principally consisted of the FAME database, supplemented by a range of other commercial business information databases. Importantly, the location of the interacting firm was confirmed or identified through this process. In a very small number of cases where firms operated across multiple sites, and where it was not possible to identify the location of a relevant establishment from university documentation, the address of the firm's UK headquarters was utilised.

A comparison of this dataset of firms with the top R&D spending firms listed in the 2008 R&D Scoreboard of DIUS/BERR identified a total of 504 large R&D-intensive firms, which were common across both sources, and a total of 1,460 interactions.[1] The 504 identified firms represent a cross-section of 32 industrial sectors headed by (1) pharmaceuticals and biotechnology (13.9% of firms); (2) electronic and electrical equipment (10.3%); and (3) technology hardware and equipment (9.9%) (Appendix Table 2 in the supplemental file presents the number of interactions by the location of universities at the regional level). A test of representativeness indicates that the sectoral distribution of interacting firms in the sample is significantly correlated with the distribution of all firms on the two R&D rankings by DIUS/BERR.

The dataset distinguishes the number of interactions each university has with large R&D firms and the connectivity of those interacting firms with other universities, making it possible to examine whether any effects arise from a university's network position. Clearly, the social network analysis stemming from this data could include other interactions such as firm-to-firm and university-to-university links. However, as seminal proponents of such analysis have made clear, the 'total network' of any community stretches within and beyond any imposed boundaries, and it is always advisable to identify a particular segment, or 'partial network', that is the focus of analytical attention (Mitchell, 1969; Scott, 2000). Only thorough the study of partial networks and particular relationships can content and meaning become clear (Mitchell, 1969), and in this case the focus of attention principally concerns the question of whether the networks formed by universities with large R&D-intensive firms impact on their performance in terms of generating research income from industry. Therefore, it makes methodological sense to concentrate on these particular university-industry links.

Nevertheless, the edge and boundary effects this imposes on the analysis is acknowledged, as this is the case with any social network analysis whereby fixed boundaries are required to be enforced to aid meaningful study (Hunter et al., 2008).

Analytical Framework

Based on the data outlined above, the analysis focuses on the network of interactions between UK universities and large R&D-intensive firms, using social network analysis software (Pajek 1.24) as a means of measuring the networks with social network indicators as well as graphically representing the interactions between universities and firms. This is followed by regression analysis in which a university's externally generated industrial research income from UK industry is regressed on a set of explanatory variables, including variables stemming from the social network analysis. The regressors employed are divided into the following three groups: a university's internal characteristics; its regional environment; and its interactions with large R&D-intensive firms. Descriptions of the dependent and independent variables are provided below.

Research grants and contracts – The dependent variable is the amount of income a university earns from research grants and contracts from UK industry. The period covered in the analysis includes three academic years, 2008–09, 2009–10, and 2010–11. The period of the dependent variable assumes that there is some lapse between a university's bids for research contracts and its undertaking of research services as recorded in its financial accounts. The aim is to analyse whether a university's interactions with large R&D-intensive firms in the 2005–08 period affects a university in attracting industrial research contracts, as recorded in the university's financial accounts for contracts awarded and undertaken in the period of 2008–11, with a view to dealing with an issue of endogeneity (which will be discussed in the section on model estimation). Since part of the industrial research income is expected to derive from multi-year contracts, some of the contracts that record research income in the period of 2008–11, and particularly in its earlier years, may have started in the period of 2005–08. To reduce the influence of potential overlapping, a weighted average for 2008–09, 2009–10, and 2010–11 is tested with larger weights given to more recent years (i.e., 1, 2, and 3 to 2008–09, 2009–10, and 2010–11 respectively), as well as a mean average of the three years. Taking averages over the period aims to reduce fluctuations in industrial research income over years, which are particularly large for universities generating relatively small amounts of research income.

University internal characteristics – It is clearly important to understand how the internal resources of universities impact upon the research income earned. Employment measures are often used as a control for size (e.g., Segarra-Blasco and Arauza-Carod, 2008; Tether and Tajar, 2008), and in this case the analysis utilises a university's full-time equivalent (FTE) employment in 2005–06. As is often utilised to capture the effects of increasing difficulties in control and coordination related to the growing size of an organisation, a quadratic term is added. Another variable that may play a role in explaining university research income generation is the portfolio of active patents in 2005–06, which is a proxy for a university's stock of knowledge that may prove to be of commercial value, and the capacity of a university's technology transfer/support office. Although it is a reasonably reliable measure of innovative output/activity (Rondé and Hussler, 2005; Tappeiner et al., 2008), it is recognised that patent activity is an imperfect measure since, for example, not all university research is codified into patents and may manifest itself through other forms of knowledge commercialisation (Fritsch and Slavtchev, 2007).

To specify a university's distinct character, and to an extent, its research or teaching orientation, universities are classified into three groups by first distinguishing 'old'—representing traditional research-focused universities (so called pre-1992 institutions)—and ‘new’—representing the former polytechnics and teaching colleges (so-called post-1992 institutions), and then dividing ‘old’ institutions into those affiliated with the Russell Group, which are generally regarded as the most prestigious group of UK universities, and those which are not. Accordingly, a set of two dummy variables are constructed, one for ‘old’ universities affiliated with the Russell Group and the other for ‘old’ universities not affiliated with Russell Group, using ‘new’ universities as the baseline. Furthermore, as there are significant variations across academic disciplines in the amount of research contracts and funding (Perkmann et al., 2011), with universities specialised in medical research/education showing a tendency to earn a higher amount of research income per staff member, a dummy for medical specialisation is also included.[2]

Regional environment – Proximity to an agglomeration of highly intensive R&D firms may have an impact on university income generation. To discern this clustering effect, a variable is constructed to measure the number of highly intensive R&D firms in the dataset that are located within a university’s own region, defined by UK NUTS-1 regions. In a similar vein, another variable is constructed representing the aggregated regional amount of R&D investment made by interacting firms in the sample, representing the size of R&D in each of the 12 UK NUTS-1 regions that is potentially available to local universities. Also, the analysis includes a set of 11 dummies, each of which corresponds to a respective UK NUTS-1 region, with a view to better discerning differentiated environments across the 12 UK NUTS-1 regions. As a baseline for the 11 regional dummies, South East England is chosen, since the region shows the highest concentration of highly intensive R&D firms in terms of both their number and their R&D investment.

University interactions with large R&D-intensive firms – Four variables representing a university’s interactions with large R&D-intensive firms are tested. The first is the number of interactions a university has with large R&D-intensive firms, which represents the university's 'degree centrality' within university-industry networks. The second is the sum of R&D expenditures made by the firms with which the university interacts.

The third is a university's network position measured in terms of a composite of degree centrality and eigenvector centrality. To create such a composite, Burt's (1992) measure of constraint is employed, alternatively called structural holes, which was originally designed to measure the degree to which an actor is constrained from accessing non-redundant sources of information. Within the measure of constraint construct, the extent to which actor i's network is directly or indirectly invested in a relationship with contact j is given by:

$$c_{ij} = \left(p_{ij} + \sum_{k \neq i,\, k \neq j} p_{ik} p_{kj} \right)^2$$

where $p_{ij} = \frac{a_{ij} + a_{ji}}{\sum_k (a_{ik} + a_{ki})}$ and a_{ij} is the value of the link from i to j. For the dataset of interactions between universities and large R&D firms, $a_{ij} = a$ (constant) for any i and j. The sum of c_{ij}, $C_i = \sum_j c_{ij}$, gives the value of Burt's constraint measure for actor i. The variable is greater than zero, and is equal to one when an actor i is isolated or linked to only one actor.

When applied to the dataset of university-industry interactions, Burt's constraint measure is seen as a composite of two aspects of centrality—'degree centrality' and 'eigenvector centrality'—and thus distinct from the number of interactions a university has with large R&D-intensive firms, as represented by 'degree centrality' alone. Within Burt's constraint measure, $c_{ij} = \left(p_{ij} + \sum_{k \neq i,\, k \neq j} p_{ik} p_{kj} \right)^2$ consists of two components p_{ij} and $\sum_{k \neq i,\, k \neq j} p_{ik} p_{kj}$.

Since the dataset of university-firm interactions does not include any university-to-university interactions or firm-to-firm interactions, and the first component p_{ij} concerns the university in question (university i) and firms it interacts with alone, not including any other universities, its value declines as the number of firms university i interacts with increases. This component can be seen to represent degree centrality, which measures the number of actors a focal actor is directly connected to.

The second component $\sum_{k \neq i, k \neq j} p_{ik} p_{kj}$ is determined by the connectivity of firms the university in question interacts with. For a given university i, nodes k and j represent the firms it interacts with and any other universities those firms interact with, respectively. This component takes a value of zero when these firms do not interact with any universities other than the university in question (university i). For each of the firms (expressed as node k in the formula), if it interacts with any other university, the component takes a positive value. The value of this component declines as those firms interact with a greater number of other universities, and asymptotically approaches the value of zero (which is taken when the firms are linked exclusively with the focal university, i.e., the focal university monopolises access to the intellectual assets of the firms). Thus, this component can be seen as a proxy for eigenvector centrality, a measure of how well-connected those firms with which the focal university interacts are to other universities.

Accordingly, Burt's constraint measure can be seen as a composite of two types of centrality: the centrality in terms of the number of large R&D-intensive firms the focal university interacts with, and the centrality in terms of the status of those firms measured by the number of other universities they interact with (see Appendix Figure 2 in the supplemental file for an illustration of this). A lower value for Burt's constraint measure implies a higher degree of this composite centrality, and therefore a negative association is expected for the relationship between the research income universities gain from industry and their composite centrality indicator.

Finally, the average physical distance between the location of a university and each of the firms it interacts with outside its own region (expressed in thousand miles) is included as the fourth variable. Whilst the variables for regional environment aim to capture the potential clustering effect of highly intensive R&D firms within a university's own region, this variable is seen as a proxy for a university's geographical reach with large R&D-intensive firms. The variable is constructed using information on the postcodes of the university's main campus and the firm's branch/office where an interaction is recorded (descriptive statistics for the dependent and independent variables that are reported in the ensuing section of empirical results are provided in Appendix Table 3 of the supplemental file).

Model estimation and further considerations

The model for the regression analysis is expressed as:

$$INCOME_i = \mathbf{UNI}_i \boldsymbol{\alpha} + \mathbf{REG}_i \boldsymbol{\beta} + \mathbf{INT}_i \boldsymbol{\gamma} + INCOME_{-1,i} \lambda + u_i$$

where $INCOME_i$ is the average research income earned by university i from industry in the UK in academic years 2008–09, 2009–10, and 2010–11. As noted earlier, a mean average was undertaken, as well as a weighted average, of the three years. $\mathbf{UNI}_i$, $\mathbf{REG}_i$, and $\mathbf{INT}_i$ are vectors for the variables representing the university's internal characteristics, regional environment, and interactions with firms, respectively; $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and $\boldsymbol{\gamma}$ are vectors of the coefficients for each, and u_i is the error term. The values of the vectors $\mathbf{UNI}_i$, $\mathbf{REG}_i$, and $\mathbf{INT}_i$ are taken for the period 2005–06 or 2005–08, ensuring their precedence to undertaking research services for which income from industry is reported in the financial accounts. The variables on the right hand side of the equation indicate the conditions at the time when a university considers making bids for particular research contracts, while the variable on the left hand represents their aggregated incomes reported in their financial accounts. The activities on both sides of the equation—preparation of a bid which may begin by obtaining insider information, and the undertaking of research services for the contract awarded—often take place with a lag. With the model's structure, the aim is to shed light upon the knowledge and network assets of the industrial relationships a university continuously draws upon.

Furthermore, $INCOME_{-1,i}$ is a lagged measure of industrial research income earned by university i, controlling for the unobserved heterogeneities of universities. Part of the research contracts generating research income in academic years 2008–09, 2009–10, and 2010–11 are expected to derive from multi-year contracts that start earlier. To avoid an overlapping between the dependent variable and the lagged dependent variable in their contracts from which income is reported, an average of 2003–04 and 2004–05 for the lagged dependent variable is taken. Also, the analysis goes further back, testing an average for 1999–2000 and 2000–01. Finally, λ is a coefficient for $INCOME_{-1,i}$.

Potential sources of endogeneity are mitigated in the estimation, with one such potential source being unobserved heterogeneities across universities. Such unobserved heterogeneities may affect $INCOME_i$ and at the same time be correlated with explanatory variables, particularly those representing a university's interactions with firms as well as its regional environment, producing biased estimates. The lagged dependent variable in the model $INCOME_{-1,i}$ is a proxy variable used to account for such unobserved factors, reducing the risk of this particular form of endogeneity (Wooldridge, 2010, pp. 70–71). Another unobserved factor potentially contained in the error term is the price for university research services, which might be correlated with both $INCOME_i$ and the university's interactions with firms. However, the costs of researchers, a key production factor of university research services, are uniform across UK universities for given levels of researcher time. This makes the price for research services relating to particular specifications largely constant across universities, eliminating the possibility of it correlating with either $INCOME_i$ or a university's interactions with firms at the same time.

Finally, another potential source of endogeneity is simultaneity between the dependent variable $INCOME_i$ and a university's interactions with firms. Meaning that, while $INCOME_i$ is determined in the manner expressed by the above equation, the university's interactions with firms is determined by $INCOME_i$ and other factors, some of which are not present in the model. Again, this relationship is unlikely since it assumes that a university already knows future $INCOME_i$ in 2008–11 before it enters collaborations with firms, which are either still active or completed during the period of 2005–08. Although universities often set targets for future research income, they do not necessarily achieve these goals due to uncertainties involved in the competitive bidding process for research contracts. For this reason, it is safe to say that simultaneity is not a serious problem.

Revenues from research grants and contracts show a highly skewed distribution with a long right tail.[3] In view of this, a generalised linear model with the gamma distribution is adopted. The gamma distribution is useful for modelling terms that are nonnegative and skewed toward larger positive values. Maximum likelihood estimates for coefficients of model variables are obtained by the Newton-Raphson algorithm with Fisher scoring (Gill, 2001).

4. Results

The overall university-industry network consists of those universities identified as collaborating with any of the large R&D firms during the period 2005–08 (see. Appendix Figure 2 in the supplemental file for a diagrammatic representation). If the most interlinked element of the network consisting of 16 universities is considered (Figure 1), it represents predominantly older and more prestigious institutions in the UK, covering 40.1% of all links. Measured by the composite indicator of degree centrality and eigenvector centrality discussed earlier, the University of Cambridge appears as the main hub, followed by Imperial College London and University College London.

Figure 1 About Here

The results of the regression analysis of the research income universities received from industry are presented in Table 1. Models 1 to 8 differ in terms of the variables representing a university's interactions with large R&D-intensive firms, which include the number of large R&D-intensives firms a university interacts with (i.e., degree centrality), the sum of R&D expenditures made by the large R&D-intensives firms, the university's composite indicator of degree centrality and eigenvector centrality, and the average crow-fly distance between the university and the large R&D-intensives firms it interacts with outside the university's region. While each of the four variables is entered in turn into Models 1 to 4, Models 5 to 8 include either the degree centrality indicator or the composite centrality indicator, together with the two other interaction variables. Furthermore, two variables controlling for regional environment—aggregated regional number of large R&D-intensive firms interacting with universities and the aggregated regional amount of their R&D expenditures—are entered in Models 1 to 6, whereas a set of regional dummies are entered in Models 7 and 8. As for the variables controlling for a university's internal characteristics, all six variables are entered in Models 1 to 8. Table 1 shows the results for the mean average of industrial research income earned in 2008–09, 2009–10, and 2010–11 as the dependent variable. For the lagged dependent variable controlling for the unobserved heterogeneities of universities, the mean average of industrial research income earned in 2003–04 and 2004–05 is used.

Of the six variables controlling for a university's internal characteristics, FTE employment, its quadratic term, a dummy for old universities not affiliated with Russell Group, and a dummy for medical specialisation enter the model at the 1% significance level through Models 1 to 8. While the coefficient for FTE employment takes a positive sign, its quadratic term enters the models with a negative sign, showing a decline in the marginal effect of the size of FTE employment upon research income. This may reflect growing difficulties in control and coordination within a university's organisation as it increases in size. As for a university's focus and esteem, a set of two dummies is employed to divide the sample into three mutually exclusive groups: old universities affiliated with the Russell Group, old universities not affiliated with the Russell Group, with new universities as a baseline. Whilst there is strong evidence that old universities not affiliated with the Russell Group earn higher research income than new universities, old universities affiliated with the Russell Group do not show any strong signs of earning higher research income than new universities when other variables, including FTE employment and the portfolio of active patents, are held constant.[4] The dummy for specialisation in medical research and education enters all models significantly with a positive sign, indicating greater research income from industry. By contrast, a university's portfolio of active patents shows no strong indication of a relationship with research income earned from industry.

As for the variables controlling for a university's regional environment, there are no strong indications that they impact upon a university's research income generation from industry. In Models 1 to 6, neither of the two variables—the aggregated regional number of R&D-intensive firms interacting with universities and the aggregated regional amount of their R&D expenditures—is found significant. Also, each of them fails to enter Models 1 to 6 significantly when only one of them is entered (not reported in the table). A model that includes the six variables relating to a university's internal characteristics without any variables representing its interactions with large R&D-intensive firms is also tested, finding that neither of the two variables representing regional environment enters the model significantly.

Furthermore, in Models 7 and 8, a stronger test by adopting a set of 11 dummies is undertaken, each of which corresponds to a respective NUTS-1 region (other than South East England, which represents the baseline). With a greater degree of freedom lost, Models 7 and 8 by definition have greater explanatory power as indicated by a smaller deviance statistic. The result shows that none of the regional dummies enters the models significantly. On the whole, there is no strong evidence that the clustering of highly R&D-intensive firms within a university's own region (Models 1 to 6), or any unobserved heterogeneities of regional environment (Models 7 and 8), impacts upon a university's ability to earn research income from industry.

Four variables representing a university's interactions with large R&D-intensive firms are tested—the number of interactions with large R&D-intensive firms (i.e., degree centrality), the sum of R&D expenditures made by the large R&D-intensive firms, the composite centrality measure consisting of degree centrality and eigenvector centrality, and the average crow-fly distance between the university and the large R&D-intensive firms it interacts with outside its own region. Of these, the number of interactions with large R&D-intensive firms (which is the university's degree centrality measure) and the sum of R&D expenditures made by the large R&D-intensive firms fail to significantly enter Models 1 and 2 respectively. By contrast, the composite of degree centrality and eigenvector centrality enters Model 3 at the 1 % level with an expected negative sign, meaning that universities better situated within the university-industry network tend to generate a greater amount of research income from industry. When this is compared with the result of Model 1, it is clear that while the degree centrality measure alone shows no strong relationship with a university's industrial research income (Model 1), the composite of the two types of centrality—degree centrality and eigenvector centrality—is significantly related (Model 3).

Model 4 examines the spatial reach of a university's interactions with large R&D-intensive firms outside its own region. Excluding firms within a university's own region from consideration, this variable aims to evaluate whether spatial reach of interactions has any bearing upon its ability to earn research income from industry. The average crow-fly distance enters the model at the 1% significance level with a positive sign, meaning that the greater the average distance a university goes to forge a link with large R&D players, the greater research income it earns from industry. The sum of the crow-fly distances between a university and the firms it interacts with outside its region is also tested, which fails to show any significant relationship with industrial funding. When the degree centrality measure is entered together with the average crow-fly distance in Models 5 and 7, the average crow-fly distance remains significant at the 5% and 10% levels respectively. In contrast, when the composite centrality measure is entered together with the average crow-fly distance in Models 6 and 8, only the composite centrality measure enters the models significantly (at the 5% level) with an expected negative sign. This means that when a university's network position measured by the composite of degree centrality and eigenvector centrality is controlled for, the university's spatial reach to large R&D-intensive firms shows no clear relationship with the amount of research income it earns from industry.

In order to account for potential variations across industry sectors in terms of the size of the research contracts firms make with a university, two variables were constructed, representing the proportion of all interactions a university is engaged in with large R&D-intensive firms operating in primary and tertiary (i.e., service) sectors, respectively. Again, neither of the variables enters the models significantly, showing that the industrial sector of firms interacting with a university has no significant bearing upon industrial research income generation.

Furthermore, Models 1 to 8 were tested with a weighted average of industrial research income earned in 2008–09, 2009–10, and 2010–11 (with weights of 1, 2, and 3 given to the three academic years respectively) as a dependent variable, obtaining the same key findings as discussed above. As a lagged dependent variable, an average of industrial research income for 1999–2000 and 2000–01, rather than an average for 2003–04 and 2004–05, were also tested with the same set of models. Again the key findings remain unchanged.

Table 1 About Here

5. Discussion and Conclusion

The preceding results serve to highlight a number of key trends in terms of the association between the capability of universities to raise research income from industry and the network structure through which they interact with large R&D-intensive firms, as well as the nature of spatial environment in which these interactions takes place. Whilst it is clear that the specific characteristics of universities, particularly in terms of their size and type, such as research-intensiveness, are of significant importance, it is also found that a university's network position measured by a composite of degree centrality and eigenvector centrality is significantly associated with the amount of income earned from research grants and contracts with industry.

When other factors are controlled for, universities with a greater number of links to firms that are in turn connected with a greater number of other universities are found to earn a greater amount of income from industrial research grants and contracts. It is also shown that a university's connectivity with large R&D-intensive firms measured by degree centrality alone shows no clear relationship with its performance in generating industrial research income. Clearly, therefore, the wider connectivity of the large R&D-intensive firms with which a university forges links is strongly related to research income generation, suggesting the importance of the reputation and status a university may enjoy, as well as the knowledge it acquires, through the networks it develops with industrial partners that are well connected to other universities. Therefore, it can be concluded that these connections do indeed act as network capital that is associated with university performance (Lavie, 2006; Gulati, 2007; Huggins and Thompson, 2014).

In contrast, there is no strong evidence to suggest an association between industrial funding and the other industrial interaction characteristics analysed. Neither the number of interactions a university has with large R&D players alone nor the R&D expenditures made by those firms shows any clear association with industrial research income. Furthermore, once the network position of a university measured by the composite of degree centrality and eigenvector centrality is controlled for, the spatial reach of interactions a university has with large R&D firms shows no clear relationship with industrial research income. Also, the regional environment, in terms of the clustering of large R&D-intensive firms, is not associated with industrial research income.

The evidence suggests that, when the internal characteristics of universities and their interactions with industry are controlled for, there is generally a level playing field across regions even when any other unobserved regional characteristics are considered. Whilst spatial factors may play a role in determining the formation of university-industry links in the first instance, as suggested by other studies (Huggins et al., 2012; D'Este et al., 2013), they do not appear to influence the subsequent organisational performance of universities, as measured by their capability to earn industrial research income. Instead, it is the position universities hold within the networks formed with industry, along with their own particular internal characteristics, that shows the most significant association with performance differentials. As Boschma and Ter Wal (2007) argue, success is not always a matter of being in the right place, but more about being a part of the right network. From a theoretical perspective, the findings indicate the importance of understanding and including the structural elements of networks within relational geographic analysis that is often focused on the local-global dimensions of such networks (Drejer and Lund Vinding, 2007).

From the perspective of university administration and policymaking, it is probable that universities which are weakly positioned within wider networks of university-industry interactions lack the requisite number of knowledge brokers and gatekeepers to plan, forge, and manage links with large R&D-intensive firms (Harada, 2003). Such universities may fail to build positions within university-industry networks that allow them to generate research income from industry. This may call for policies aimed at assisting universities to connect with industry, especially the large R&D-intensive firms that are the focus of this study (Goddard et al., 2012; Hughes and Kitson, 2012). In a world of heightened competition across the university sector, it is likely that institutions will increasingly need to implement the forms of knowledge and network management practices that have become commonplace in the industrial sector.

As for the potential limitations of the study, it is based on the known publicly available interactions between firms and universities. Of course, there may be a number of more private or informal relationships between universities and large R&D-intensive firms that would influence the results presented in this study. Also, universities interact with many more firms than just large R&D-intensive firms, and including these in future analysis may shed further light upon the nature of university-industry relationships and their impact.

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[1] Some of large R&D-intensive firms record interactions with universities at more than one establishment. In our social network analysis, those interactions are aggregated at the firm level.

[2] Four universities are specialised in medical research and education, including Institute of Cancer Research, London School of Hygiene & Tropical Medicine, School of Pharmacy, and St George's Hospital Medical School.

[3] The values of skewness and kurtosis for the mean average of industrial research income earned in three academic years, 2008–09, 2009–10, and 2010–11 are 2.89 and 11.99 respectively. For the weighted average, the statistics are 2.82 and 11.32.

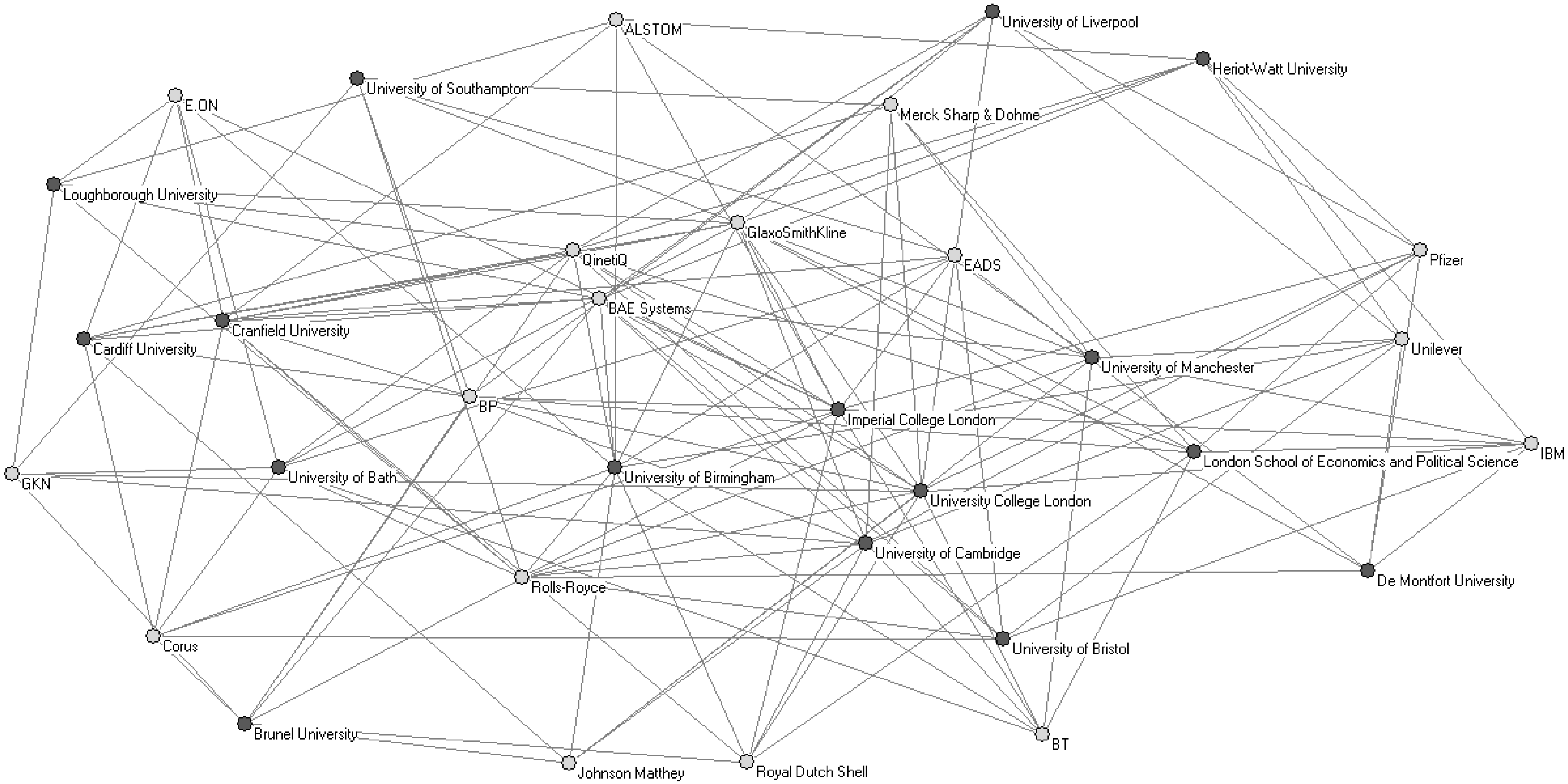
[4] The mean average of active patents per FTE employee is 0.050, 0.030, and 0.005 for old universities affiliated with the Russell Group, old universities not affiliated with the Russell Group, and new universities respectively.

Table 1: Results of generalised linear models: research income from industry

Dependent variable: Research grants and contracts from industry (mean average of 2008–09, 2009–10, and 2010–11)								
Model	1	2	3	4	5	6	7	8
Observations	156	156	156	156	156	156	156	156
FTE employment	1.390*** (0.188)	1.411*** (0.192)	1.100*** (0.216)	1.217*** (0.199)	1.200*** (0.208)	1.055*** (0.217)	1.416*** (0.238)	1.251*** (0.253)
(FTE employment)^2	–0.108*** (0.020)	–0.109*** (0.020)	–0.082*** (0.023)	–0.090*** (0.021)	–0.090*** (0.022)	–0.077*** (0.023)	–0.108*** (0.024)	–0.093*** (0.026)
Active patents	0.211 (1.274)	–0.023 (1.315)	0.328 (1.211)	–0.505 (1.090)	–0.639 (1.247)	–0.060 (1.200)	–1.140 (1.316)	–0.330 (1.311)
'Old' universities affiliated with Russell Group	0.188 (0.565)	0.180 (0.578)	0.250 (0.581)	0.307 (0.557)	0.335 (0.593)	0.299 (0.583)	0.137 (0.640)	0.112 (0.644)
'Old' universities not affiliated with Russell Group	1.199*** (0.245)	1.225*** (0.250)	1.230*** (0.248)	1.241*** (0.242)	1.235*** (0.253)	1.238*** (0.247)	1.220*** (0.273)	1.225*** (0.274)
Medical specialisation	1.787*** (0.677)	1.806*** (0.694)	1.864*** (0.688)	1.794*** (0.681)	1.906*** (0.707)	1.877*** (0.696)	1.985*** (0.727)	2.006*** (0.742)
Aggregated regional number of firms interacting with universities	–0.006 (0.010)	–0.007 (0.010)	–0.010 (0.011)	–0.009 (0.010)	–0.010 (0.011)	–0.011 (0.011)		
Aggregated regional amount of R&D expenditures of firms interacting	0.004 (0.019)	0.007 (0.020)	0.012 (0.020)	0.017 (0.020)	0.018 (0.021)	0.016 (0.021)		
East Midlands							–0.289 (0.561)	0.084 (0.597)
East of England							–0.056 (0.586)	0.047 (0.598)
London							–0.065 (0.419)	–0.133 (0.433)
North East							–0.371 (0.714)	–0.417 (0.729)
Northern Ireland							–0.307 (1.100)	0.045 (1.122)
North West							–0.128 (0.530)	–0.100 (0.536)
Scotland							0.392 (0.567)	0.787 (0.620)
South West							–0.548 (0.517)	–0.500 (0.518)
Wales							0.640 (0.552)	0.599 (0.551)
West Midlands							0.369 (0.528)	0.464 (0.537)
Yorkshire and the Humber							–0.369 (0.536)	–0.328 (0.547)
Degree centrality (number of interactions with firms)	0.016 (0.012)				0.005 (0.022)		0.010 (0.024)	
R&D expenditures of firms interacting		0.022 (0.016)			0.012 (0.030)	–0.002 (0.018)	0.008 (0.032)	–0.007 (0.021)
Composite of degree centrality and eigenvector centrality (Burt's measure of constraint)			–1.044*** (0.317)			–0.835** (0.424)		–1.169** (0.514)
Average crow-fly distance with firms outside the university's region				4.050*** (1.506)	3.835** (1.540)	2.173 (1.639)	3.306* (1.863)	0.241 (2.295)
Research grants and contracts from industry (mean average of 2003–04 and 2004–05)	0.108 (0.070)	0.132** (0.065)	0.136** (0.064)	0.167*** (0.063)	0.136* (0.077)	0.148** (0.068)	0.134 (0.088)	0.150* (0.081)
Constant	3.708*** (0.343)	3.731*** (0.349)	4.772*** (0.505)	3.494*** (0.343)	3.535*** (0.355)	4.436*** (0.597)	3.046*** (0.452)	4.169*** (0.679)
Deviance	278.1	278.0	262.5	267.9	265.7	258.9	254.1	244.7
Deviance/df	1.918	1.917	1.810	1.847	1.858	1.811	1.896	1.827
AIC	14.343	14.342	14.242	14.277	14.289	14.245	14.330	14.270

Notes: The gamma link function is used. * (**) (***) denote significance at the 10 (5) (1) percent levels respectively. Standard errors are in parentheses ( ). Units of variables are shown in Appendix Table 3 with the exception of million £ for research income from industry (mean average of 2003–04 and 2004–05).

Figure 1: The most interlinked element of the network



Note: Kamada-Kawai's *free* algorithm is used.

Appendix Table 1: Indicative details of the initial data capture process

Name of University	Name of Interacting Firm	Type of Interaction	Evidence/Extract	Full Publication Details	URL
Cranfield University	Nestlé	Consultancy	"Nestlé, one of the world's largest food companies, turned to Cranfield for help as it moved into the production of flavoured waters. When creating any new product there are certain factors that manufacturers need to consider – the likely shelf-life, for example, and the sorts of problems likely to arise which may spoil the quality of the product and affect human health. And it is answers to these questions that Cranfield helped Nestlé predict. Cranfield scientists worked on determining the contamination-free shelf-life of the company's new flavoured water products, especially with regard to heat-resistant spoilage. They developed a novel 'challenge test' which could be used by Nestlé to make spoilage predictions when creating new formulations of drinks."	Cranfield University Annual Report "World Changing" 2008	http://www.cranfield.ac.uk/annualreport/annualreport_2008.pdf
Institute of Cancer Research	Novartis	Collaborative research	"Commercial partners collaborating with The Institute and supporting clinical trials at The Royal Marsden during 2007 included Novartis, Pfizer, GlaxoSmithKline, Sareum, Bayer, Cougar, Elekta and Synarc."	Institute of Cancer Research Annual Research Report 2007	http://www.icr.ac.uk/about_us/annual_research_report/9724.pdf
Kingston University	Pilkington	Contract research	"The European Commission and glass manufacturer NSG- Pilkington Group are funding a second study into how window panes respond to flames. When cracks occur during a house fire, backdraft can cause fire to develop rapidly, putting firefighters' lives at risk. During the two-year programme, University specialists will help to design glass that is more heat resistant."	Kingston University London Annual Report 2006-2007	http://www.kingston.ac.uk/aboutkingstonuniversity/factsandfigures/annualreports/documents/annual_report_0607.PDF
London South Bank University	Rolls Royce	Contract research	"The research carried out by Professor Ezugwu and his team has enabled Rolls Royce to develop a capability that could lead to a 30-50 per cent reduction in manufacturing times and a five-fold improvement in consumable costs."	Services for business, Knowledge+innovation+ Success, London South Bank University (2005)	http://www.lsbu.ac.uk/rbdo/docs/S4BBrochure05(2).pdf
North East Wales Institute of	Ciba Specialty Chemicals	Collaborative research	"Polymeric additives to control the spraying and deposition of fluids.	Materials Science Research Centre, Annual Research Report 06/07	http://www.newi.ac.uk/en/Academicschools/ScienceTechnology/MaterialsScienceRe

Higher Education			EPSRC Cooperative Award in conjunction with Ciba Specialty Chemicals”	(2006/7)	searchCentre/TheFile,8861,en.pdf
Queen Mary, University of London	Airbus	Collaborative research	“Queen Mary already has established several strong collaborations with Chinese HEIs together with UK companies such as Airbus and QinetiQ in the fields of aerospace, clean energy, nano-technology, biometrics and security, wireless telecommunication and biotechnology.”	Queen Mary, University of London Annual Review 2006	http://www.qmul.ac.uk/about/collegeinfo/docs/annualreview_2006.pdf
University of Edinburgh	BP	Contract research	“Eight organisations have already joined the consortium, contributing over £400,000 towards studentships and research projects. These organisations include significant players in the energy sector, such as: ARUP; BP; E-ON; Schlumberger; Scottish and Southern Energy; Scottish Power; and Shell, as well as Scotland’s regional development agency, Scottish Enterprise.”	Infinite, Annual Review of Research and Commercialisation at the University of Edinburgh, Issue 6 (2007)	http://www.research-innovation.ed.ac.uk/information/Infinite2007.pdf
University of Greenwich	Pfizer	Collaborative research	“Current collaborations involve the London School of Pharmacy, Imperial College London and various industrial companies, including Pfizer and new spin-off companies such as Toximet Ltd and Ilika Technologies Ltd.”	School of Science, Guide to Research and Enterprise, University of Greenwich (2008)	http://www.gre.ac.uk/__data/assets/pdf_file/0020/173522/Research-2008.pdf
University of Leeds	Network Rail	Consultancy	“Dr Andrew Smith is working with the Office for Rail Regulation (ORR) and Britain’s rail infrastructure provider, Network Rail, to benchmark the efficiency performance of Network Rail against the organisation’s counterparts in twelve European countries.”	Impact. Research and Innovation at the University of Leeds, Issue 3, Summer 2008	http://www.leeds.ac.uk/impact/impact08.pdf
University of Sheffield	Qinetiq	Collaborative research	“The team are working closely with the Home Office and the UK Border Agency to ensure the device meets their needs. QinetiQ, a leading international defence and security technology company, is working in partnership with our researchers to address the human factors and understand how users will interact with the robots.”	U-Inspire - Knowledge Transfer Newsletter, Issue 4, Summer 2008, University of Sheffield	http://www.shef.ac.uk/content/1/c6/08/61/33/uinspire4.pdf

Appendix Table 2: Number of identified interactions between universities and large R&D-intensive firms

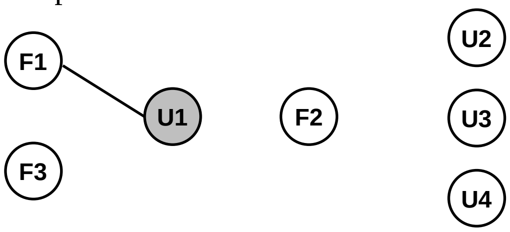
Region (Number of universities)	Same Region Interactions	Different Regions Interactions
East Midlands (9)	15	116
East of England (9)	37	121
London (39)	98	215
North East (5)	24	38
Northern Ireland (2)	3	19
North West (13)	41	80
Scotland (15)	37	95
South East (17)	65	91
South West (13)	24	92
Wales (11)	8	44
West Midlands (12)	21	88
Yorkshire and the Humber (11)	18	70

Appendix Table 3: Data descriptives for regression analysis (*N*=156)

	Mean	S.D.
Dependent variable		
Research grants and contracts from industry (mean average of 2008–09, 2009–10, and 2010–11, thousand £)	1833.23	3605.86
Research grants and contracts from industry (weighted average of 2008–09, 2009–10, and 2010–11, thousand £)	1807.83	3510.07
University internal characteristics		
FTI employment (thousand)	1.91	1.78
$(\text{FTI employment})^2$ (million)	6.80	12.95
Active patents (thousand)	0.06	0.16
'Old' universities affiliated with Russell Group (dummy)	0.13	0.34
'Old' universities not affiliated with Russell Group (dummy)	0.33	0.47
Medical specialisation (dummy)	0.03	0.16
Regional environment		
Aggregated regional number of firms interacting with universities	82.73	44.37
Aggregated regional amount of R&D investment made by interacting firms (billion £)	34.24	23.22
East Midlands (dummy)	0.06	0.23
East of England (dummy)	0.06	0.23
North East (dummy)	0.03	0.18
Northern Ireland (dummy)	0.02	0.11
North West (dummy)	0.08	0.28
Scotland (dummy)	0.10	0.30
South East (dummy)	0.11	0.31
South West (dummy)	0.08	0.28
Wales (dummy)	0.07	0.26
West Midlands (dummy)	0.08	0.27
Yorkshire and the Humber (dummy)	0.07	0.26
University interactions with large R&D-intensive firms		
Number of interactions with firms	9.36	16.15
R&D expenditures of firms interacting (billion £)	5.23	9.94
Structural Holes	0.55	0.43
Average of crow-fly distances with firms outside the university's region (thousand miles)	0.08	0.09
Lagged dependent variable		
Research grants and contracts from industry (mean average of 2003–04 and 2004–05, thousand £)	1575.56	3359.39
Research grants and contracts from industry (mean average of 1999–2000 and 2000–01, thousand £)	1588.98	3009.49

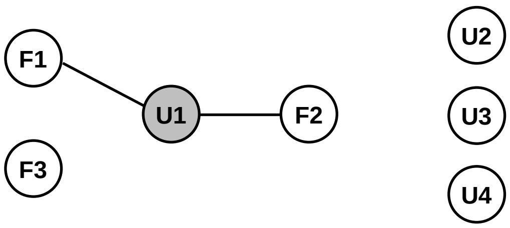
Appendix Figure 1: Illustrative example of variations in the value of the composite of degree centrality and eigenvector centrality (Burt's measure of constraint) – *see note overleaf*

Example 1



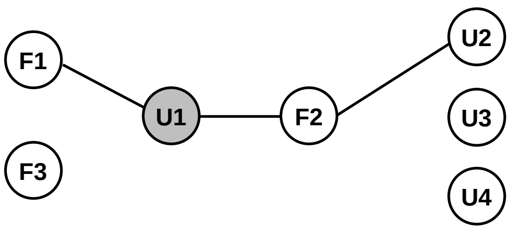
$$(1+0)^2 = 1$$

Example 2



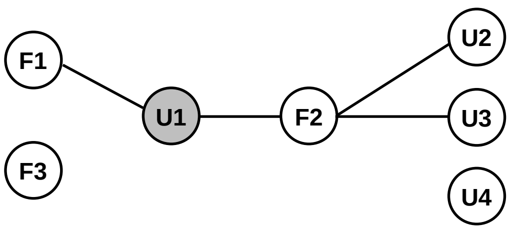
$$(0.5+0)^2 + (0.5+0)^2 = 0.5$$

Example 3



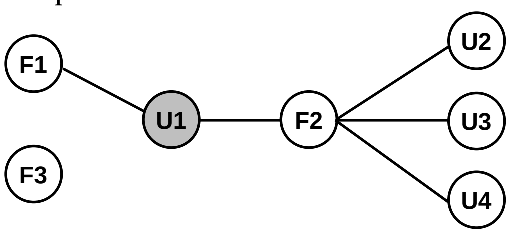
$$(0.5+0)^2 + (0.5+0)^2 + (0+0.5\times 0.5)^2 = 0.63$$

Example 4



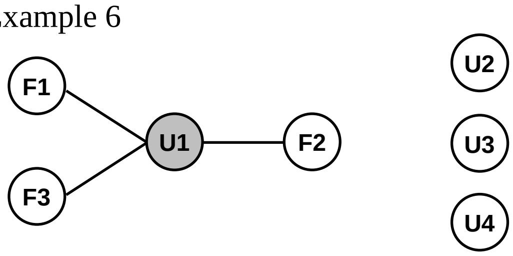
$$(0.5+0)^2 + (0.5+0)^2 + (0+0.5\times 0.33)^2$$
$$+ (0+0.5\times 0.33)^2 = 0.56$$

Example 5



$$(0.5+0)^2 + (0.5+0)^2 + (0+0.5\times 0.25)^2$$
$$+ (0+0.5\times 0.25)^2 + (0+0.5\times 0.25)^2 = 0.55$$

Example 6



$$(0.33+0)^2 + (0.33+0)^2 + (0.33+0)^2 = 0.33$$

Note to Appendix Figure 1:

To illustrate this composite measure of centrality, Appendix Figure 1 provides a set of examples showing variations in centrality based on the values of Burt's constraint measure. By definition, the value of centrality is determined by the number of firms a focal university interacts with directly and the number of other universities those firms interact with directly. In each example, four universities—U1, U2, U3, and U4—and three firms—F1, F2, and F3—are considered, although not all of them are connected. The value of centrality concerns U1. In example 1, U1 interacts with one firm, F1, whilst in examples 2 to 5 the university interacts with two firms and in example 6 with three firms. As can be seen, the value of centrality varies with the number of interactions a university has with firms. Its value declines as the university interacts with a greater number of firms, as is evident by comparing examples 1, 2, and 6. Furthermore, the value also varies with the connectivity of firms the university interacts with. By comparing examples 2 to 5, it is evident that in each case U1 has two interactions with firms; however, the centrality value is different due to one firm, F2, possessing links to additional universities (U2, U3 and U4).