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Title: It's not only what you know: Simulating research networks in the UK university sector

Journal: Emergence: Complexity and Organization

ISSN: 1521-3250 **Year:** 2014 **Pages:** 1 - 28

Volume: 16 **Issue:** 2

Abstract: Networks are a common structural form through which institutions, including universities, compete. However, institutional theories such as the Resource Advantage Theory of Competition (RATC) which offers explanations of how institutions continually refresh resources to offset the changing competitive resource configurations, fail to consider this context. Our research objectives are to extend understandings of the RATC in a network context, and to contribute to the emerging body of work on netwo ...

It's not only what you know…. simulating research networks in the UK university sector

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Jarratt D. and Thompson J. (2012) "Virtual business models to address real world strategic challenges". *Emergence: Complexity and Organisation* 14 (2): 1-24.

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It's not only what you know…. simulating research networks in the UK university sector

Abstract:

Our research sought to contribute to the body of knowledge on structuration and network properties through examining network structure in market systems requiring differing levels of resource complexity. Simulations were used to model the dynamics of university science departments as they link with others in competing for national grants. Research Assessment Exercise (UK) grant and other research data were used to interpret the structural forms observed. Simulations revealed the network structures that form as a consequence of the increasing complexity of grant requirements and imperatives to improve RAE rankings. Our findings suggest that for those with limited resources, resource specialisation can be an effective strategy to link with others and build market position. This strategy has value for others competing in an inimitable market system, and therefore facilitates network formation. In this context it is the comparative advantage of the network and its structural properties that can create improved market position.

1. Introduction

Modern institutions operate within networks to maximise their access to resources that are critical to achieve comparative advantage. In the case of universities, networks are formed through government, individual, and department strategic initiatives as a consequence of priorities to acquire National Competitive Grants (NCGs). But, "knowledge development and its significance is a ... complex affair involving networks of human and non-human acting in local contexts of contest and controversy and within shifting alliances and resistances" (Alferoff and Knights, 2009: 127).

As institutions adopt network forms, the structuring of those networks becomes central to resource exchange, innovation and performance. Network structures evolve as a consequence of institutions exiting, new institutions attaching at existing nodes and/or new linkages being forged between current network members as new objectives emerge. Prior and recent studies have considered how network structure is influenced by patterns of entry, prominence of network position and embeddedness of network links. Work by Barbarassi et al. (1999), and Powell et al. (2005), Rosenkopf and Padula (2008: 671) commented that "graph theorists have ….. emphasized how firms develop ties with even more distant, unfamiliar firms —those that have not yet entered the network". Prominence of network position signals attractiveness to non-attached members who are also prominent in other networks (Gulati and Gargiulo, 1999). However, Rosenkopf and Padula (2008: 670) argue that such centrally located firms "will also have little incentive to accept peripheral players". Others have linked network evolution to dimensions of both embeddedness (developing trust, knowledge exchange and repeated transactions) and prominence (demonstrating desirability, high levels of attachment and successful network history). Particularly, Peng and Bourke (2009: 382) noted that: "different types of connectedness may have different influences on competition and cooperation between actors." Particularly, in a projectised context such as university research grants, networks dissolve and reform to meet changing complexity and subsequently, resource requirements, and unattached firms may become attractive to those firms driving network structure.

To date, no research has examined the structural properties of networks in market systems requiring differing levels of resource complexity to sustain or grow market position. Our research addresses this challenge through simulating the dynamics of the network structures in the complex world of university research departments as they link their resources with others to compete for scarce NCG grant funding. Through employing an agent-based modelling simulation, we will focus attention on the interactivity of relational and competitive market behaviour of these institutions as they grow and access resources.

Our research aims to contribute to the body of knowledge on structuration and network properties. Specifically, we seek to address the question: How is network structure impacted by increasing levels of resource complexity required to sustain or build an institution's market position? We are particularly interested in examining the network structures emerging from network attachments under different resource complexity conditions as institutions operating within a market system strive for competitive advantage through internal resource re-investment and accessing resources through networks.

2. Literature Review

Structuration Theory and Structural Properties of Networks

Drawing on a stream of work emanating from European sociologists, Anthony Giddens (1979; 1984) advanced conceptualization of structuration theory through integrating opposing views of social capital as a product of social structures and of the interpretive systems of human agents. The structural properties of signification, domination, and legitimation described by Giddens were argued to both define and be defined by the structure of interactions, the interpretive schema of human agents and communication, which influence and are influenced by normative and dominating behavior. Giddens (1979) spoke of these properties of social systems as both defining the social capital produced and re-enforcing the social structures of the system. His view of structure as 'both medium and outcome of the reproduction of practices' (Giddens 1979: 69) is consistent with complexity explanations of self-organisation.

Building on these principles, seminal research by both Coleman (1988) and Burt (1992) addressing network connectivity and structural holes (connection gaps between members who provide overlapping information) provided a foundation for understanding network properties of power locus, dependency, control, commitment and trust between network partners and their impact on collaboration. While Coleman argued the importance of mutual connectedness (embeddedness) and network closure in supporting collaboration, Burt (1992) proposed that a firm can maximise its non-redundant knowledge exchanges by uncoupling network linkages to create structural holes. For example, if firms A and B are connected, then, firm C need only connect to A or B to access the same knowledge (Borgatti and Foster, 2003). Research on the application of social networks to inter-organisational form has generally focussed on the impact of network structure (density, centrality, structural holes) on network performance (Casanueva, Gallego and Sancho, 2013: 441).

The structural properties identified by Giddens (1979; 1984) as underpinning social interaction are reflected in specific aspects of university research networks through, for example, membership of a specific university category signifying a hierarchy in research endowment, the domination of those located in higher order categories through having access to more and diverse and/or higher order resources, and legitimisation of a member's contribution to the formation of social capital defined through network position. Giddens speaks of resources as only having value when 'activated' through structuration (Giddens, 1984). Structuration is therefore critical for leveraging and integrating the resources required for the delivery of university network research outputs.

Leveraging Resources to Build Competitive Position

The Resource Advantage Theory of Competition (RATC) (Hunt, 1997, 1999, 2000; Hunt and Morgan, 1995) shares affinities with the resource based view of the firm, evolutionary economics, institutional economics and economic sociology, i.e. theories that explain the strategic drive of institutions to achieve superior performance through achieving differential resource advantage. It is the re-investment in resources that reinforces resource heterogeneity, and builds comparative advantage (Hunt, 2000). This process increases in complexity when the resources are accessed via a network of relationships, particularly where the technologies, skills and knowledge base required to create new knowledge are not located in one institution (Hendry and Brown, 2006). Competitive behaviour and performance then becomes not just a function of competition between institutions, but also of competition between networks (Gulati et al., 2000 and Goerzen, 2007) and the structural properties of those networks.

Our definition of resources is consistent with that offered by Bingham and Eisenhardt (2008) which incorporates both tangible and intangible assets and organisational processes/capabilities to leverage those assets. The particular focus on resources in our study is on intangible knowledge assets and research services, physical assets of research infrastructure and relational resources (processes, skills and infrastructure) necessary to build network relationships, and access and leverage knowledge resources across the network.

A university's competitive position is determined in the research market system in the UK by Research Assessment Exercise (RAE) rankings. Forming networks to facilitate the creation of new knowledge is particularly important for institutions with limited research resources seeking to enhance their competitive position. In the context of universities, collaborative behaviour of individuals as they form networks across institutions to access resources for the purpose of competing for NCG's against other similarly formed networks are anticipated to lead to improved competitive advantage of institutions (Boschetti and Brede, 2009). Contrary to conclusions drawn from studying the healthcare industry that "two organizations will compete and cooperate simultaneously when each organization has complementary but distinctly different sets of resources and when the field of competition is distinctly separate from the field of cooperation" (Peng and Bourne, 2009: 377), collaboration within networks formed to conduct academic research co-exists with competition for NCG's between other similar networks. Further, network members directly compete with each other as they strive to retain or enhance their RAE standing. Both the new knowledge (in the form of academic publications) created through drawing on the resources of the research network, and acquiring NCGs, are important outcomes that can enhance RAE standing of individual network members. Acquiring NCGs provides a) evidence of quality, innovative projects, b) the achievement of and potential for quality outputs through publications and c) the foundations for advancing RAE ranking.

Market System Complexity and Network Formation

Market systems in which institutions operate reflect different attributes and structures, and may comprise few or many interrelated resources. A market system may be simple, with a range of independent products that require limited, specialised resources. A market system may also be complex requiring a combination of interconnected, specialised resources and deliverables. Here we define the market system as the organisation of activities through mutual interactions of buyers and sellers (Lindblom, 2001). Lindblom describes a market system as "a method of social coordination by mutual adjustment among participants" (pp.27). The university sector has many interrelated components, and its stakeholders often reflect conflicting objectives. The sector exhibits a multitude of products (research, courses, degrees and delivery modes), infrastructure requirements (libraries, laboratories, language services), multi-faceted governance with private and public sector funding, often spanning more than one country and requiring a diverse resource base and an ability to flexibly integrate those resources to take advantage of emerging opportunities. Competitors in this market system need to be large or to partner extensively to succeed, while others may choose to focus on achieving excellence in one domain (for example, teaching) with research resources focussed in limited departments.

Within this sector, the university research market system can be viewed as low complexity (requiring limited, specialised knowledge and other resources) or complex (requiring multiple, integrated knowledge domains and other resources). If market system complexity is high, to achieve market growth an institution needs to access a high level of diverse knowledge domains and other resources to compete successfully in the market. In turbulent and highly complex environments, in the short term (the timescale being dependent on the network to independence investment ratio), the easiest way to gain access to and integrate a large number of diverse resources is through building a network of relationships. Institutions with complementary resources will group together, providing the capacity to develop resources critical for growth or survival, while retaining the benefits of traditional hierarchical architectures (Cravens et al, 1996, Powell et al., 1996, Shenkar and Li, 1999, Combs and Ketchen Jr, 1999, Lorenzoni and Lipparini, 1999, Tallman and Jenkins, 2002, and Goerzen, 2007). In academic research networks, we anticipate that both limited and extensive research networks will be observed.

Burt (1992) recommended efficiency of knowledge exchange in networks through removing redundancy by uncoupling network linkages to create structural holes. However, both Adler and Kwon (2002) and Ahuja (2000) speak of network density (i.e high connectivity and embedded ties) and the absence of structural holes as fundamental to social capital, in enabling the pursuit of collective goals and defining performance outcomes. Walter, Lechner and Kellermans (2007) explain how denseness facilitates effective and efficient transfer of both explicit and tacit knowledge. “Explicit knowledge refers to information that can be easily communicated among individuals, whereas tacit knowledge such as skills, competence and talents is more difficult to directly communicate to someone else in a verbal or other symbolic form" (Huggins 2010: 516). Sub-group inter-connectivity has been shown to evolve to manage the increased complexity of knowledge generation (Guimera et al., 2005). It is therefore anticipated that structures observed in a simulation of academic research networks will contain networks exhibiting subgroups and direct and indirect connectivity. Thus,

> Proposition 1: Institutions focussed on high complexity market systems will favour a relational model exhibiting many network forms, including subgroups and direct and indirect connectivity.

The increasing breadth of knowledge and other resource requirements of complex market systems will stimulate increased networking as institutions seek to expand their market space (Hendry and Brown, 2006 and Goerzen, 2007), thus:

> Proposition 2: The size of networks formed will increase with increased market system complexity.

Gilbert et al. (2007: 100) confirmed that "firms with different knowledge stocks attempt to improve their economic performance by engaging in radical or incremental innovation activities and through partnerships and networking with other firms". Thus:

> Proposition 3: Under conditions of high market system complexity, higher levels of specialization and increased diversity of institutions in networks will be observed.

Simulations as a mechanism of discovery

Simulations have been described as an extension of deduction and induction approaches to scientific discovery. In his book on the Complexity of Cooperation Robert Axelrod (1997) explains how simulations, like deduction, are defined through a set of assumptions and, like induction, can be used to find patterns in the data. However, simulation cannot be used to prove consequences from those assumptions, and unlike induction, the data is generated from a set of rules. Axelrod argues that social scientists have found this approach extremely useful in the discovery of new knowledge. Agent-based modelling is a form of simulation used in the social sciences to build understanding of fundamental processes of complex phenomena characterised by interactions and emergent behaviour.

For many social systems, models which admit of a fuller description of agent behaviour are desirable, i.e. agent-based models (Batten, 2000, Tesfatsion, 2006 and Epstein, 2006), but full cognitive models of agents may not be necessary in order to capture underlying dynamics. In economics a variety of such models exist. Kirman's Marseille fish market (Kirman and Vriend, 2000) and Lux and Marchesi's (1999) stock market successfully modelled key market behaviours using traders operating in a very primitive cognitive space. More recently, Tay and Lusch (2005, 2007) employed agent- based modelling to explore the RATC, adopting an emphasis on evolutionary processes, with market disequilibrium generated through knowledge discovery and sellers' behaviour defined through fuzzy logic. Their findings provided support for a number of principles underpinning the RATC and encouraged the development of a more intensive simulation.

3. Research Plan and Method

Our methodology required the selection and study of a specific market that would form the basis of defining the simulation parameters and provide 'real world' interpretations of the behavior of agents observed in the simulation findings. We chose the research sector of science departments within the UK university sector as our frame of reference as this sector has been assessed through the RAE during subsequent periods. In our findings we compare the observed agent behaviour to recent RAE data and research grant activity. The RAE data offers examples of universities moving up and down in the rankings, with others maintaining their positions.

We identified research linkages across institutions on the basis of grants funded through the Engineering and Physical Sciences Research Council (EPSRC). As a snapshot of research grant activity we captured EPSRC grants instigated from 2006 to identify the extent of linkages with other institutions situated at a higher, similar or lower ranking as designated by the previous RAE. From 2006 (http://gow.epsrc.ac.uk/GowDefault.aspx accessed February 19-26, 2010), EPSRC had supported 5,610 grants of £3,551,059,394. This information provided a basis for explanations of the patterns of interactivity observed in the simulation (i.e. the impact of the investment choices between internal resource investment and resources derived through network access). Secondary data were collected on ten institutions offering examples where rankings remained at high levels, rankings remained at medium levels, rankings remained at low levels and rankings demonstrated movement across levels. The institutions included 'old' Universities, 'red bricks' and 'third wave' Universities.

Each EPSRC grant is recorded against one individual at a specific institution, and therefore the data is not reflective of the collective researchers undertaking the project in cases where others are involved in the grant. In this way the data is aligned with RAE data. To show the extension of cross-institution participation in projects we have included in the EPSRC data (see Appendix 1) the rankings of other institutions involved in funded projects. We recognised the possibility that individuals from specific institutions with multiple grants will represent a number of the network structures observed in the simulation, and thus developed an aggregated, university department view capturing the multitude of networks across institutions. However, the individual view is important for observing differences in network structures, while department connectivity is reflective of the collective network connectivity of individual researchers.

The simulation component of the project had three phases:

1. A model market system was constructed that was prototyped in Netlogo.
2. A range of scenarios were implemented to address the propositions specified above.
3. Visualisation of findings

3.1 The Model Market System

The model market system design was based on characteristics of the higher education market, with agents assigned combinations of research and relational resources and designated ‘old’, ‘red brick’ or ‘third wave’ science departments. Agents linked to science departments within these three categories were assigned, respectively, high, medium and low funds to invest randomly in research resources to achieve research outcomes. The research market system was simulated by letting each researcher within a department search for researchers in external departments or already existing networks with whom to join to achieve higher aggregate research resources in order to compete for grant income.

Science departments, like all other university departments, are comprised of, or can access via a network, research resources such as university resources (e.g. grant expertise), department resources (e.g. physical resources) or discipline knowledge resources. In a research network it was assumed that only the highest level of each resource across the network added value to the network. Each individual researcher then might add one or more resources to a network. It was assumed here that research resources were not additive i.e. a mid-tier resource in one department plus a mid-tier similar resource in a second department did not sum to a top-tier resource department. The research outcome of a network was the sum of the highest values of the research resources taken across the researchers in the network.

3.2 Simulations

Patterns of network emergence arise as a consequence of interaction between the:

- changing resource requirements (following changing strategic priorities or market requirements),
- level of investment in research resources,
- ratio between internal resource investment and access of resources through network attachment,
- complexity of market knowledge flows, capabilities and competencies, and
- extent to which an institution operates independently or relies on network collaborations to undertake research activity (institution propensity for relationships) (Henderson and Clark 1990, Achrol and Kotler, 1999, Birkinshaw et al., 2002, Beckman et al., 2004, Jarratt, 2006 and Hendry and Brown, 2006).

The specific research resources in our simulation could have multiple interpretations, but one possible interpretation would be that the resources are made up of:

1. relational resources (0, 1, 2)
2. research support resources (0, 1, 2)
3. physical research infrastructure resources (0, 1, 2), and
4. one or more discipline-specific or cross-discipline resources representing the human skill resource level in each discipline required to carry out the research for which the departments are competing (0, 1, 2).

Transaction cost economics theory advises that relationship development at a network node will derive cost efficiencies. However Jarratt and Katsikias (2008) and Narayandas and Rangan (2004) agree that cost efficiencies may not always accrue to the institution forging network relationships. A relational resource has been incorporated into the design of our simulation, with the ‘cost’ of relationship development being captured through assigning a negative resource value to the relational resource.

The level of relational resource limited the research networks that a researcher could potentially join. A level of 0 in the relational resource meant that the researcher could not join a network, but had to compete for NCGs as a sole investigator. A level of 1 in the relational resource meant that the researcher could join a research network with one other research actor, or a larger network, but not as a research leader. Each network with more than two researchers required at least one research leader with a relational resource level of two.

For simplicity, 20% of agents were designated as ‘old’ departments, 40% as ‘red brick’ and 40% ‘third wave’. Researchers at ‘old’ departments were assigned the highest level of funding units, at ‘red bricks’ a medium level of funding units and at ‘third wave’ the lowest level of funding units at the beginning of the simulation, to represent the historical research funding balance across these institution categories. When the number of resources through internal investment or by forming a link with another institution reached a maximum level (i.e. maximum value for each disciplines-specific plus support resources and physical resources) they were assumed to stop searching for more partners.

We ran three separate simulations with different numbers of resources requirements (physical, support and relational resources plus a single discipline resource, three discipline resources or five discipline resources) to provide increasing knowledge complexity requirements to test our propositions. In each case we are increasing the number of resources each network must bring to a NCG but we are not increasing the amount each individual researcher has. The simulations chosen were ones where the output was typical for that choice of parameters.

3.3 Visualisations

Simulation work of this kind produces large volumes of data, which is best interpreted in the first instance by graphs. We have used standard graph visualisation techniques to look at how networks of researchers form. We present six figures: two from each of a simulation with a relatively low complexity, a medium complexity and a high complexity environment. Institutional department affiliations of researchers are represented by the circle (old), square (red brick) and triangle (third wave) shapes, while research networks are represented by lines linking the research partners in a network. We draw some qualitative conclusions based on comparisons between the three simulations.

The outcome of a simulation is presented in each case from a "researcher" view in one figure and a "department" view in a second figure. The researcher figure represents a successful research network and the researchers within it. The department view shows the number of research links between researches in one university to their network partners in other universities.

A low complexity environment is interpreted here as research requiring only one discipline resource in addition to relational, research support and infrastructure resources (the three foundational resource requirements). A medium complexity environment is research that requires three discipline resources to excel in addition to the foundational resources. A high complexity environment is research that requires five discipline resources in addition to the foundational resources. Network faces (lines linking network partners) close where both agents exhibit maximum levels of relational resources.

4. Simulation Findings

The simulation experiments show the impact of different resource investment choices (internal investment versus external resource access via network relationships) in contexts of increasing knowledge complexity. We show that behaviour in this simulated research market system demonstrates consistencies with behaviour anticipated from prior research (propositions tested) and with behaviour observed in the sector.

[Figure 1a about here]

[Figure 1b about here]

In the low complexity environment (Figure 1a), three of the networks have three partners, however a large number of the research networks have only two partners. None of the researchers from old universities required partners to be competitive in the research market and so did not form or join a network. Researchers from red brick universities tended to network with other red brick university researchers. From the university view (Figure 1b) it is evident that networks formed are concentrated between red brick institutions, but there are a few links extended to third wave institutions. The third wave researchers who are successful in getting into research networks are the ones who have invested (specialized) in one discipline resource (i.e. attained a high knowledge level).

[Figure 2a about here]

[Figure 2b about here]

In the medium complexity environment (Figure 2a) we observe larger networks forming with three (12), four (8) and six node (1) research networks, with only one successful two-node research network. Both open and closed structural forms of four node networks were observed. The best resourced departments are in networks with other old university departments or with the red brick university departments. Successful old university departments are all in networks, rather than choosing to stay outside networks as some old university departments did in the simpler environments. It is evident from the university view of this environment (Figure 2b) that denser ties are developing between the old universities and between old and red brick universities, with very few ties to the third wave universities.

[Figure 3a about here]

[Figure 3b about here]

In a high complexity environment (Figure 3a) we observe a greater diversity of network partnering. There are now a seven-node, two six-nodes and seven five-node research networks. These large networks are composed of old university departments and red brick university departments, but now more third wave institutions are linked to old and red brick science departments. This integration of third wave institutions in the networks structures is also visible in the university view (Figure 3b) which exhibits ties between old, red brick and two third wave institutions.

[Table 1 about here]

Table 1 contains network data at each of the three levels of complexity. The table reports values for the networks that achieve the minimum value for a successful NCG. The data indicates that in high complexity environments, fewer, denser and more diverse networks are likely to form than in low complexity environments.

The simulations provide support for the three propositions deduced from structuration theory, network structures and the networking behaviour of institutions

Proposition 1: Comparing Figure 3a to Figure 1a, we see that old departments could compete successfully outside networks forms in simple environments. However, in more complex environments these same departments were more likely to join research networks to remain competitive. In the most complex environment all successful researchers are joined into larger and more diverse research networks, which included subgroups and direct and indirect connectivity. Moving to more complex environments induces researchers to access research networks.

Proposition 2: In Figure 1a the dominant network form was a simple two-node network of a researcher and its research partner. In Figure 2a the three and four node networks were more common, while in Figure 3a we see more five, six and seven node networks appearing. As we moved to more complex environments in Figure 2a and Figure 3a, larger networks formed as networks needed a broader range of disciplines to be able to compete for research outcomes. This is reflected in the average network size reported in Table 1 increasing as market system complexity increases.

Proposition 3: We anticipated that higher levels of specialization and increased diversity of institutions in networks will be observed in more complex environments. The university view of the simulation of the most complex environment is given in Figure 3b. We see that all of the old departments have joined into research networks, as well as all of the red brick departments. Networks between old and third wave universities have now started to appear, which were absent in the simple environment (Figure 1b).

The column “Average Network Diversity” in Table 1 measures the maximum difference between the highest tier and the lowest tier researchers in a single network. This number could take on a minimum value of 0 for a network composed only of researchers from the same type of university to a maximum value of 2 for a network that included researchers from both old and third wave universities. This figure was then averaged over all the successful networks in the simulation.

The diversity of the members of successful research networks increased as the complexity of the NCG increased. In high complex environments, third wave departments need to exhibit a strong degree of resource specialisation to be able to fund a resource level that is attractive to an old department in a research network. All of the successful third wave researchers specialised enough in a single discipline area to be attractive to a research network.

These findings indicate the importance of specialised internal disciple knowledge investment and investment in relational resources for third wave institution seeking to build comparative advantage in this complex environment. The statistical data indicate an increase in network density and diversity of network form and participants in complex market systems.

4.1 Networking behaviour by science departments under the Research Assessment Exercise

In this section we provide some evidence of networking behaviour of United Kingdom university science departments. Of interest to this research are the size of research networks and the ranking of research partners in each network. Ranking data of departments is derived from the United Kingdom's Research Assessment Exercise (RAE) which has been conducted four times in 1991, 1996, 2001 and 2008. The RAE produced rankings for researchers and departments in individual disciplines, including Chemistry and Physics, the two discipline areas we examine in this research. Although the ranking data is at department level and the grants are allocated to individuals within those departments we have assumed that grant recipients in administering departments are project leaders and this data is correlated with RAE department rankings.

In the 2001, RAE rankings were conducted on a 7 point scale: 5*, 5, 4, 3a, 3b, 2 and 1. In 2008 this single index for departments was abandoned in favour of multiple indices listing the proportion of researchers in a department who were deemed to be of a certain rank (4*, 3*, 2* and 1*). In the Appendix we report the 2001 RAE ranking of the ten selected Chemistry and Physics departments. As the 2008 RAE did not report departmental ranking, we used the weighted average of the researchers for each department to represent the department ranking. This is the same method used by the U.K. Times Higher Education (2008) to rank departments and universities in the 2008 RAE. Weighted averages were translated back into the original 7 point scale by ensuring that equal proportions of each rank (5*, 5, etc) were allocated in the 2008 ranking as in the 2001 RAE.

To identify research networks and research network partners, we used the database of research grants from the Engineering and Physical Sciences Research Council (EPSRC). The list of research grants for each of the chosen departments was downloaded as of February 19-26, 2010, which included grants still operating from 2006 onwards. For each of the chosen departments, the EPSRC database listed the principal investigators for current grants who were members of that department, as well as the departmental affiliation of co-investigators on the grants. This database provides evidence of the networking relationships between members of different Chemistry and Physics departments.

We present the RAE ranking and networking data for Chemistry and Physics departments at 10 United Kingdom universities in Appendix 1. All universities selected had separate Chemistry and Physics departments. Each table in Appendix 1 presents the ranking and network activity for the departments at a single university. The rankings included are the 2001 RAE rankings and an imputed 2008 RAE ranking. The tables in the Appendix also present the number of current EPSRC grants and the value of all current EPSRC grants where a department member was a principal investigator.

Each table lists the rankings of the research partners for current EPSRC grants for each department. These research partners are the departments of the co-investigators of the EPSRC grants. We simply list the number of research partners for each department by their 2001 RAE rank. Only other United Kingdom university departments are included as other research partners, international universities and industry partners have been excluded at this stage.

There are several features apparent in the tables in Appendix 1. Physics departments have fewer and smaller networking relationships than do Chemistry departments. While the Chemistry department at Oxford has established research networks with multiple departments at different rankings, the Physics department has only a single research partner which has a 5* ranking. This is despite the fact that both departments have similar numbers of current EPSRC grants. The sole exception to this pattern is at the University of Manchester, where the Physics department has a larger research network than the Chemistry department, as well as a larger number of grants. However, generally, the research networks for Physics departments resemble the networking behaviour in the simple environment in our simulations (Figures 1a and 1b). Thus, successful Physics departments normally compete for research funds outside research networks or with a single research partner- usually at an equivalent ranking.

On the other hand, the research networks for Chemistry departments generally resemble the networking behaviour in the most complex environment in our simulations (Figures 3a and 3b) taking on a larger number and a wide range of research partners in order to compete for research funds. Not only do we see larger networks, but we also see more diverse networks and some evidence of resource specialisation. While in Physics research we see departments taking on a single research partner typically at a similar ranking, in Chemistry we see departments with a 5* ranking taking on research partners with a 3a ranking. This type of network can arise in a complex environment if the lower ranked department is investing a significant proportion of its resources in a single, valued area.

5. Conclusions

A simulation framework was developed to account for the various strategic options facing institutions as they compete for National Competitive Grants. In our simulation some institutions followed a strategy of building comparative advantage through reinvesting in their own resources (Eisenhardt and Martin, 2000, Fiol, 2001 and Wright et al., 2001). Other institutions chose to build comparative advantage through directing their limited financial resources towards enhancing the quality of their relationship resource, and linking their specialised resources with others accessed through a network of relationships. Under this strategy, an institution sought to access resources required to effectively competing through forming linkages with one or more others that had invested internally to retain the quality of their specialised discipline resources.

Our simulation has demonstrated that under lower levels of market system complexity, network attachment reflected that supported by network theory, particularly dimensions of embeddedness and member prominence (e.g. Powell et al., 2005) i.e. when linkages occurred they did so between members of similar standing. Embeddedness and social capital were evidenced in these relationships through high levels of relational resources existing in, and linking, network members. However, under high levels of market system complexity, networks attracted members from different standing which had not been considered previously. Here, advances in graph theory, facilitating the entry of new members, offers greater explanatory power (Rosenkopf and Padula, 2008).

Our research has contributed to the body of knowledge on network structure through demonstrating how more intense, specialised, diverse and closed networks of relationships are formed in increasingly complex market systems. In low complexity market systems, the network structures formed were simple and open (reflecting Burt's (1992) structural holes), accessing quality resources directly and indirectly to achieve comparative advantage. Of the few networks that were formed, those with limited resources sought relationships with institutions having equal or higher quality resources to effectively compete against institutions which have already achieved the highest quality resource levels.

However, in high complexity market systems, the network structures formed to access resources displayed very different properties. Networks exhibited both Burt's (1992) open (structural holes) and Coleman's (1988) closed (social capital) properties. Both the size (number of members) and the diversity (comprising different categories of members) of the networks were greater in these high complex environments. The research has confirmed that in complex market systems the most successful strategy involves joining larger and more diverse research networks, which exhibit closed sub-components that facilitate the development of social capital.

The propositions derived from network and structuration theory and examination of the simulation outcomes suggest that in more complex market systems we observe competing institutions engaging in a) more networking exhibiting different network structures (P 1), b) larger networks (P 2), and c) more diverse networks containing members from different groups (P 3).

This work has contributed to agent-based computational economics defined by Tesfatsion (2002: 55) as "the study of economies modelled as evolving systems of autonomous interacting agents". Agent-based computational economics researchers utilise computational frameworks to study the evolution of economies under experimental conditions.

6. Implications for Management

The networking behaviour of UK university departments under the RAE supports the simulation findings. More complex research environments lead to more diverse and larger research networks. In addition, in more complex environments we observe even relatively weaker institutions being able to compete by specialising in one area so that they have the ability to create value in a research network. It is not just what resources an institution possesses, it matters how those resources fit into the network through which the institution competes and builds comparative advantage. The simulation and real world data suggest that for those with limited resources, a concentration of internal investments in a specialised resource(s) can be an effective strategy to link with others and build market position. Specialising in a resource that has value for others competing in a complex and inimitable market system facilitates network formation. In this context it is the comparative advantage of the network that can create improved market position.

These findings point to the importance for those with limited resources being strategic about a) in which resources to invest (specialised discipline resources that have strong market value), b) being able to identify, attract and retain discipline “stars” with extensive networks to underpin that specialisation, and c) building relational and resource integration capabilities to facilitate the leveraging of that valued resource through network participation.

From the perspective of an old university with a resource advantage, it is not only important for researchers to work independently but also to constantly look externally for resources that can complement internal resources to ensure they continue to build comparative advantage.

7. Continuing research

We plan to add an evolutionary component to the simulation and study change over time to reveal how each department's network partnerships evolve. Studying the behaviour of the economies in this fashion will enable us to apply appropriate mathematical abstractions of network characteristics (such as structures or small world behaviour or network flows), phase transitions (where the economy re-organises in a sudden and dramatic way such as bubbles and crashes), or other behaviours so far uncharacterised. Intelligent agents (in this case, researchers in science departments) 'learn' from the changing dynamics of total sector research investment, and the research performance consequences of decisions about the efficiencies and effectiveness of internal resource investment compared to resources accessed through networks. As a consequence of learning, agents will adjust resource investment and the ratio of future investment between internal and external resource access.

In high knowledge, complex market systems, over time, retaining network structure has been posited to negatively affect performance (Rowley et al., 2000, Christensen and Raynor, 2003 and Goerzen, 2007). The evolutionary component will allow us to test whether, long term, firms competing in these markets through networks will invest internally in new resources and add new network nodes to sustain comparative advantage and performance.

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Table 1

Statistical attributes of the three levels of complexity

Complexity	**Number of Successful Networks**	**Average Network Diversity**	**Average Network Size**
Low	78	0.12	1.54
Middle	22	1.00	3.45
High	10	1.20	5.40

Figure 1a

Research networks in a low complexity environment

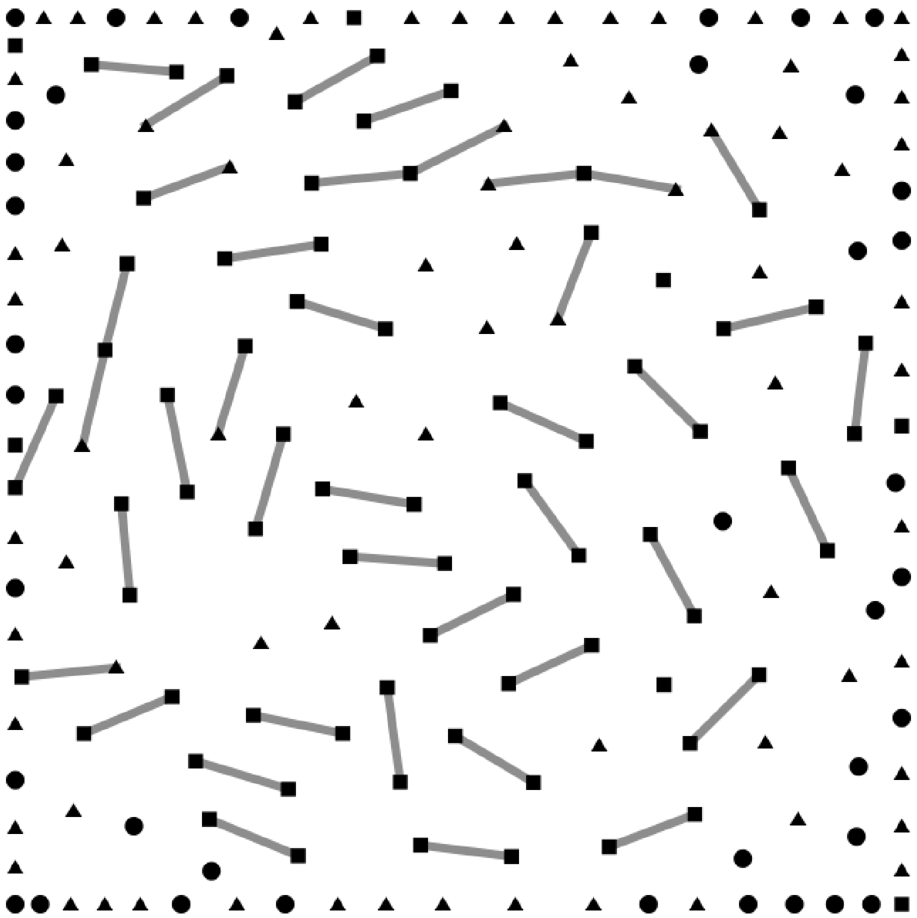


Figure 1b

University department view – aggregation of research networks

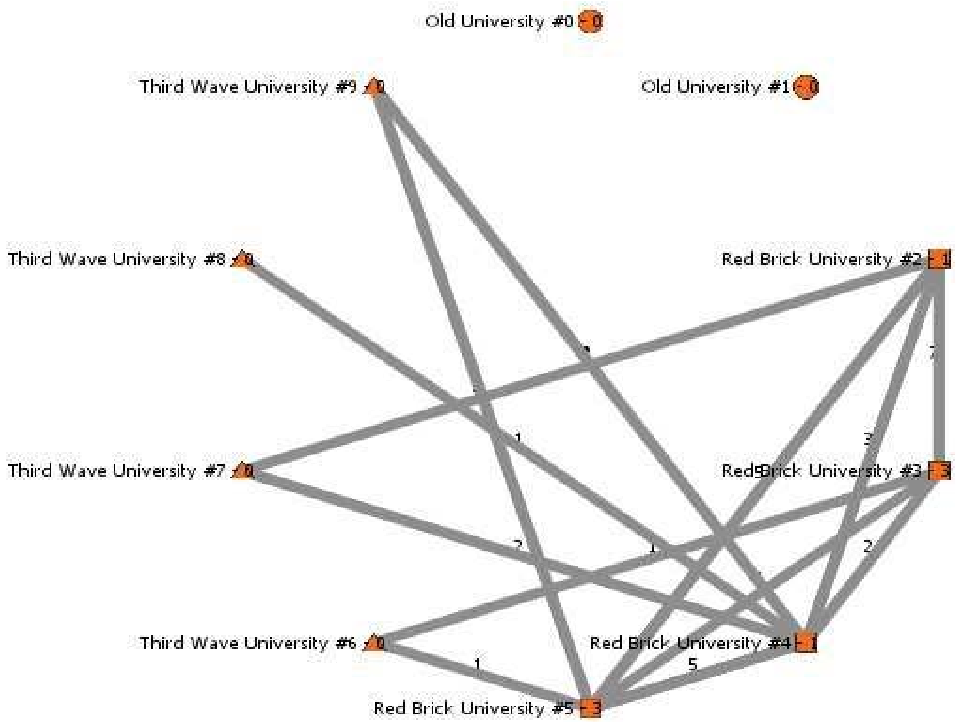


Figure 2a

University research networks in a medium complexity environment

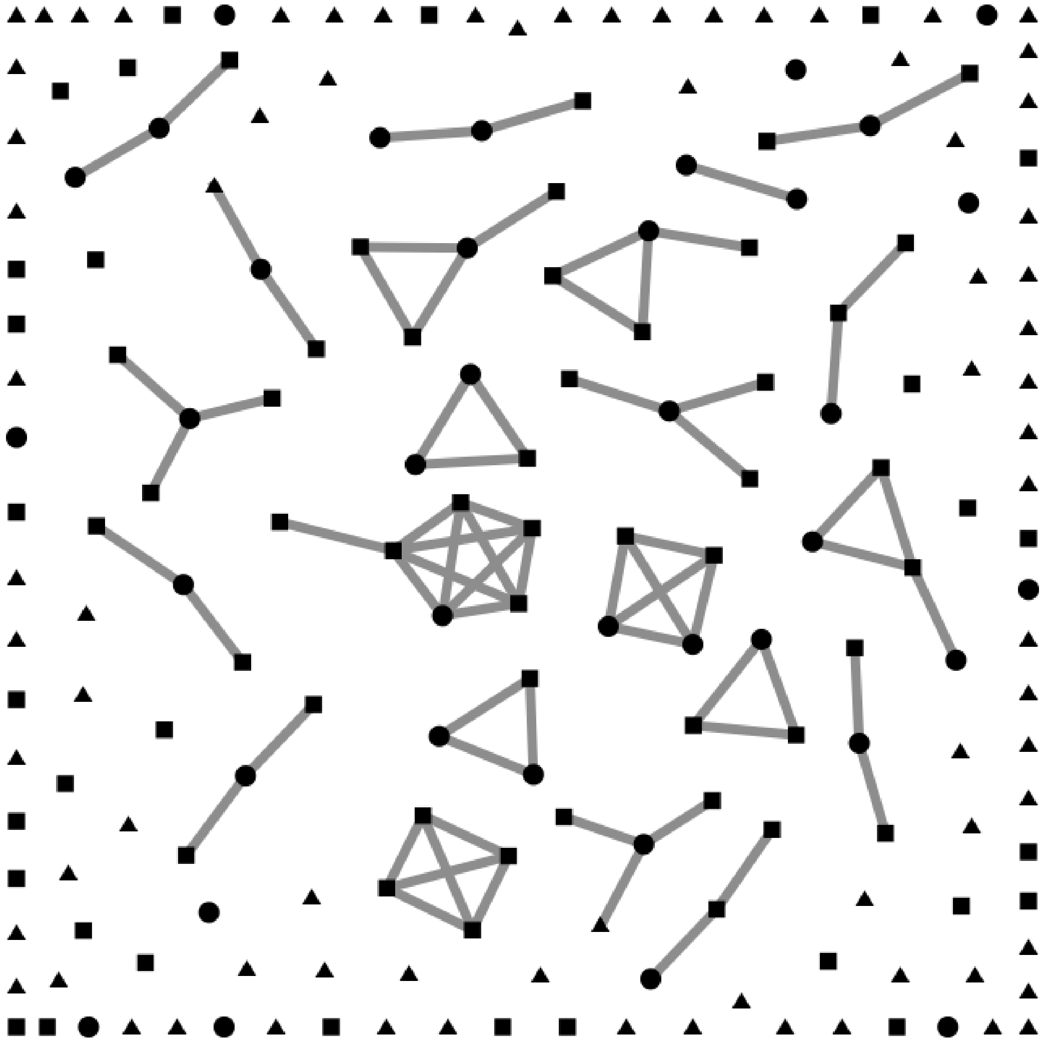


Figure 2b

University department view – aggregation of research networks

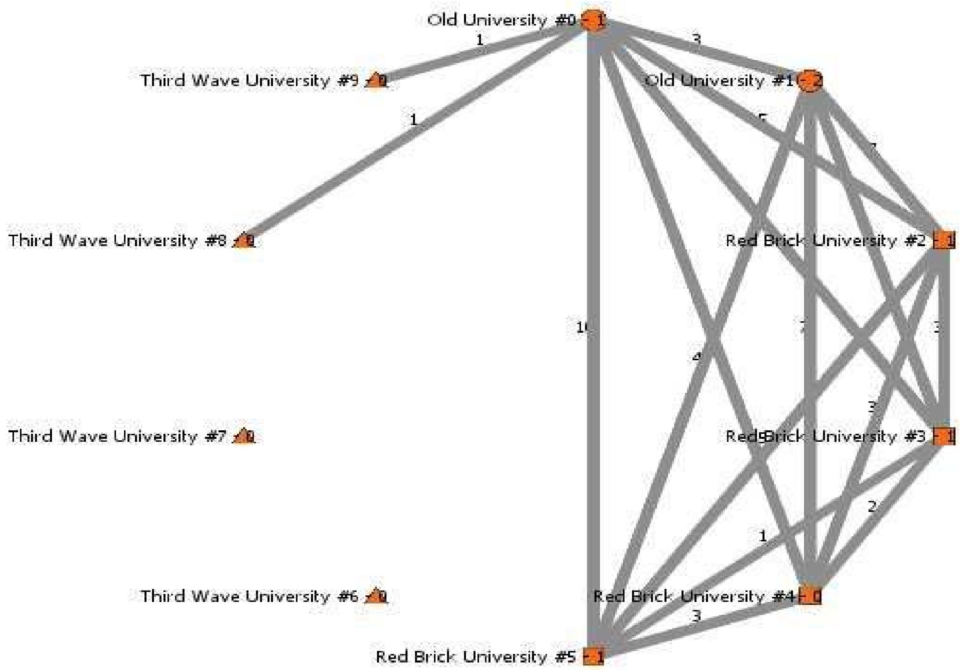


Figure 3a

University research networks in a high complexity environment

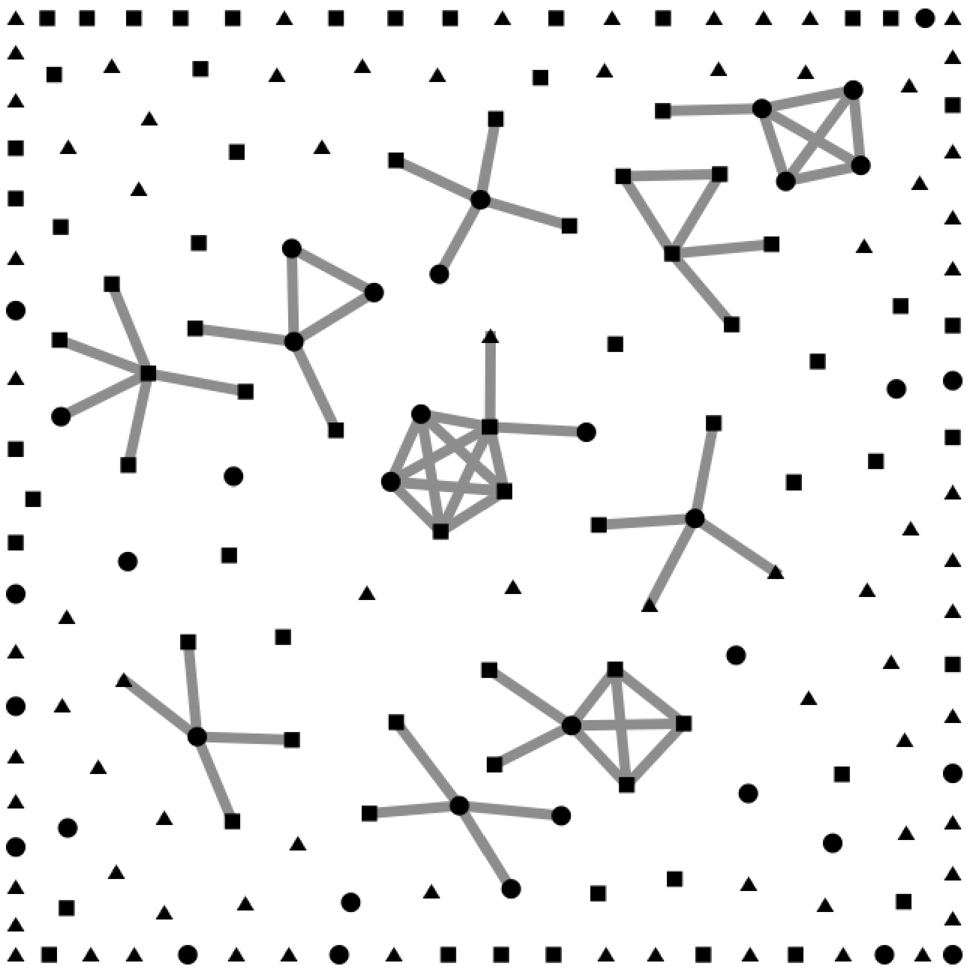
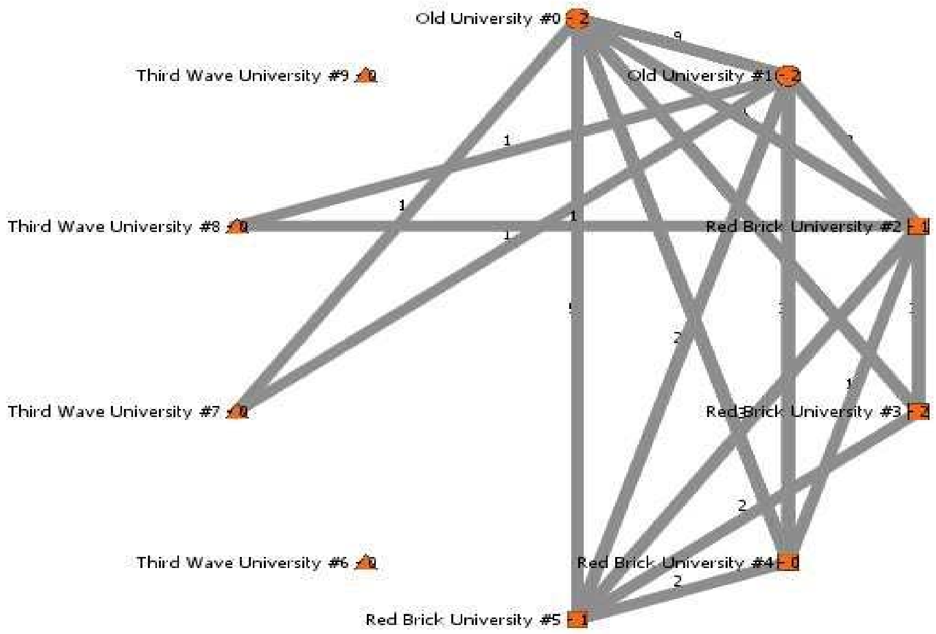


Figure 3b

University department view – aggregation of research networks



Appendix 1

		Cardiff University				**Loughborough University**				**University of Bath**				**University of Bristol**			
Department		Chemistry		Physics		Chemistry		Physics		Chemistry		Physics		Chemistry		Physics	
Year		2008	2001	2008	2001	2008	2001	2008	2001	2008	2001	2008	2001	2008	2001	2008	2001
Rank		4	4	4	5	3a	4	5	5	4	4	5*	4	5*	5*	5	5
Number of Grants		25		5		4		3		31		14		37		28	
Sum of Grants		£11.7m		£1.8m		£0.7		£1.0		£9.3		£5.2		£22.2m		£9.8m	
Ranking of research partners	**5***	2		-		-		-		2		1		1		-	
	5	1		-		-		1		3		1		2		1	
	4	3		-		1		-		4		-		3		-	
	3a	-		-		-		-		1		-		-		-	

		University of Edinburgh				**University of Glasgow**				**University of Manchester**			
Department		Chemistry		Physics		Chemistry		Physics		Chemistry		Physics	
Year		2008	2001	2008	2001	2008	2001	2008	2001	2008	2001	2008	2001
Rank		5*	5	5	5	4	4	5	5	5	5	5	5
Number of		30		14		23		5		4		20	
Sum of Grants		£13.7		£16.0		£10.2		£1.6		£1.0		£19.9	
Ranking of research partners	**5***	3		1		-		-		-		3	
	5	2		-		1		-		-		4	
	4	-		-		4		-		-		-	
	3a	-		-		-		-		-		-	

		University of Oxford				University of Reading				University of Surrey			
Department		Chemistry		Physics		Chemistry		Physics		Chemistry		Physics	
Year		2008	2001	2008	2001	2008	2001	2008	2001	2008	2001	2008	2001
Rank		5*	5*	5	5*	3b	4	n/a	4	-	3a	4	5
Number of Grants		54		50		15		2		1		6	
Sum of Grants		£25.3		£25.4		£4.3		£0.1		£0.3		£1.9	
Ranking of research partners	**5***	2		1		-		-		-		-	
	5	3		-		-		-		-		-	
	4	4		-		-		-		-		-	
	3a	1		-		-		-		-		-	