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# The role of NPOs and international actors in the National Innovation System: a network-based approach

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**Abstract**

This paper conducts an explorative analysis of the UK's nanotechnology research collaboration network to understand the contributions of the different institutions in the development and generation of knowledge. Framed in the National Innovation System (NIS) and the Triple Helix (TH) model literature, this paper makes use of social network analysis (SNA) tools to identify the role and involvement of different institutional actors in the interactions and collaborations within the nanotechnology network. Building on the traditional university–industry–government three-helix interaction model, our paper includes two extra dimensions in the model to account for the increase in international collaboration and the increasingly important role of non-profit organizations (NPOs) in knowledge generation. In this way, our paper responds to recent calls to adapt the traditional NIS models to reflect the new realities of scientific collaboration.

**Keywords:** National Innovation System (NIS), Triple Helix (TH) model, NPOs, International collaboration, Network analysis, Nanotechnology

# 1. INTRODUCTION

The generation and application of new knowledge are primary drivers of economic growth (Ribeiro-Soriano et al., 2019). The collaboration between different entities and actors has increasingly become an important mode of knowledge generation across different science-based disciplines (Wuchty et al., 2007). The OECD (2018a) has pointed out that the extent and intensity of industry and science links are essential contributors of high innovation performance at all levels of the economy (i.e. firm, industry and country levels).

The innovation systems literature has examined the dynamics of the interactions and technology-driven collaborations between these different economic actors (e.g. universities, governments, industry, users or suppliers). The National Innovation System (NIS) literature underscores the importance of interactions between different actors in the economy (firms, universities and government) for innovation success (Freeman et al., 1987; Lundvall, 1992; 2007). A popular lens to examine the structure of the NIS is the Triple Helix (TH) framework (Etzkowitz and Leydesdorff, 2000; Leydesdorff and Meyer, 2006), which depicts the relations among universities (U), firms (I) and government (G). The TH model enables the study of both bilateral and trilateral interactions between different spheres (universities, industry and government) in an innovation system (Etzkowitz and Leydesdorff, 2000; Park and Leydesdorff, 2010). The relevance of the TH model has been reflected in the academic literature, with an increasing number of papers employing the TH framework to examine the patterns of interactions between different institutional actors (e.g. Guerrero and Urbano, 2017; Zhang et al., 2019).

However, as recently pointed out in the literature, by including only UIG actors, the traditional TH model fails to portray the full NIS, and thus misses out many collaborations (e.g. Hoglund and Linton, 2018; Lew et al., 2018; Zhang et al., 2019). In particular, the traditional TH model fails to reflect two important forces that are shaping the current knowledge economy, namely globalization and social movements. First, the increasing permeability of geographical borders has promoted the mobility and circulation of people, knowledge and capital, allowing the internationalization of R&D and increasing the interrelation of innovation processes that are geographically distant (Binz and Truffer, 2017). Second, the emergence of the organized civil society and of non-profit organizations as manifestations of broader social movements has significantly transformed the economic landscape, contributing extensively to the areas of environmental protection, human rights or science (Campbell, 2007; Kourula, 2010). Thus, recognizing the complexity of the NIS, and following recent calls for extensions of the TH model (e.g. Leydesdorff, 2012; Zhang et al., 2019), this paper proposes a five-helix model in which international and non-profit organizations (NPOs) are included as additional helices to the traditional TH model. Our research question evaluates the importance of NPOs and international institutions in the NIS and explores the interaction of these two actors with the traditional UIG actors.

Our paper explores this question using social network analysis (SNA), a popular tool to analyse the structural nature and patterns of NIS (Borgatti and Halgin, 2011; Newman, 2001). SNA encompasses different measures that allow the exploration of the interaction from a macro level, i.e. the structure and dynamics of a particular system, and the interactions at a micro level, i.e. observing the particular characteristics of an individual. As compared with other methodologies, SNA enables the analysis of complex relations between different actors that can be used for discriminating structures in systems based on the relation of the systems' actors rather than the attributes of the individual actors (Guan and Zhao, 2013; Sena et al., 2019).

To illustrate the interest of studying an enlarged TH model, we conduct an exploratory analysis of the UK nanotechnology NIS. The first part of our analysis consists of examining the UK nanotechnology scientific network to understand its structure and identify the main institutional actors taking part in the production of knowledge and their level of importance. The second part of our analysis shows, using the modified TH model, the interactions between the different actors that justify the need for their inclusion.

Our empirical set-up is the UK's nanotechnology research collaboration network. Nanotechnology is considered as a key emerging technology (OECD, 2018b) with multiple applications in different technological domains, such as biotechnology and pharmacy, advanced materials and electronics (US National Nanotechnology Initiative, 2020). Nanotechnology has the potential to significantly improve advanced materials and manufacturing techniques, which are crucial for the competitiveness of national industries, and it is expected to be one of the major future technologies as its applications are regarded as involving radical innovation (Kostoff et al., 2007; Lavie and Drori, 2012; US National Nanotechnology Initiative, 2020). Because of potential applications to other fields and benefits to society, the development of nanotechnology has received attention from governments and policymakers, which have fostered its progress with different programmes.

Nanotechnology is an emerging science-driven industry in which collaboration is key for knowledge creation (Lavie and Drori, 2012; Thursby and Thursby, 2011). As compared with consolidated industries, where inter-firm alliances are the main form of collaboration, emerging science-driven industries have a locus of knowledge in universities and are characterized by the collaboration of teams of scientists (Darby and Zucker, 2005; Lavie and Drori, 2012; Thursby and Thursby, 2011). Thus, our study uses co-authorship information on scientific publications, which allows the exploitation of the multimodal structure of publication data. Scientific publications are established indicators of knowledge generation, which contain information on the innovation process and the intensity of collaboration between different actors (Graf and Kalthaus, 2018). Moreover, publications are widely used in the Triple Helix literature as indicators of collaboration in the knowledge generation process (e.g. Guan and Zhao, 2013; Leydesdorff and Sun, 2009; Park and Leydesdorff, 2010; Zhang et al., 2019).

This paper provides important insights for scholars and policymakers alike. First, our paper contributes to the existing NIS literature by highlighting the increasing complexity of the NIS and by including two additional dimensions to the traditional TH model. The inclusion of these two dimensions provides a better and more comprehensive tool to understand the interaction of the different actors forming the NIS. Second, by examining the structure of the network and the role of the different institutional actors in it, we are able to uncover the main strengths and weaknesses of the emerging innovation system in nanotech.

## 2. LITERATURE REVIEW

### Networks of scientific collaboration

Knowledge generation is a cumulative and interactive process, in which the interactions and connections between different actors are key for the exchange and diffusion of knowledge (Powell et al., 1996). The collaboration between different entities and actors has increasingly become an important mode of knowledge generation across different science-based disciplines (Wuchty et al., 2007). External links that provide access to knowledge are crucial for the innovative performance of firms. This is particularly true in high-tech sectors, in which the complex and fast-evolving knowledge bases impede individual entities to keep up with the technological developments (Cantner and Rake, 2014). This rise in collaboration has been facilitated by the increasing specialization and division of labour arising from the cumulative and dispersed nature of knowledge (Graf and Kalthaus, 2018; Fleming and Sorenson, 2004). Collaboration is also a means for different actors (such as academia, public research institutes and corporations) to pool, interchange and develop ideas, knowledge and other resources, and to reduce technological, market, financial and operational risks (Cantner and Rake, 2014; Powell et al., 1996).

Previous research has noted the relevance of collaboration for knowledge creation, pointing out that innovation output resulting from this collaboration tends to be more valuable than that generated in isolation (Wuchty et al., 2007). This is because innovation is a process of recombination in which firms can benefit from the input gained through interactions with partners in the form of knowledge spillovers (Fleming and Sorenson, 2004). A fruitful collaboration that has gained a lot of attention is that of universities and businesses. For instance, previous studies have explored how top universities (Stanford University, the MIT and the University of Cambridge) have contributed to the growth of high-tech economies throughout the different interactions (i.e. providing well-educated graduates, engaging in joint research or conducting commissioned research and consultancy work for firms) with the industry (Christopherson et al., 2008).

Traditionally, collaboration was understood and explored in the framework of strategic alliances, in which trust, similarity of partners and governance were key elements in successful collaborations (e.g. Dyer and Singh, 1998; Gulati, 1995). However, more recent research noted that the type of collaboration that promotes knowledge generation is to a large extent determined by the level of maturity of the industry (Lavie and Drori, 2012). In emerging industries, an alliance perspective is more relevant in knowledge application contexts, while knowledge generation is more associated with universities (Lavie and Drori, 2012). For example, in the area of nanotechnology, an emerging science-driven industry, knowledge creation is driven by the collaboration between teams of university scientists rather than inter-firm alliances (Lavie and Drori, 2012). The aggregate structure of these collaborations and interactions can be analysed in so-called knowledge networks (Graf and Kalthaus, 2018). Knowledge networks are best represented by co-authorship networks, where institutions such as academia, public research institutes and corporations are connected to each other by joint publications (Graf and Kalthaus, 2018). Co-authorship represents an explicit product of scientific collaboration and a particular type of network of scientific collaboration for knowledge generation (Knights and Scarbrough, 2010). Publications have been reported to be the dominant channel of knowledge flows across actors (Nelson, 2009).[1] Scientific publications are a key channel for knowledge diffusion and exchange in industries like nanotechnology that take advantage of basic science and research conducted by universities (Lavie and Drori, 2012). While in universities and public research organizations publications are a common output, corporations might be less likely to publish as doing so will imply openly sharing knowledge (Nelson, 2009). Nevertheless, in emerging industries firms engage in significant publishing activities since the need to be embedded in inter-organizational sharing networks outweighs the

[1] Previous studies have suggested that patents and patent citations may fail to capture both inventive and innovative activities (Brouwer and Kleinknecht, 1999; Nelson, 2009).

disadvantages of revealing important information to competitors (Nelson, 2009; Powell et al., 1996). For instance, for nanotechnology, Darby and Zucker (2005) indicate that large corporations encourage their scientists to publish, while Li et al. (2015) also note an active participation of SMEs in publication activities.

**The National Innovation System and the Triple Helix model**

The innovation systems literature has examined the dynamics of these interactions and scientific collaborations among different economic actors (e.g. universities, governments, industry, users or suppliers). The NIS is the network of institutions, both in the private and public sector, with the aim of interacting, importing, modifying and diffusing new technologies (Freeman, 1987, p.1). It understands innovation as a sophisticated and complex process in which different elements of the system, e.g. corporations, end-users, universities or public research institutes, are linked to each other, enabling the sharing of knowledge and the mutual support for innovation activities (Lundvall, 1992). The NIS is composed of the linkages and flow of information among the different actors of the system in relation to the generation of ideas and the innovation process (Lundvall, 2007).

The importance of NISs as engines for innovation has been highlighted in the literature, in particular with reference to emerging technologies and innovations (Nelson, 1993; Lundvall, 2007), and has been addressed by different governmental policies that have aimed at connecting different actors of the economy. For instance, governmental policies are increasingly aimed at engaging universities with the corporate sector, which is believed to promote economic growth and innovation (Christopherson et al., 2008). Successful examples of these policies are “Silicon Valley” and “Route 128” in the US, or the “Cambridge phenomenon” in the UK. Similarly, scholars have emphasized the role of universities as sources of new knowledge, with particular relevance in the fields of science and technology (Etzkowitz and Leydesdorff, 2000), which has generated links with the industry (Rothaermel and Thursby, 2005).

The structure of the NIS can be examined through the TH framework (Etzkowitz and Leydesdorff, 2000; Leydesdorff and Meyer, 2006), which depicts the relations between universities (U), firms (I) and government (G). In the TH context, the interactions in the UIG network build a knowledge infrastructure that represents the core of knowledge-based innovation with knowledge circulating among the three actors, fostering the creation of new technologies and knowledge-based innovations (Park and Leydesdorff, 2010).

Etzkowitz and Leydesdorff (2000) classified the interactions of UIG actors into three configurations, as shown in Figure 1. The first institutional arrangement, *the etatistic model* or

*Triple Helix I*, is a top-down approach to innovation, whereby the government oversees universities and industry and directs the relations between them. In this set-up, the lack of bottom-up initiatives makes it difficult to stimulate innovation at universities and industries (Park and Leydesdorff, 2010). This model is typical of the former Soviet Union, some European countries such as France, and countries in Latin America. The second configuration is the *laissez-faire model* or *Triple Helix II*, where the three actors are clearly split from one another with strong boundaries and highly limited relations. In this set-up, the industry has the leading role in the generation of innovations, with government and universities having secondary roles. This model is characteristic of the US or the Swedish economy (Park and Leydesdorff, 2010). Finally, the *Triple Helix III model* is an interactive configuration, with dynamic interactions between the three actors and overlapping institutional spheres. This kind of set-up leads to the emergence of hybrid organizations, such as incubators, university spin-offs or strategic alliances, at the interfaces (Park and Leydesdorff, 2010). This type of model has been shown to lead to the most desirable outcomes in terms of knowledge production and generation, and it has been encouraged by governments with the implementation of policies that range from financial assistance to the introduction of specific laws such as the Bayh-Dole Act in the USA (Park and Leydesdorff, 2010).

Previous studies have used the TH framework to explore a wide array of questions ranging from the interaction of the different actors to the application of the TH model to regional setups, comparisons across countries and the performance of the NIS. For example, some studies explore the UIG interactions from the viewpoint of universities to determine the role of UIG contexts in determining the performance of the third role of universities (Kapetaniou and Lee, 2017) and the role of universities in knowledge exchanges in UIG interactions (Chen and Lin, 2017). Other studies have focused on the outcomes of TH interactions; for instance, on the success of Israeli high-tech clusters (Wonglimpiyarat, 2016), on the overall performance of national research in South Korea (Park and Leydesdorff, 2010), on the emergence of regional entrepreneurial ecosystems (Brem and Radziwon, 2017) or on the scientific performance of research institutes in China (Zhang et al., 2019). Another strand of literature has explored the nature of UIG interactions, looking, for instance, at synergies in different geographical, technological and organizational levels (Leydesdorff and Porto-Gomez, 2019), or the R&D network interactions in Korea (Kwon et al., 2012; Lee and Kim, 2016). Some authors have also applied the TH model to regional contexts in order to understand the role of the different actors as well as the UIG interactions in, for example, Wales (Pugh, 2017) or southeast Norway (Elvekrok et al., 2018).

**An extension of the TH model: international and NPO actors**

Recent studies have highlighted the need for an extension of the TH model to include additional dimensions (Leydesdorff, 2012). As a consequence, several studies have moved towards Quadruple and Quintuple Helix models that embed different dimensions of the NIS, such as citizens and stakeholders (Hoglund and Linton, 2018; McAdam and Debackere, 2018), the environment (Carayannis et al., 2018; Gouvea et al., 2013) or international institutions (Kwon et al., 2012; Leydesdorff and Sun, 2009; Lew et al., 2018). Our research question evaluates the importance of international institutions and NPOs in the NIS and explores the interaction of these two actors with the traditional UIG actors.

The increasing permeability of geographical borders has promoted the mobility and circulation of people, knowledge and capital, allowing the internationalization of R&D and increasing the interrelation of innovation across countries (Binz and Truffer, 2017). International collaboration has attracted particular attention in the last few years due to the spectacular rise in the number of such collaborations (Wagner et al., 2019). Pushed by the increase in global competition and the fast pace of technological changes, international R&D collaboration has become a critical way for countries and individual organizations to foster and maintain innovation competitiveness (Chen and Lin, 2017). Previous literature has linked higher citations, higher output and elite scholars with international collaborations (Wagner et al., 2019). In the context of the TH model, existing studies incorporating international actors as a fourth helix have found that international collaboration has had a substantial effect on the dynamics of interaction between the traditional UIG actors. For example, Leydesdorff and Sun (2009) find the international dimension to be a source of synergy, but also a source of uncoupling in the UIG interactions of Canada and Japan. For Italy (in the region of Trentino), Lew et al. (2018) find that international connections play a key role in the acquisition of knowledge and resultant innovations by the local industry. Finally, Kwon et al. (2012) find that R&D bilateral international collaborations between universities and industry increased in Korea, but at the expense of the created synergies not being harvested at national level.

The emergence of the organized civil society and of non-profit organizations, as manifestations of broader social movements, has transformed the economic landscape. NPOs were born as a response to government and market failures in the provision of public goods (Steinberg, 2006). NPOs represent a central part of the social context of modern economies due to their engagement in large-scale social issues (Zimmermann, 2002) and their key role in the delivery of services to society (Al-Tabbaa et al., 2019). NPOs operate in a wide range of fields such as education, health, culture, science or environment (Doh and Teegen, 2002). In the business and economics literature, NPOs are considered as one of the key actors in the global economy, together with corporations and governments (Kourula, 2010).

NPOs are essentially different from government and businesses in their innovation-related characteristics (Fyvie and Ager, 1999). Firstly, NPOs deviate from businesses in their concerns and objectives as well as the values and culture by which they operate (Doh and Teegen, 2002). As compared with businesses, the vision of NPOs is not based on financial targets for the organization but rather on the mission of the organization itself (Doh and Teegen, 2002). While businesses are profit-centric and competitive-driven and conduct innovation as a way to access higher revenues for firms, NPOs are socially driven, participative and cooperative, and profit is not an incentive to conduct innovation (Al-Tabbaa et al., 2019; Fyvie and Ager, 1999). Secondly, while governments are characterized by centralization, bureaucracy and control, NPOs are characterized by flexibility and non-hierarchical values and relationships that affect the way in which innovation is conducted (Edwards and Hulme, 1994). NPOs also differ from governmental bureaucracies in that the purpose of NPOs has to be embraced by contributors/supporters and does not need to be debated and established through the collective political process (Doh and Teegen, 2002). From a stakeholder theory perspective, NPOs are considered discretionary stakeholders, with the attribute of legitimacy but without power or attention over businesses, as compared with the high levels of power and attention represented by governments (Holmes and Smart, 2009).[2]

Previous studies in the public administration literature have also explored and acknowledged the collaboration between NPOs and governments or corporations (Furneaux and Ryan, 2014; Salomon and Toepler, 2015). In this regard, while previous studies have recognized the role of NPOs as actors of the NIS (Holmes and Smart, 2009), no studies have included NPOs as formal actors in the TH model. NPOs have been acknowledged as actors in R&D networks in a few works, such as Wen and Kobayashi (2001) or, more recently, Lew et al. (2018), and as contributors to innovation (Zimmermann, 2002). The contribution of NPOs to R&D and innovation has been widely praised in the pharmaceutical industry, where NPOs have been pioneers in the research of gene therapies and rare diseases (Jarosławski and Toumi, 2019). For-profit firms lack the commercial incentives to develop and research treatments for

[2] As noted by the John Hopkins Comparative Nonprofit Sector Project, in western economies there is a significant financial tie between governments and NPOs as public funding represents a significant source of NPOs' budgets. However, these monetary contributions have not been found to be detrimental to the independence of NPOs (AbouAssi and Bies, 2018), with previous studies not finding an effect of this resource dependence on NPOs' missions or goals (Fraussen, 2014; Verschuere and De Corte, 2014).

rare diseases (i.e. diseases that affect small portions of the population) as the R&D investment is high but the potential profits are low due to the limited number of potential users (Jarosławski and Toumi, 2019).

## 3. DATA AND METHODOLOGY

### Context: the UK nanotechnology sector

Broadly speaking, nanotechnology is the set of technologies that enables the manipulation, study or exploitation of very small (typically less than 100 nanometres) structures and systems as well as the incorporation of these structures into applications (OECD, 2018b). Nanotechnology is considered a key emerging technology (OECD, 2018b) with multiple applications in different technological domains, such as biotechnology and pharmacy, advanced materials and electronics, which has a wide range of applications, such as new cancer therapies, improving the efficiency of fuel production, detecting biohazards or improving the transportation infrastructure (Alencar et al., 2007; US National Nanotechnology Initiative, 2020). Nanotechnology has the potential to significantly improve advanced materials and manufacturing techniques, which are crucial for the competitiveness of national industries, and it is expected to be one of the major future technologies as its applications are regarded as involving radical innovation (Kostoff et al., 2007; US National Nanotechnology Initiative, 2020). The global market for nanotechnology has been growing in the last couple of years at a rate of almost 20% annually, with an estimated market of over USD 90 billion in 2019 (European Commission, 2018).

Because of potential applications to other fields and benefits to society, the development of nanotechnology has received attention from governments and policymakers, which have fostered its progress with different programmes (Lavie and Drori, 2012). Since 2000, governments around the world have invested over USD 67 billion in nanotechnology, and it is estimated that in 2015 the investment (including also private investment) reached a quarter of a trillion (European Commission, 2013). For instance, the EU highlights nanotechnology as one of the four key enabling technologies (KETs), essential to the competitiveness and new market expansion of EU industries, and supports and prioritizes the development of nanotechnologies in the Horizon 2020 framework (European Commission, 2018). As an enabling technology, nanotechnology is relevant to different pillars of the EU's Horizon 2020 programme (H2020) and helps to address some of the EU's key societal challenges, such as medical needs of an ageing population, more efficient use of resources and development of renewable energies (European Commission, 2018). Nanotechnology projects represent about 8.8% of H2020 programmes, which are mostly dominated by universities (44% of projects), governmental research institutes (30%) and industry (23%) (European Commission, 2018).

In this context, the UK stands out as a leading European power in terms of research and development of nanotechnology (Goves, 2013; Munari and Toschi, 2011). The UK possesses a large base of firms dedicated to nanotechnology, having the second-largest number of nanotechnology firms in Europe after Germany (Materials UK, 2010). Companies such as 2-DTech, BREC Solutions, Efficiency Technologies, Graphitene and Phase Focus are at the forefront of nanotechnology production. The UK has shown a strong patenting and publication record in the field of nanotechnology, leading the EU rankings with Germany, as well as being among the top world nations after China, the US, South Korea and Japan. While the US and China alone produce 50% of all publications in nanotechnology, the UK follows closely behind South Korea (8.1%), Germany (7.6%) and Japan (7.4%) with 5.1% of total publications in nanotechnology (Web of Science, 2019).

**Data**

For our empirical analysis, we make use of data in publications in the field of nanotechnology extracted from the Web of Science databases (Web of Science, 2019). We measure collaboration with co-authorship networks at the organizational level, i.e. we evaluate the meso-structure of scientific collaboration networks (Graf and Kalthaus, 2018). As indicated in the literature review, while there are different products of collaboration, scientific publications are the best indicator of collaboration in the knowledge generation process of emerging industries such as nanotech. In the context of the Triple Helix model, co-authored publications have been widely used and validated as a proxy for the dynamics of collaboration (e.g. Guan and Zhao, 2013; Leydesdorff and Sun, 2009; Park and Leydesdorff, 2010; Zhang, 2019).

We identify the relevant publications for the construction of the network using the Web of Science categorization by selecting journal articles in English that belong to the category “Nanoscience & Nanotechnology”. Our search is limited to the period 1977–2018, and to those papers for which at least one of the affiliations of the authors is in the UK. This provides a total of 19,437 publications. This data was processed and manually checked to identify basic information such as journal, publication date, keywords and research areas, authors’ affiliations and type of organization (university, government, industry, NPOs and foreign institutions), citations and usage count. We removed those publications for which it was not possible to obtain data on the affiliation for at least one of the authors, with a resulting sample of 17,868 publications, which corresponds to 2,823 different institutions and 47,522 authors (see Table 1 for a full description). The number of publications is unevenly distributed throughout the period of interest. As shown in Figure 2, the number of publications in the field of nanotechnology increased exponentially since the early 2000s, with the number of publications per year doubling every five years to reach over 1,900 in 2018.

## Methodology

To understand the interactions between different actors in the NIS, we rely on social network analysis and the extended TH model.

### *Social network analysis*

Social network analysis (SNA) has been particularly popular among economics and management scholars to study collaboration networks, knowledge spillovers or the development of technologies (Arranz et al., 2020). SNA is an excellent tool for understanding and disentangling the complex relations between different economic actors as it allows the distinguishing of structures in the NIS according to the relations between the system's components, rather than the attributes of individual cases (Newman, 2001; Guan and Zhao, 2013). A network analysis approach can help with understanding the evolution of the interactions and relations that make up the NIS (Sena et al., 2019). Modelling the interactions of UIG, foreign and NPO actors as a complex network allows the examination of NIS properties and the assessment of the effect of those interactions on the overall performance of the NIS and the performance of individual actors within it (Sena et al., 2019). Moreover, SNA understands observed structures and attributes of the networks as pathways for information exchange and partnership development, which is of interest to researchers studying the interactions of the NIS (Sena et al., 2019).

A network can be defined as a set of nodes connected by a set of links (Borgatti and Halgin, 2011). For the NIS network, the nodes are the different institutions (UIG, foreign and NPOs) undertaking research and publishing papers, and the links are formed through the co-authorship of papers, so that two institutions are connected if their researchers have published a paper together.

For each year in our dataset, we construct a matrix in which we record all the possible co-authorship relations between all the institutions in our dataset. The adjacency matrix (A) records the existence of a co-authorship relation between a pair of institutions; for a given entry $a_{ij}$ of the adjacency matrix $A$, $a_{ij}=1$ if institution $i$ and institution $j$ have published a paper together in a particular year $t$, and $a_{ij}=0$ otherwise (Newman, 2001; Jackson, 2008). Thus, our network data consists of a sequence of $N_t \times N_t$ adjacency matrices, for t=1977, …, 2018. The construction of the network, as well as the obtaining of indicators both at the network and node levels, is done with the software environment for statistical computing R, and in particular with the aid of the igraph library.

We analyse the network at two levels: first, at the aggregate level, where the aim is to characterize the overall network, paying special attention to the structure of the network, and second, at the node level, where the position of each institution in the network is studied, with centrality measures being the core of the analysis.

At the aggregate level, we explore the following measures: network density, graph centrality, network diameter, average path length, cliquishness and clustering coefficient. *Network density* quantifies the proportion of all possible connections that the network contains. It is the ratio between the actual number of links of the network and the total possible number of links, and it is calculated as the sum of all non-zero entries in the adjacency matrix divided by the total number of entries, *n(n-1)* (Newman, 2001).

*Graph centrality* indicates the extent to which the nodes in a network are close together (Freeman et al., 1979). It depicts the relative dominance of a node in the network by considering the magnitude to which the centrality of the most central point exceeds that of the other nodes in the network (Freeman et al., 1979). The perfect centralized network, often referred to as "star", has only a single node as a receiver/sender of information from/to the rest of the nodes in the network. This single node is connected to every other node in the network and acts as the intermediary between all the nodes, which are only connected to it and to no other node (Freeman et al., 1979). The centrality of a network, based on node degree, is defined in Freeman et al. (1979):

$$C_D = \frac{\sum_{i=1}^{n}[C_D(p^*) - C_D(p_i)]}{n^2 - 3n + 2}$$

Where $C_D(p^*)$ is the largest value of degree centrality, $C_D(p_i)$ is the degree centrality of node $i$, and $n$ is the number of nodes in the network.

The distance between two nodes is the number of links in the shortest path (also known as geodesic path) between them (Jackson, 2008). The distance between a pair of institutions in the nanotechnology network is of interest as it determines the speed and costs of information and knowledge diffusion. Two of the main indicators of distance are the diameter and the average path length. The *diameter* of a network is the largest distance between any two nodes

(Jackson, 2008). The *average path length* or characteristic path length is the average over the shortest paths between all pairs of vertices (Jackson, 2008).

To understand the level of integration of the different institutions in the network, we employ the number of cliques and clustering coefficient measures. A *clique* is a subset of a network where every possible pair in the subset is connected by a link, meaning every node is connected to every other node via a direct connection (Jackson, 2008). The *clustering coefficient* or transitivity measures the probability that adjacent vertices of a node are connected (Newman, 2001). Newman (2001) calculates the clustering coefficient as the ratio of triples that form a triangle to the number of triples in the network. The clustering coefficient counts the number of institutions that share the same third-party institutions as co-authors.

At the node level, we study degree, betweenness, closeness and eigenvector centrality. *Degree centrality* assesses the number of links that each node has. It provides a measure of how connected a network is. Freeman et al. (1979) proposes a normalized measure of degree centrality, in which the node degree of each institution is divided by the theoretical maximum of links.

*Betweenness centrality* measures how important a node is in terms of connecting other nodes (Jackson, 2008). It is measured as the number of geodesic or shortest paths that go through a particular node computed in its normalized form, i.e. with a score in the range of [0,1] (Freeman et al., 1979):

$$C'_B(p_k) = \frac{2C_B(p_k)}{n^2 - 3n + 2}$$

where $n$ represents the number of links in the network and $C_B(p_k)$ is the sum of all partial betweenness of a particular node $p_k$. Note that when $p_k$ is the only geodesic path connecting two nodes, the score $C_B(p_k)$ is increased by 1, while if there are alternative geodesic paths, the score grows proportionately to the number of times that $p_k$ is part of the alternative shortest paths (Freeman et al., 1979). From an information flow perspective, betweenness can be interpreted as measuring the potential a node has to control an information flow; for example, in the case of a star network, the central node, which connects every node in the network with others, has a relative betweenness value of 1, while the rest of the points have a score of 0.

*Closeness centrality* measures how easily a node can reach others (Jackson, 2008). It is defined as the sum of distances from that node to all other nodes in the network, where the distance is measured as the number of links contained in the shortest path (Freeman et al., 1979); in other words, it measures the number of steps required to reach every other node. The concept of closeness is related to the cost efficiency and time incurred in the transmissions of information, where it can be interpreted as the expected time until the arrival of a particular piece of information that is flowing in the network (Newman, 2001). In this context, a node is considered as central if all of its shortest paths to every other node in the network are minimal so that it will tend to receive the information sooner than other nodes with lower scores (Sabidussi, 1966). Therefore, closeness is measured as the inverse of the sum of all geodesic distances from a particular node to all of the other nodes; a node is considered to be central if the score in closeness is high. Beauchamp (1965) refined this measure by normalizing Sabidussi's index:

$$C'_C(p_k) = \frac{n-1}{\sum_{i=1}^{n} d(p_i, p_k)}$$

where $n$ is the number of nodes in the network, and $\sum_{i=1}^{n} d(p_i, p_k)$ is the number of links in the geodesics connecting node $p_i$ and $p_k$.

Finally, *eigenvector centrality* determines the centrality of a node in the network by exploring how important, central and/or influential the node's neighbours are. It is calculated with the values of the first eigenvector of the network's adjacency matrix. The values in the eigenvector are extracted from the centrality of the nodes to which a particular institution is connected to, that is, the centrality of a node is proportional to the sum of the centralities of the nodes it is linked to. Bonacich (1972) defines eigenvector centrality as the sum of the centrality of its neighbours:

$$\lambda C_i^e(g) = \sum\nolimits_j g_{ij} C_j^e\,(g)$$

where $C^e$ denotes the eigenvector centrality associated with a network $g$, and $\lambda$ is a proportionality factor. Eigenvector centrality identifies as central nodes those which are connected to many nodes, which are in turn also connected to many others.

## 4. ANALYSIS

In this section, we explore the main characteristics of the networks formed by co-authorship of nanotechnology scientific papers and discuss the flows of information across different actors in the NIS.

### Network aggregate level

The measures discussed below investigate the network from a macro level, describing its broad properties and structure.

We begin the analysis by looking at the evolution of the number of nodes and links of the UK nanotechnology co-publication network. It is worth noting that for the early years of our data (ca. 1977–1995), there are gaps in the network. This is because during those years there were no co-authored publications, which indicates the infancy of the nanotechnology field in those years. The network connections and number of publications take off from 1995 onwards. Taken as a whole, our network is one large component.[3]

Similar to the above-mentioned growth in the number of papers, our data also displays an exponential growth in the number of institutions publishing in the field of nanotechnology (with a total of 2,823 different institutions in the period of interest). While universities are responsible for the bulk of scientific output, from the 2000s onwards the industry, government and NPOs start to take part in nanotechnology research (Figure 3). Non-university institutions display similar levels of participation and similar evolution trends. Regarding the number of links, measured in co-authored papers, the growth in the number of collaborations also displays an exponential pattern. On average, two-thirds of these links are collaborations with foreign institutions (Figure 4).[4]

Figure 5 shows the evolution of graph centrality and network density. In the early years of our sample, there are very few connections and published papers in nanotechnology, which results in very erratic behaviour and few points in both series. From 1995 onwards, the graph centrality indicator shows an upward trend, reaching the value 0.5 in the last year of the series. As for the network density indicator, we can observe that already from the late 1980s it follows a decreasing path, getting very close to zero in the contemporary years.

To evaluate the level of connection between institutions in our network, we explore the diameter and the average path length. Figure 6 shows that both the diameter and the average path length of the network have increased over time. Until the mid-1990s, the network was relatively small, in the sense that in a maximum of two steps, any node was connected to any other node. From the mid-1990s onwards, with the boom in the number of publications and the increase in participation of different institutions both nationally and internationally, the network has considerably expanded, to double the scores in average path length and diameter.

To examine the level of integration in the network we measure the clustering coefficient. As shown in Figure 7, the clustering coefficient decreases with time, reaching the range of 0.15 in the 2010s. As a consequence of the growth in the number of network participants, the clique number shows an upward trend. While it displays a spike in 2017, in the later years of the series, the clique number is around 10 to 20. This means that about 10–20 actors in the network are

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[3] We dropped 11 institutions that were not connected to the main component and that were only appearing in the early years of our database in small separated components.

[4] For a breakdown of the type of international institutions, please see Table A1 in the Appendix.

connected to each other directly, out of over 1,000 different institutions taking part in the network in the later years.

### Network node level

The measures discussed in this subsection investigate the network from a micro level, allowing us to compare different nodes and types of institutions and to examine the relation of a particular node with the overall network. As explained in the methodology section, we focus on different dimensions of centrality. Since at the node level there is a high variation when considering the network in each year separately, we aggregate the network over time blocks.[5] Figures A1 to A4 in the appendix show the aggregate and average level of degree, betweenness, closeness and eigenvector centrality, respectively. These figures show that UK universities are the largest contributor to the total sum of the different normalized centrality measures. At national level, government, corporations and NPOs contribute at comparable levels to the total sum of degree, betweenness and eigenvector centrality, while corporations are ahead of government and NPOs in contributing to aggregate closeness centrality. These results are also reflected in Table A2 in the appendix, which provides a ranking of the top ten institutions in terms of the different dimensions of centrality. Not surprisingly, we found top UK universities among the most central institutions.

### Interaction of NIS institutions

As explained above, we find that the largest portion of scientific articles is generated by universities. Thus, we first focus on the number of links which involve a UK-based university. Figure 8 illustrates that a large fraction of the total links involving universities is due to collaborations with non-UK institutions. This fraction appears to be much larger than the number of links within UK universities, even though both graphs show a clear upward trend.

While the total number of links between universities, government, corporations and NPOs is considerably smaller than the number of links within UK universities, Figure 9 shows that collaborations with the government, the industry and NPOs are roughly of equal importance for universities. Again, all three graphs appear to follow an upward trajectory over time, with a particularly strong increase starting approximately in 1995 for University–Industry and University–Government interactions and about ten years later for University–NPO interactions within the UK.

[5] We analyse the network in six blocks as follows: 1977–1988, 1994–1998, 1999–2003, 2004–2008, 2009–2013 and 2014–2018.

Figure 10 illustrates the overall number of links between UK universities and NPOs by considering not only collaborations with national but also international NPOs. As is evident from the graph, collaborations with international NPOs are of much higher importance to UK universities in comparison with collaborations with national NPOs. Moreover, this gap seems to be widening over time, as the number of links between domestic universities and foreign NPOs increases much faster than the corresponding number of links within the UK.

Figure 11 shows the evolution of the number of links between domestic government and corporations and foreign institutes over time. While the total number of links between these players stays far behind the number of collaborations between domestic universities and foreign institutes, the graphs nevertheless show an upward trend with accelerating growth rates towards the end of the time frame considered here. Comparing Figures 9 and 11 further shows that the volume of collaborations with foreign institutes is of a similar size to the number of collaborations with domestic universities, both for the UK government and UK corporations.

## 5. DISCUSSION

The nanotechnology network of R&D collaboration in the UK has grown substantially since its first publications in the 1970s. This has been reflected in an exponential increase in the number of papers as well as nodes and links, which have grown proportionally in number.

Overall, these measures indicate that the nanotechnology network has evolved from a small core of institutions to a much larger network that includes distant and not-well-connected collaborators. This was supported by the increasing trajectory of the diameter, cliquishness and the average path length, and the decrease in the network density and clustering over time. Our analysis also suggests that the UK nanotechnology network has grown in such a way that there is a core of institutions that are well connected to each other but that at the same time are connected to distant collaborators. As a whole, these measures depict the nanotechnology network as one with a low level of engagement of nodes and a low level of cohesion and integration of the network. In terms of knowledge diffusion and access to information, our analysis suggests that the increase in complexity and in the number of participants in the nanotechnology network has come hand in hand with a polarization of the access to information and knowledge contained in the network. The current structure of the network particularly benefits institutions at the core of it (i.e. those with higher node centrality measures) in terms of access to information and knowledge. As explained by Graf and Kalthaus (2018), this kind of structure fosters “national champions”.

These results contrast with previous studies at both the macro level, such as international collaboration between countries (e.g. Graf and Kalthaus, 2018) and at the micro level, such as co-authorships at the researcher level (Knights and Scarborough, 2010), which display a much higher level of connection and cohesion in the networks of scientific collaboration. There might be several explanations for this disparity. First, as pointed out by Borgatti and Halgin (2011), organizations display a recurrent behaviour in establishing partnerships, so that organizations are more reluctant to collaborate with others outside their current core of partners, thus explaining the isolation of more peripheral nodes. Second, a possible reason for this disparity in findings might be partly explained by the design of our study which focused only on UK institutions, favouring a core-periphery structure.

At the node level, our paper finds, not surprisingly, that universities are at a central position in the nanotechnology network. Across the four measures of centrality (degree, betweenness, closeness and eigenvector centrality), we consistently find that universities have the highest centrality score. The central position held by universities provides them with a very fast connection to other institutions in the NIS as well as with access to a larger amount of and more diverse information (Borgatti and Halgin, 2011; Gulati, 1995). All in all, our node-level analysis confirms previous literature that points to universities as important engines of knowledge generation (Ardito et al., 2019), and highlights the research mission of universities (Kapetaniou and Lee, 2017).

Regarding the interaction between different NIS actors, we find that universities mostly collaborate with other universities, which reinforces their predominance in the core of the network. Moreover, while having many foreign collaborators, our analysis shows that the frequency of interaction with these foreign actors is rather low (Borgatti and Halgin, 2011).

As compared with intra-university connections, the interactions of universities with other NIS actors is not very pronounced. Universities have similar levels of interaction with industry and government. While these interactions validate the traditional TH model, our analysis also finds a growth in the importance of NPOs as actors of the NIS, especially from 2010 onwards. Interestingly, while the role of UK NPOs is not very prominent (yet) in the NIS, we find that UK universities profusely interact with foreign NPOs to the point that these interactions are much greater than the combined number of interactions with UK industry and government actors. This finding is in line with recent research in the biotech and pharmaceutical areas, where NPOs are being praised for their contribution to innovation and knowledge generation (Jarosławski and Toumi, 2019; Lew et al., 2018).

Supporting previous studies that highlight the importance of the foreign actor as pivotal in the NIS (Lew et al., 2018; Wagner et al., 2019), our analysis reveals a high level of bilateral interactions between foreign actors and UK government, and foreign actors and UK industry. These interactions are comparable to the UI and UG interactions, and in the most recent years higher. Our study thus corroborates recent work in the TH literature that has included extra helices (such as the international or stakeholders dimension) in the model (e.g. Hoglund and Linton, 2018; Lew et al., 2018), or that more generally has acknowledged the increasing diversity of the NIS and the necessity to reflect this in the number of helices (Leydesdorff, 2012).

## 6. CONCLUSION

This study has explored the evolution of the UK's nanotechnology scientific collaboration network since its inception in the 1970s taking an NIS and SNA approach. We find that the network has grown larger and wider over the years. Our analysis reveals that universities are behind the large bulk of research in nanotechnology and that they are also the main actors at the centre of the network, with other players such as government or industries having a peripheral position. Our research has implications for academics and policymakers alike.

The implications for academia are twofold. First, our study stresses the dynamic nature of innovation systems, in which the ever-changing interactions between actors and the entry of new actors facilitate the generation of new knowledge. Moreover, it highlights the importance of revisiting and adapting the existing lenses of analysis. Our paper engages in current conversations of the NIS literature (e.g. Hoglund and Linton, 2018; Leydesdorff, 2012; Lew et al., 2018) regarding the necessity to revisit the NIS paradigm that, as shown in this paper, falls short in capturing the complexity that the innovation systems have grown to. Second, this paper enriches recent literature on the extended TH model by confirming international actors as key collaborators of the NIS and by unveiling NPOs as emerging actors of it. While NPOs have been largely neglected by current TH literature, our aggregate-level and individual-level network indicators suggest that NPOs played a similar role as government and industry in recent years. Therefore, our paper suggests that these two extra dimensions to the traditional TH model are helpful for a better understanding of the interactions and the interrelations in the NIS.

From the point of view of policymakers, our paper flags the growing disequilibrium in the NIS, where universities bear the weight of generating knowledge while industry and government have a residual role. If, as pointed out by the OECD (2018a), the industry–science links are a key contributor to innovation performance, we suggest UK policymakers revisit their existing policies to foster increased interaction between UIG and to promote the role of industry and governments in the generation of innovations. Moreover, given the increasing importance of NPOs as institutional actors of the NIS, the UK government should closely follow the developments in the upcoming years and plan accordingly. Governments should make sure there is no competition with NPOs (see the literature on public provision of services, e.g. Coule and Patmore, 2013), but rather synergies that foster the interactions within the NIS.

From an international lens, our paper also suggests that the current idea of an innovation system coordinated at the national level might be outdated as foreign institutions are increasingly having a prominent role in the national innovation system. Based on our analysis, we recommend policymakers set an agenda to secure integration in international research networks and to make sure the UK is embedded in those networks (Graf and Kalthaus, 2018). What is more, linking with recent discussion post-Brexit (Wilsdon, 2020), we suggest that UK policymakers should undertake a dual approach in which they nurture the already existing informal relations with EU NIS actors and actively engage with European institutions to explore new formal collaborations between the UK NIS and the EU NIS, exploiting the existing informal links (Fernandez-Esquinas et al., 2016).

As a final note, we would like to point out some of the limitations of this study and some possible future avenues of research. Our study only observes collaboration based on co-authorships. While being a well-established indicator of scientific collaboration, it requires institutions to actually produce a scientific article as an output for their collaboration. This conceptualization might be missing collaborations in terms of co-patenting and alliances or R&D projects, where no paper is generated. Future research might want to consolidate collaborations at the co-publication level with that of co-patenting or R&D projects/alliances. Additionally, our study has focused on the UK, but it would be interesting to include other countries and provide a comparative analysis of the structure of NISs across different countries.

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## TABLES

### Table 1. Description of the sample.

| | |
|---|---|
| Number of documents | 17,868 |
| Period | 1973 - 2018 |
| Number of institutions | 2,823 |
| Number of Authors | 47,522 |
| Documents per Author | 0.376 |
| Authors per Document | 2.66 |
| Co-Authors per Documents | 5.92 |
| Collaboration Index | 2.7 |
| Average citations per documents | 32.73 |

# FIGURES

**Figure 1. UIG interactions.**

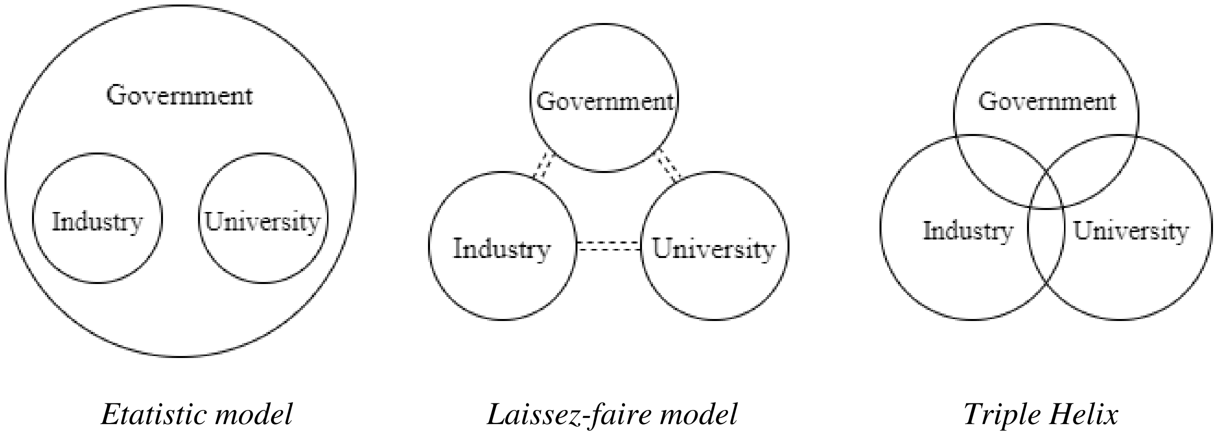



**Figure 2. Evolution number of papers.**

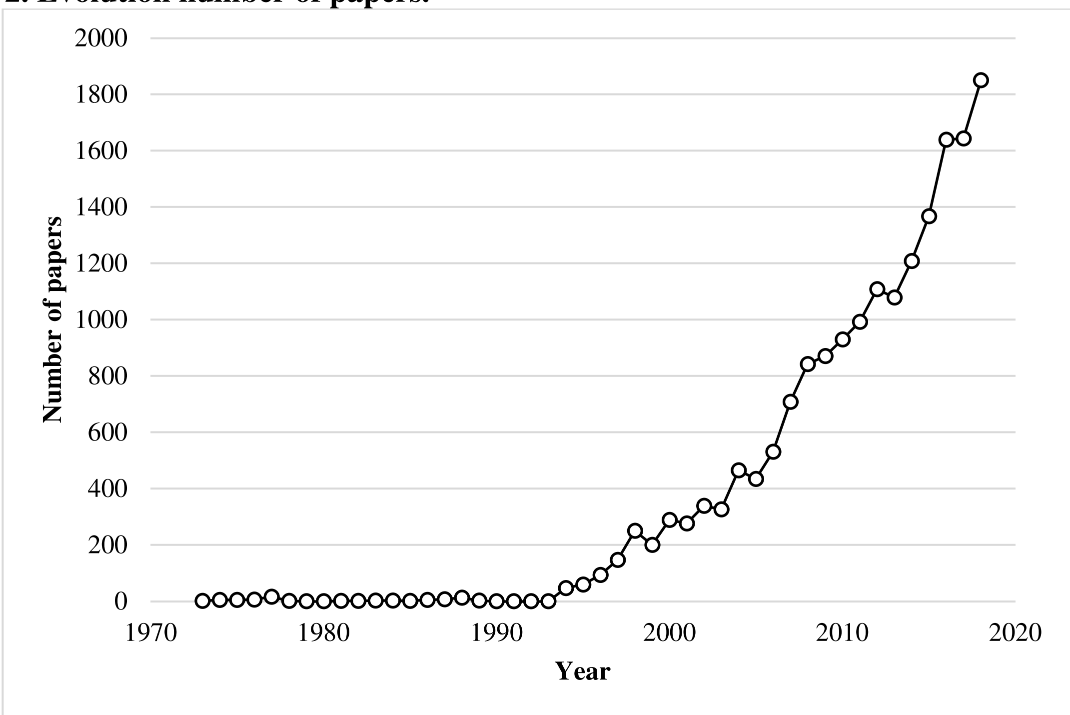


**Figure 3. Evolution number of network participants (number of nodes).**

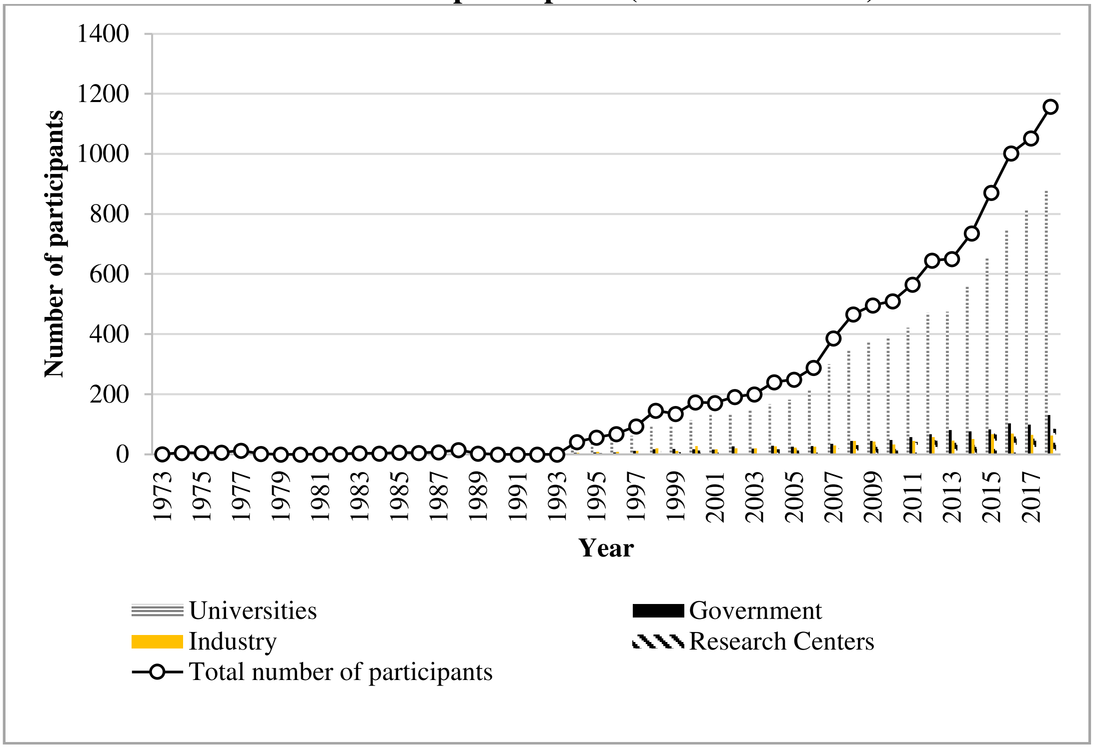



**Figure 4. Evolution number of network collaborations (links).**

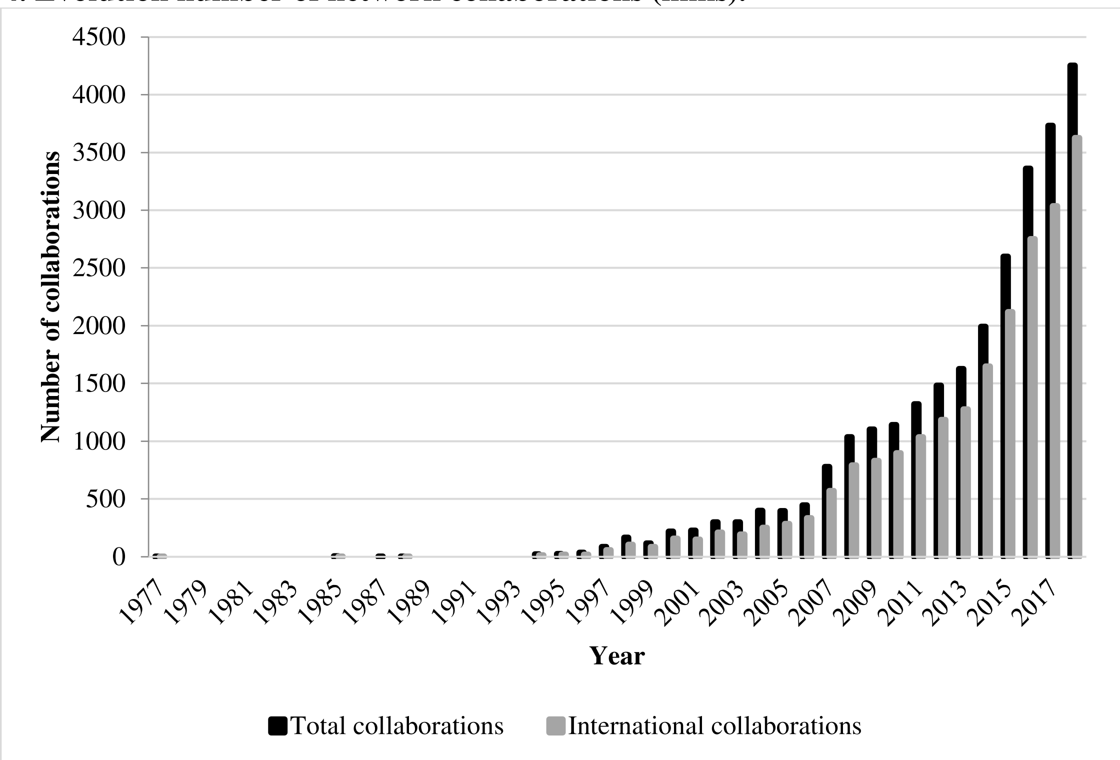


**Figure 5. Evolution of density and graph centrality.**

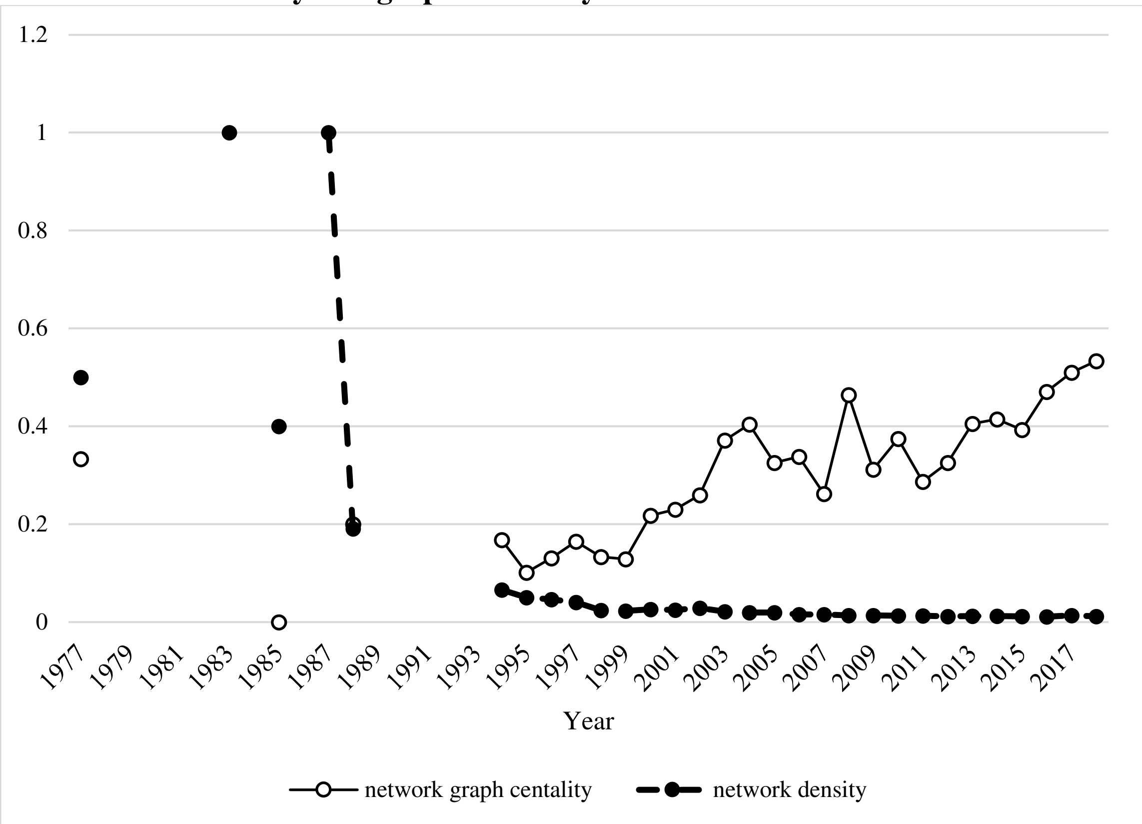



**Figure 6. Evolution of network diameter and average path length.**

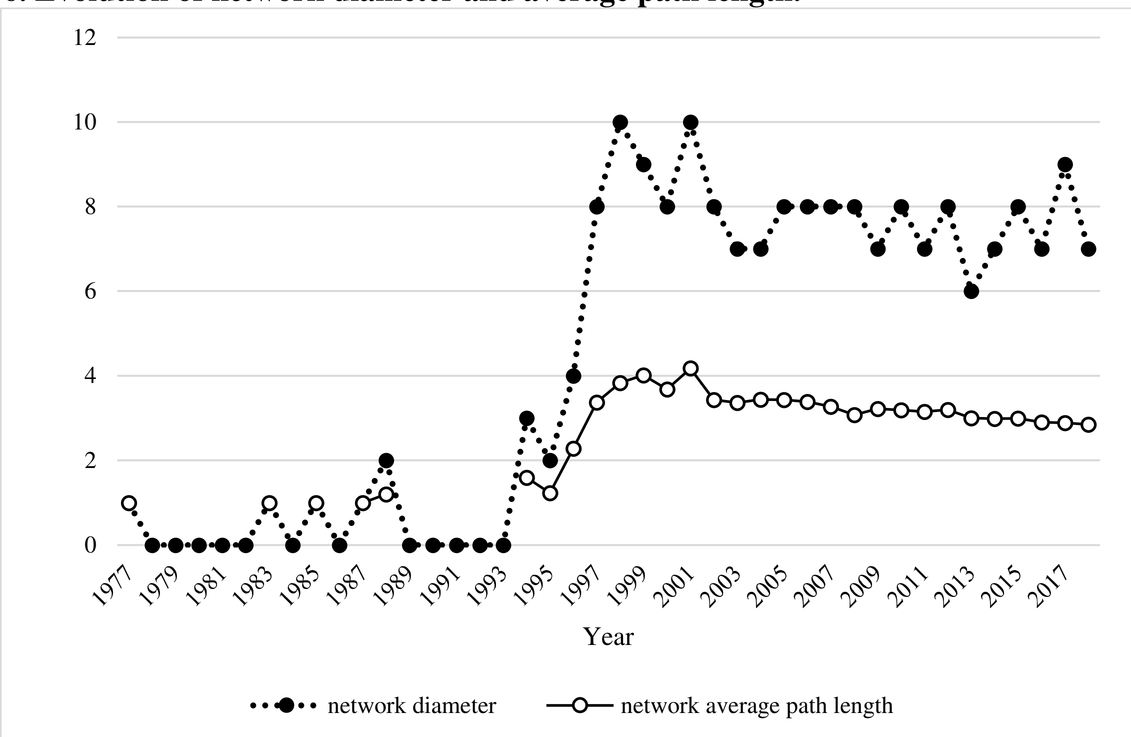


**Figure 7. Evolution of cliquishness and clustering coefficient.**

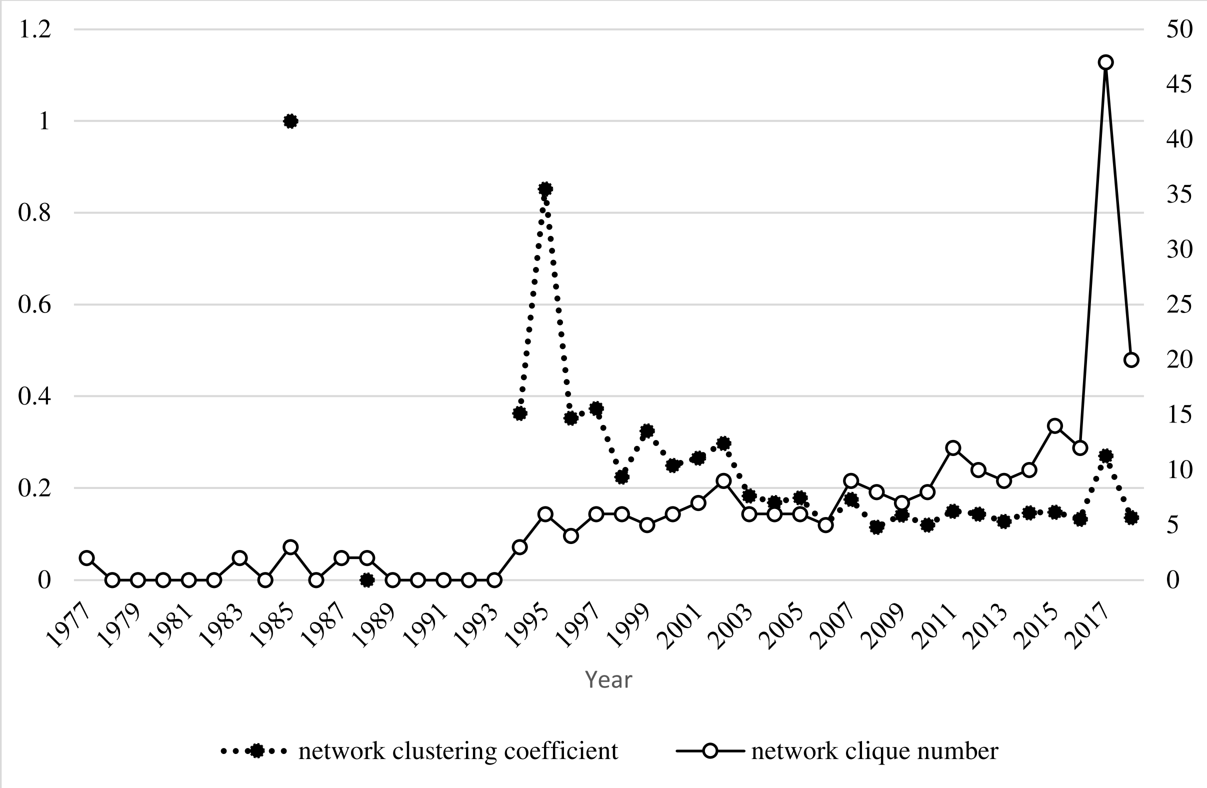


**Figure 8. Evolution number of links within UK Universities and between UK Universities and Foreign Institutes.**

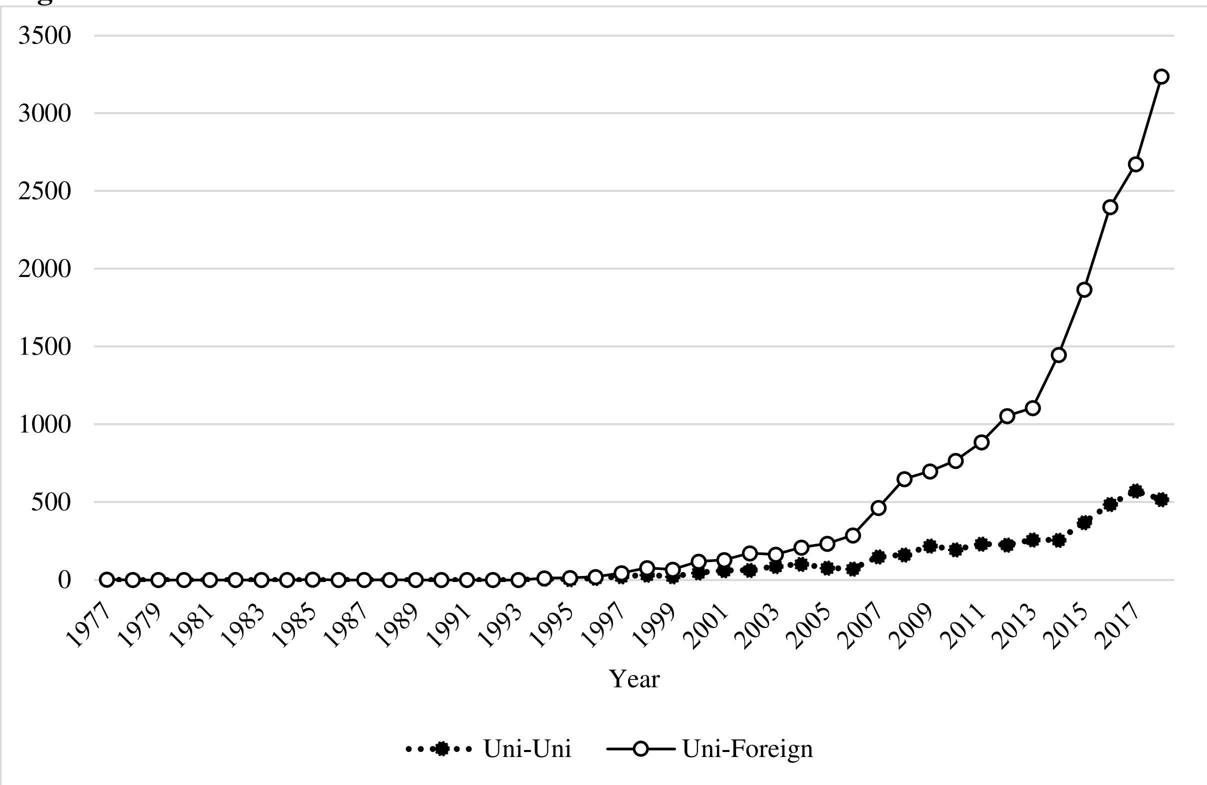



**Figure 9. Evolution number of links between Universities, Industry and NPOs within the UK.**

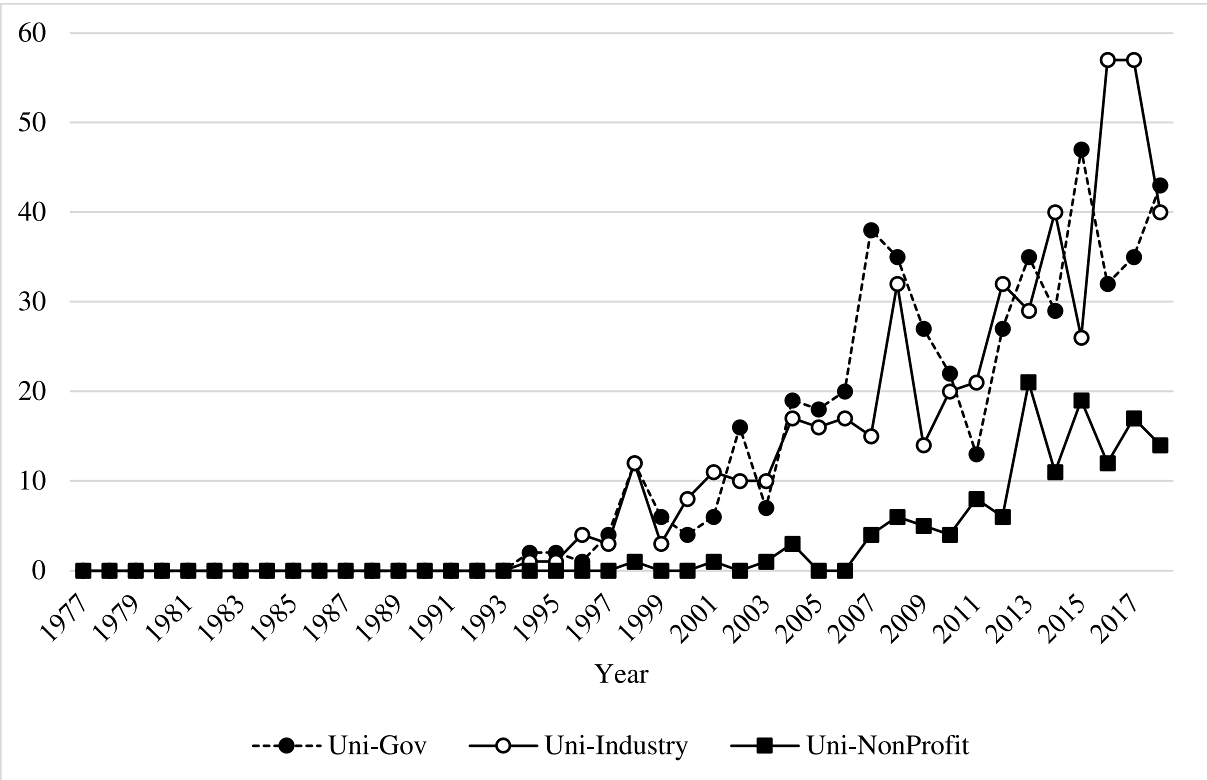


**Figure 10. Evolution number of links between UK Universities and domestic and Foreign NPOS.**

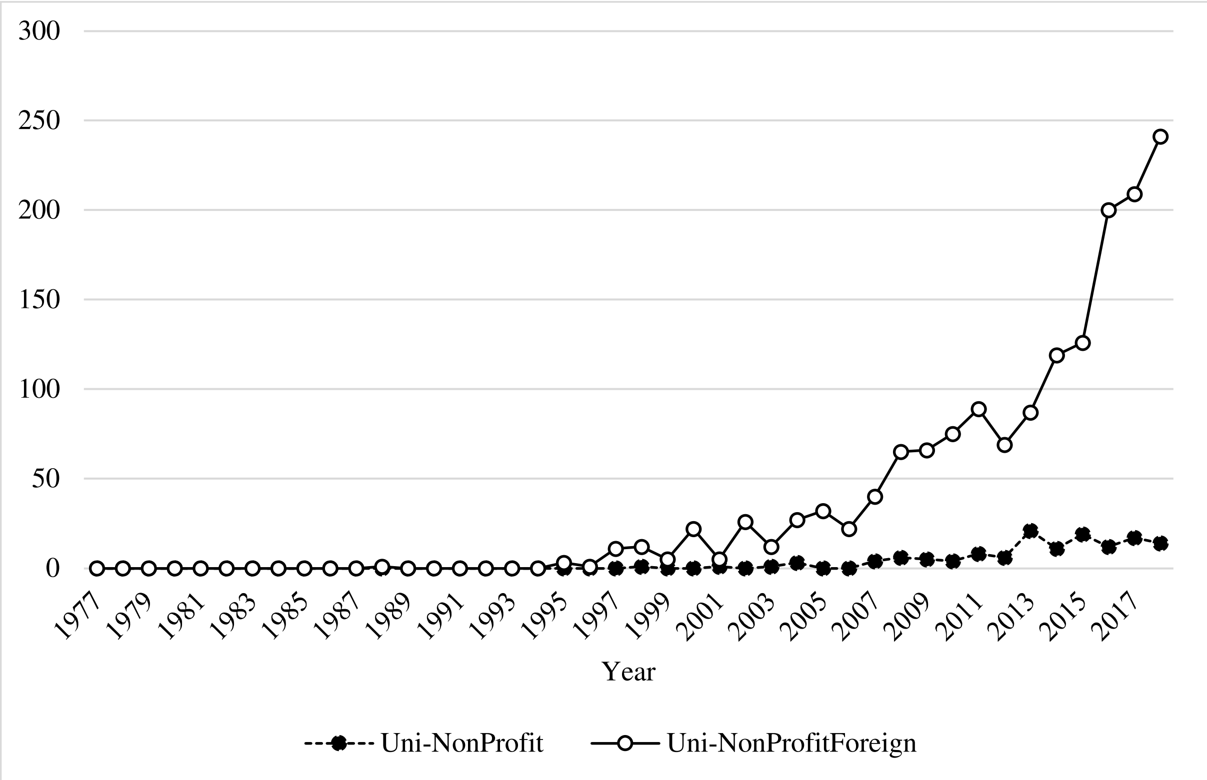
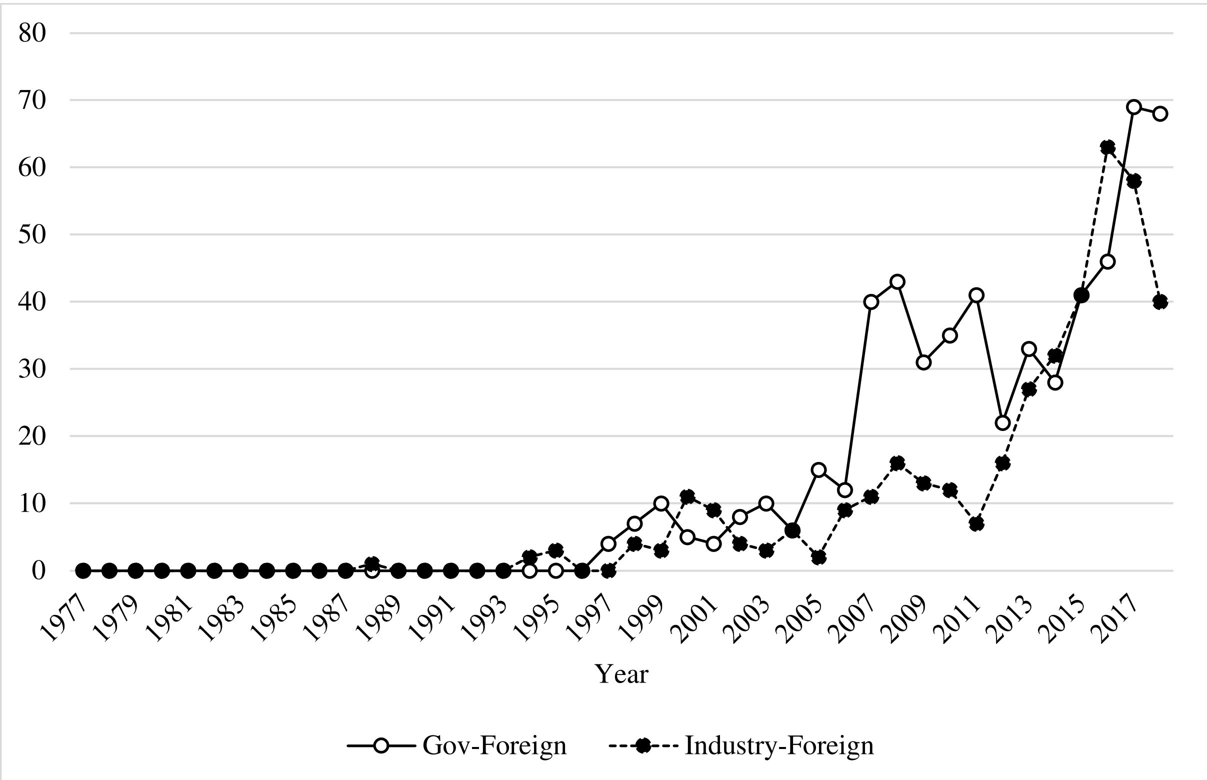



**Figure 11. Evolution number of links between UK Government, UK Corporations and Foreign institutes.**



**APPENDIX**
**Tables**

**Table A1. Decomposition of international actors by type of institution.**

| | % Universities | % Government | % Industry | % NPO |
|---|---|---|---|---|
| 1977-1988 | 55.6 | 22.2 | 11.1 | 11.1 |
| 1994-1998 | 66 | 12.9 | 10.2 | 10.9 |
| 1999-2003 | 73 | 11.6 | 9.4 | 6 |
| 2004-2008 | 75.4 | 9.3 | 7.4 | 7.8 |
| 2009-2013 | 71.7 | 11 | 8.6 | 8.6 |
| 2014-2018 | 72.1 | 11.7 | 6.8 | 9.5 |

**Table A2. Top 20 institutions in terms of centrality.**

| | Degree centrality | | Betweenness centrality | | Eigenvector centrality | | Closeness centrality | |
|---|---|---|---|---|---|---|---|---|
| 1 | University of Cambridge | 1.5 | University of Cambridge | 0.23 | University of Cambridge | 1 | University of Cambridge | 0.59 |
| 2 | University of Oxford | 0.98 | University of Oxford | 0.13 | University of Oxford | 0.79 | University of Oxford | 0.56 |
| 3 | Imperial College | 0.88 | Imperial College | 0.13 | Imperial College | 0.72 | Imperial College | 0.56 |
| 4 | University of London | 0.76 | University of London | 0.11 | University of London | 0.56 | University of London | 0.56 |
| 5 | University Manchester | 0.56 | University Manchester | 0.08 | University of California | 0.46 | University Manchester | 0.54 |
| 6 | University of Southampton | 0.47 | University of Birmingham | 0.05 | University of Southampton | 0.43 | University of Birmingham | 0.53 |
| 7 | University of California | 0.44 | University of Southampton | 0.04 | University Manchester | 0.38 | University of Southampton | 0.53 |
| 8 | University of Birmingham | 0.39 | University of Nottingham | 0.04 | US Department of Energy | 0.34 | University of California | 0.52 |
| 9 | University of Nottingham | 0.34 | University of Sheffield | 0.04 | Max Planck Institute | 0.29 | University of Nottingham | 0.52 |
| 10 | Chinese Academy of Sciences | 0.31 | University of Leeds | 0.04 | Chinese Academy of Sciences | 0.28 | University of Sheffield | 0.52 |

## Figures

**Figure A1. Evolution of degree centrality: aggregate (left) and average (right).**

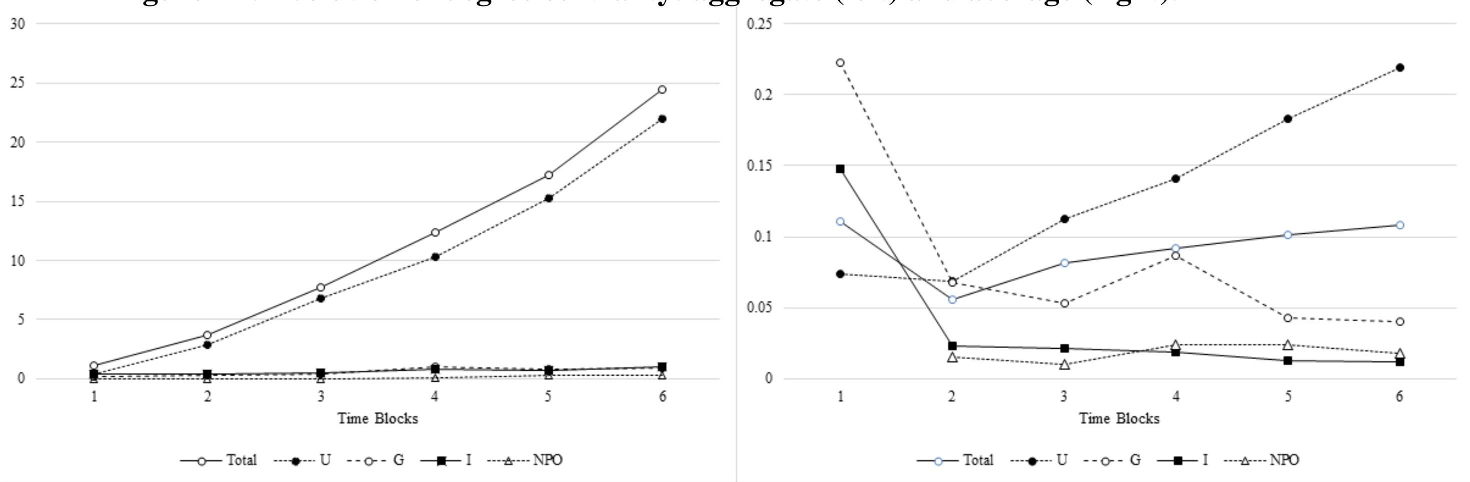



**Figure A2  Evolution of betweenness centrality: aggregate (left) and average (right).**

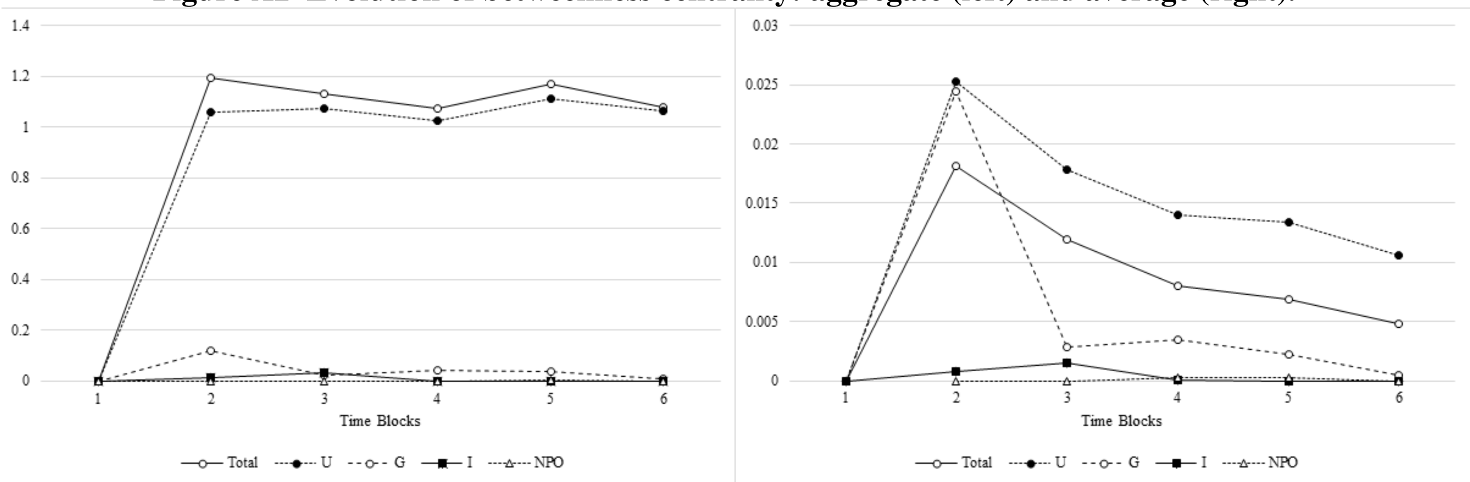


**Figure A3. Evolution of closeness centrality: aggregate (left) and average (right).**

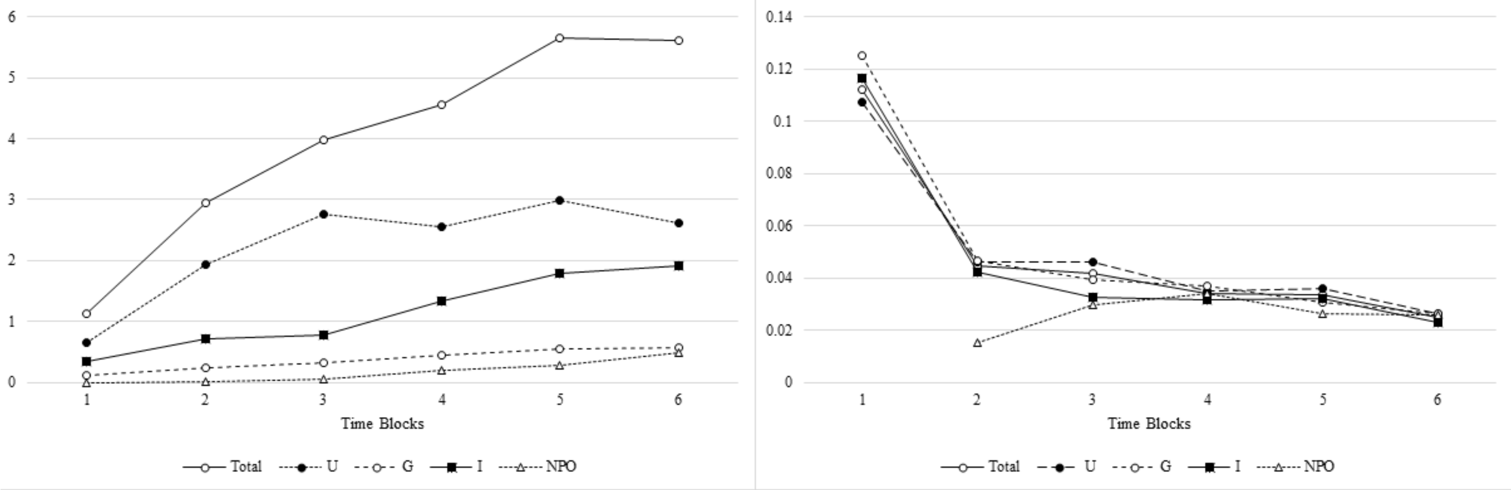



**Figure A4. Evolution of eigenvector centrality: aggregate (left) and average (right).**