Assessing the role of triple helix system intermediaries in nurturing an industrial biotechnology innovation network

Jack Barrie Girma Zawdie Elsa João

University of Strathclyde

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Abstract

The rate of transition to a circular economy would largely be influenced by how successfully sustainable niche innovation can be developed and adopted. This paper measures and evaluates the effectiveness of employing a triple helix-based system intermediary as a policy tool for nurturing a niche innovation network in line with circular economy transition. This was achieved through a complete social network analysis of a national industrial biotechnology innovation network, in which the organisation functioning as network manager was innovatively structured as a triple helix-based system intermediary. Through unique access to the entire national industrial biotechnology niche network, a large set of primary data was collected on 13 types of relational ties related to innovation between all 64 public sector, industry and academic niche network member organizations. The impact of the triple helix-based system intermediary on the level of cohesion, presence of cohesive subgroups and centralization of the niche network was empirically measured. As such, the effectiveness of the intermediary in undertaking key nurturing activities of building the network, facilitating shared learning and raising expectations were evaluated. This allowed for the most comprehensive empirical study to date on a niche innovation network and the role of system intermediaries in circular economy transition. The results of the analysis demonstrate the profound nurturing effect that the introduction of a triple helix-based system intermediary has had on the network. In particular, the results appear to confirm the effectiveness of the intermediary with regards to increasing knowledge and resource flows amongst triple helix institutions as well as between regime and niche actors.

Keywords: Circular Economy; Strategic Niche Management; Triple Helix; Innovation; Innovation Policy; Industrial Biotechnology

1. Introduction

The transition to a circular economy is increasingly being recognized as a necessary development to achieve a sustainable society. A circular economy may be defined as an economic system which is "restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times" (Ellen MacArthur Foundation, 2015, p. 2). However, literature on the topic of circular economy has overwhelmingly focused on understanding the barriers to individual businesses rather than how macro scale systemic barriers may be overcome (Geissdoerfer et al., 2017).

This paper argues that the transition to a circular economy is predicated on the successful diffusion of niche technologies, which will enable the growth of 'inner loop' circular activities such as remanufacturing and bio-refining. However, the scaling of such technologies is currently limited by systemic barriers such as technological lock-ins. By drawing from the sustainability transitions field, this paper suggests that an innovation policy tool that may offer value with regards to accelerating the growth of circular niche technologies is Strategic Niche Management (SNM). The aim of SNM is to create protected spaces for innovation experimentation in which new technologies, that are aligned with broader sustainability goals, are protected or shielded from mainstream market selection criteria and where learning processes amongst a network of technology stakeholders are fostered (Hegger et al., 2007).

However, current SNM practice has remained limited to the management of individual innovation experiments such as trialling an electric bus in a specific location, leading to low innovation adoption rates and poor learning processes. Mourik and Raven (2006) argue that SNM should instead focus on niche level management as opposed to individual experiments. Since the transition to a circular economy requires the formation of entirely new value chains requiring the management of wider niche innovation networks, this paper argues that the focus of SNM must be expanded from the individual experiment to the niche network level.

Despite the importance of niche managers on the overall success of SNM, not much has been done by way of research to explore the complex dynamics and challenges associated with the practice (Kivimaa, 2014). Few studies have attempted to critically assess how SNM is currently being operationalized through system intermediaries at the niche network level thus creating a gap between the literature and practice. This paper is therefore an attempt to make a useful contribution to the growing body of literature in the area of niche network and system intermediaries in the context of transition to circular economy.

A novel form of SNM is being practiced in Scotland, which focuses on managing the entire national niche network rather than a single innovation experiment through leveraging a uniquely structured triple helix-based system intermediary as a niche manager. This paper therefore empirically evaluates, through a complete social network analysis, the ability for such a triple helix-based system intermediary to strategically manage a national niche network.

The remainder of this paper is in six parts. The following part provides a literature review on research gaps on the topic of the circular economy. The third part provides an overview of

SNM, its current limitations and introduces the concept of a triple helix-based system intermediary. The fourth part outlines the research design for the empirical research in the light of the objective of the research. The results of the case study and the conceptual and empirical ramifications thereof are discussed in the fifth and sixth parts of the paper. The final part presents the conclusions including recommendations for future research.

2. Transition thinking: A key circular economy knowledge gap

A recent circular economy literature review by Geissdoerfer et al. (2017) demonstrated a tenfold growth of academic publications - from under 10 publications per year in 2008 to over 100 in 2016. Approximately 70% of the publications identified individual businesses as the key driver for change and sought to examine the most effective tools, frameworks, business models and management processes across different sectors.

Although research on individual businesses is necessary to support businesses to proactively drive change towards circularity, a macro-level circular economy transition will ultimatley require large scale systemic change and the reconfiguration of entire value chains (Lieder and Rashid 2016). Any circular innovation developed by individual companies which challenges the status quo, will likely experience significant resistance from interlinked socio-technical regimes which are highly resistant to change (Hegger et al., 2007).

Socio-technical regimes evolve to address fundamental societal needs such as water, energy and food supply. They form through the co-evolutionary build-up and alignment of “user practices and life styles, complementary technologies, business models, value chains, organizational structures, regulations, institutional structures, and even political structures” (Markard et al., 2012, p. 955). It is due to this co-evolutionary formation that technological lock-ins develop whereby well-established general-purpose technologies, such as the car or electricity grid, become deeply intertwined with culture and lifestyles.

Therefore, although necessary, the current focus on tools and models for individual businesses to become more circular may be compared to shuffling the deck chairs on the titanic (Meadows, 2008). Such research focuses on targeting ‘shallow’ leverage points within the current economic system, which have little impact on the goal of the system.

In recognition of the risk of linear technological ‘lock-in’, there has been increasing emphasis within the circular economy literature on the need to develop a suite of public policy measures to address legal frameworks (such as definitions of wastes), tax breaks and incentives. However, de Jesus and Mendonça, 2018, p. 78) argue that current circular policy attempts have, in themselves, been applied in an inherently linear fashion, as such attempts have led to “misaligned incentives, lacking in a conducive legal system, deficient institutional framework”. Based on this, de Jesus and Mendonça (2018, p. 85) make the case for a “multidimensional, multi-actor systemic innovation approach to CE”.

In light of limitations in both circular economy research and practice, this paper argues that there is a need for a more holistic approach to innovation policy, which acknowledges the multi-actor systemic nature of innovation and which targets the re-configuration of entire value chains through the successful diffusion of circular economy enabling technologies. Such technologies must be able to overcome the inherent linear lock-in possibilities within existing socio-technical regimes if they are to achieve scale. By drawing from the sustainability transitions literature, this paper explores the potential for adopting Strategic

Niche Management (SNM) as a policy approach for scaling circular economy enabling technologies.

3. Triple helix-based system intermediary: A new form of niche manager

SNM emerged in the early 1990s as an evolutionary policy tool to facilitate the growth of radical and sustainable technological niche innovations (Kemp et al., 1998). It is based on the rationale that if radical innovations were to successfully destabilise unsustainable technology regimes, they would require initial protection from the competitive pressures of the market through the formation of protected spaces (Raven 2006; Schot and Geels 2008; Verbong et al., 2008; Nill and Kemp 2009) . In order to achieve such goals, the SNM process is highly dependent on a niche manager (Weber et al., 1999). However, a revision of the role and format of the niche manager is required if SNM is to be successfully applied to accelerate transition to circular economy. This section provides an overview of the traditional role of the niche manager and the limitations thereof. It then introduces the concept of a triple helix-based system intermediary and outlines the potential for such an intermediary to assume the role of niche network manager.

3.1. The role of the niche manager in SNM

Weber et al. (1999) state that SNM should be driven and guided by a network manager, the role of which may be assumed by any actor, be it an individual, a citizen group, a company, an industry association, a university, a special interest group, a regulatory agency or a policy maker (Kemp, Schot and Hoogma, 1998). The aim of the niche network manager is to drive and guide the network around a niche by undertaking shielding, nurturing and empowering activities (Smith and Raven 2012).

This paper specifically focuses on the role of the niche network manager in nurturing a niche innovation network. Hoogma et al. (2002) suggest that nurturing is essential to the development of a niche network as learning is unlikely to occur naturally between organizations operating in different sectors. Nurturing cultivates the niche innovation network (Schot and Geels 2008). Yet, few studies have gone as far as exploring or defining specific activities that network managers may undertake to successfully nurture the niche.

3.2. Revising the role of niche manager for a circular economy transition

SNM is widely discussed in the academic literature[1], and several studies have highlighted the limitations in its operational approaches. Firstly, Mourik and Raven (2006) highlight that when put into practice, the scope of SNM has traditionally been restricted to managing individual innovation experiments as opposed to the wider niche network, thus leading to limited results.

Secondly, the top-down government-directed approach to niche management has also been shown to lead to various unintended consequences, such as poor learning processes, false expectations and low innovation adoption rates outside the niche (Verbong et al., 2008; de Wildt-Liesveld et al., 2015). Lovell (2017, p. 42) also acknowledges that the 'neat, staged' model of SNM has had little success and that SNM would be more effective if a more polycentric form of governance for socio-technical change were adopted.

The top-down approach to SNM is particularly limited when considering that the realisation of a circular economy depends upon the successful diffusion of several disruptive circular economy enabling technologies. Such technologies include the blockchain (Ellen MacArthur

[1] According to Web of Science, the first recorded use of SNM in academic literature was in 1994. Since then there has been a total 286 publications that include the term 'strategic niche management' in the title or abstract, growing from 6 publications per year in 2009 to 40 in the year 2017.

Foundation, 2016), big data and the internet of things (IoT) (Lopes de Sousa Jabbour et al., 2018; Nobre and Tavares 2017), bio-refining (Zabaniotou 2018; Venkata Mohan et al., 2016), and additive manufacturing (Ford and Despeisse, 2016; Despeisse et al., 2017).

The combination of disruptive technologies with new circular business models, such as offering a product as a service, will likely lead to the messy and unpredictable re-configuration of existing *or* entirely new value chains (Boons et al., 2013; Urbinati et al., 2017). As such, the future role of SNM is unlikely to involve didactically managing isolated experiments in a top-down manner, rather nurturing and empowering networks comprising of multiple cross cutting experiments.

As argued in this paper, a key role of the niche manager is to enable effective knowledge generation, transfer and use within and outwith these niche networks. There is therefore a need to revise the format and function of niche managers in order for them to perform such a role.

Barrie et al. (2017) proposed the concept of a triple helix-based system intermediary as a new format of niche manager whose focus would be on the niche network rather than on individual projects or experiments. A triple helix-based system intermediary would be nested within a niche innovation network and co-governed by public sector (regulators), academia (knowledge producers) and industry (knowledge users) network stakeholders. It would have the remit to accelerate sustainable transformation by enhancing cooperation and collaboration amongst triple helix actors within the protected space network, whilst connecting them with external actors within the regime.

In theory, a triple helix-based system intermediary offers many advantages over traditional forms of niche network manager. Firstly, unlike the traditional top-down approach to SNM, a triple helix-based system intermediary would be nested within the niche network itself through a revolving governance board made up of university, industry and public sector network stakeholders. It may therefore allow the network manager to become more responsive to the immediate needs of the network and thus undertake nurturing and empowering activities more effectively than what the traditional network manager would do.

Secondly, a triple helix-based system intermediary may act as a vehicle for increased knowledge transfer and coordination between the triple helix institutions and would thus foster shared expectations and learning necessary for niche expansion. Finally, a triple helix-based system intermediary may also act as a conduit for effective knowledge exchange between the niche and external actors, such as policy makers and regime actors, who are traditionally considered external to the niche.

Several examples of triple helix system intermediaries exist in practice in the UK (Scottish Innovation Centres (Reid, 2016), the UK Catapult Centres (Kerry and Danson, 2016)); in Europe (Sweden's Competency Centres (Stern *et al.*, 2013), Climate-KIC (Climate KIC, 2018), Germany's Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung (Fraunhofer-Society) (Reich-Graefe, 2016); and in Australia (Cooperative Research Centres) (Miles, 2015). Yet the intermediation of triple helix trilateral networks remains significantly understudied (Metcalfe, 2010; Suvinen, Konttinen and Nieminen, 2010).

Metcalfe (2010) argues that due to the continued institutional isolation of each of the university-industry-government helices, the design and provision of efficient legal intermediation practices and organizations should be of paramount importance. Triple helix-based system intermediation is therefore necessary to transcend the long-standing and pervasively practiced institutional separateness and resistance to innovate and transform among the helices (Tuunainen, 2002).

Although the proposition of a triple helix-based system intermediary as a niche manager offers theoretical advantages, it is not apparent whether this would be the same in practice. This paper therefore seeks to undertake a robust empirical test through a detailed case study, evaluating the ability of a triple helix-based system intermediary to undertake key nurturing activities on a national industrial biotechnology innovation network.

4. Research Approach

The following section outlines the empirical focus and methodology of the case study.

4.1. Empirical Focus: A National Industrial Biotechnology Innovation Centre

In January 2013, a protected space was initiated by the Scottish Government to stimulate the growth of a fledgling national industrial biotechnology niche innovation network. This was done through the launch of the National Plan for Industrial Biotechnology and a commitment of £30 million to support collaborative industry-academia research and development projects (Chemical Sciences Scotland, 2015). In order to manage the fund and nurture the national niche network, the Industrial Biotechnology Innovation Centre (IBioIC) was set-up in January 2014 with the structure that would identify it as a triple helix-based system intermediary.

This paper draws on IBioIC for empirical case study for at least three reasons. Firstly, IBioIC is the only organisation set up to mediate for all biotechnology industry related activities in

Scotland. It was established with the explicit mandate to manage the entire niche network in line with the national circular economy strategy rather than support an individual experiment (Scottish Government, 2016). Secondly, as a typical triple helix-based system intermediary, it is governed through a rotating board of stakeholders from industry, academia and the public sector. Thirdly, the authors were granted access to collect data from all network member organizations.

In this paper, we ask the question about the effectiveness of IBioIC in its mission as a triple helix-based system intermediary to nurture the industrial biotechnology protected space network. For this purpose, the method of social network analysis was used. Social Network Analysis (SNA) is a set of mathematical, graphical and theoretical tools for modelling networks. It offers a visual conceptual framework with which to identify and assess the connections between a heterogeneous network of organizations.

The studies by Caniëls and Romijn (2008), Lopolito et al. (2011) and Morone et al. (2015) highlight the specific benefit of applying SNA to the study of strategic niche management. However, these studies remain limited with regards to explaining how SNM is practically operationalized and measuring the impact of intermediaries on the nurturing of protected space networks.

In view of such limitations, this paper uniquely undertook a whole network analysis on the Scottish industrial biotechnology protected space network. The aim of a whole social network analysis is to build detailed reconstructions of the entire social networks. Whole network analysis is referred to as the ‘gold standard’ of network analysis (Butts, 2008).

Nurturing is achieved through the build-up of social capital in the niche network. This would be expected to enhance aspects of 'relational ties' that foster shared expectations, promote shared learning and grow the actor network (Schot and Geels 2008). So in order to measure the nurturing effect of IBioIC, whole network analysis was used to empirically evaluate the impacts IBioIC had on the niche network structure in terms of network density, number of ties, path length, centralisation, etc. shown in Table 4. Changes in these indicators consequent upon the introduction of IBioIC to the network have implications for the development of social capital in the niche network. Such analysis also allows for the nurturing effect the triple helix-based system intermediary has *between* and *within* triple helix institutions to be evaluated.

The whole network analysis also allows for an egocentric network analysis of the triple helix-based system intermediary. The egocentric analysis measures the level of power and influence of the triple helix-based system intermediary with regards to fostering shared expectations and promoting shared learning relative to all other network actors. The combination of whole and egocentric network analysis offers useful learning for both researchers and practitioners operating within the sphere of niche innovation networks.

The authors were provided full access to the raw dataset from a survey conducted by IBioIC in July 2017 with 121 network members representing 116 industry organizations in the Scottish industrial biotechnology network. The survey asked each respondent to identify the extent to which they agreed with a range of statements regarding the effectiveness of IBioIC as a network broker. The survey also asked the companies to identify whether IBioIC activities had contributed to nine different economic gains on the business. The results of this survey are used to compliment the findings from the SNA.

4.2. Data collection for whole network analysis

To ensure all relevant network actors were included in the whole network analysis, IBioIC staff provided a roster of organizations, which comprised of 64 network members (Public Sector Stakeholders n=5, Academia n=16, Industry n=36, Innovation Intermediaries n=7). Innovation intermediaries are knowledge brokers within the network, which operates without government stakeholders, university departments or a specific company. The innovation intermediaries are not actively engaged in managing the network *per se*; rather they support the needs of individual organizations.

Inter-organization relational data were collected via semi-structured interviews with individual representatives from each organization between September 2016 and March 2017. The individuals were identified by IBioIC as being responsible for managing inter-organizational innovation relationships within the network. Table 1 provides an overview of the 11 organization-to-organization relational ties that were observed. The relational ties were selected as proxy indicators for the impact on nurturing activities. For example, knowledge transfer and collaborative research ties indicate shared learning. Similarly, observations on project ties indicate shared expectations. The merit of the whole network analysis is that the results can be aggregated for each relational tie to give a good indicator of the impact on different nurturing activities.

Table 1: Questions each network organisation representative was asked in order to identify and value the existence of 13 different relational ties their organization held with every other network member organization

#	Questions asked to each organization regarding their relationships with each network member organizations	Response Options	Nurturing Activities that relational ties impact
1	How would you rate the quality of contact you have (on the topic of industrial biotechnology)?	Poor, Moderate, High	Shared learning
2	What is the strategic importance of industrial biotechnology knowledge transfer to your organization?	None, Low, Moderate, High, Very High	Shared learning
3	Do you expect to have a long-term relationship? (>5years)	Yes/No	Building network,

			raised expectations
4	Do you currently participate in collaborative industrial biotechnology research projects together?	Yes/No	Shared learning, Raised expectations
5	Do you currently have a strategic alliance (related to industrial biotechnology)?	Yes/No	Shared learning, Raised expectations
6	How frequently do you have contact (on the topic of industrial biotechnology)?	None, None but in future, Once a quarter, Once a month	Building Network, Shared Learning
7	What level of tacit knowledge (related to industrial biotechnology) do they transfer to your organization?	Poor, Moderate, High	Building Network, Shared Learning
8	What level of explicit knowledge (related to industrial biotechnology) do they transfer to your organization?	Poor, Moderate, High	Building Network, Shared Learning
9	Has there been industrial biotechnology technology transfer between your organizations in the past 2 years?	None, From you to them, From them to you, Both ways	Shared learning, Raised Expectations
10	Has there been industrial biotechnology intellectual property transfer between your organizations in the past 2 years?	None, From you to them, From them to you, Both ways	Shared learning, Raised Expectations
11	Has there been industrial biotechnology cash transfer between your organizations in the past 2 years?	None, From you to them, From them to you, Both ways	Raised Expectations
12	*Were your relations formed through IBioIC?*	*No, Partially, Yes*	*N/A*
13	*Relations strengthened through IBioIC?*	*No, Low, Medium, High, Very High*	*N/A*

Notes:

1. For this study, explicit knowledge was defined as knowledge which can be easily expressed and recorded as words, numbers, codes, mathematical and scientific formulae. Whereas tacit knowledge was defined as knowledge that is embedded in the human mind through experience and jobs and which is very difficult to extract and codify.
2. Respondents were asked to rate the strategic importance of knowledge transfer between all other network members - as such, although it does not explicitly state which type of knowledge, it does identify how valuable this knowledge transfer, and subsequent learning, was to the continued success of the organisation
3. Relational attribute data for relational attributes 12 and 13 were collected solely as a means to measure the impact of IBioIC on relational attributes 1-11.
4. An additional relational attribute, total knowledge transfer was included in the analysis. Total knowledge transfer is a multiplex relational attribute formed through the combination of values from tacit and explicit knowledge transfer relational attributes using the UCINET 6 multiplex function.

Burt (2000), Capaldo (2007) and Michelfelder and Kratzer (2013) found that a combination of both weak and strong ties is required to stimulate innovation within networks. Weak ties aid exploration (the generation of new ideas), whereas strong ties aid exploitation (the implementation of new ideas) (March, 1991). Therefore, a range of ‘weak’ and ‘strong’ types of relational attributes was collected.

By collecting data on 11 different types of relational ties, a fine-grained understanding of the impact of IBioIC on the three key nurturing activities [2] could be obtained – see Table 1. Two

[2] There is general agreement in the literature that there are three main (internal) processes necessary for the successful development of a technological niche: (i) shielding; (ii) nurturing; and (iii) empowering (as outlined in Table 1). They are considered “key” because without any of them the niche technology is unlikely to succeed.

additional organization-to-organization relational ties were collected (12 and 13 in Table 1) as a means to measuring the impact of IBioIC on the 11 relational ties.

To measure the strength of relational ties between two organizations, respondents were asked to fill in an actor-relation incidence matrix which listed a roster of network actors in the first column and the different types of relations they held with them in the subsequent columns. To avoid recall error during the semi-structured interview, only staff identified by IBioIC as having detailed knowledge of their respective organization relations with other network members were selected to be interviewed. In addition, several individuals were interviewed from large organizations to crosscheck the actor-relation matrix and add in any missing data. This was particularly the case for universities where knowledge of external relations from other departments was low. In the case of this paper, total knowledge transfer was added as an additional relational attribute, which was taken as the combination of tacit and explicit knowledge transfer (Carpenter et al., 2012).

Prior to the analysis of non-directional relational characteristics, it was necessary to symmetrize the actor-actor adjacency matrices for directional bonded ties. UCINET 6, developed by Borgatti, et al. (2002), was used to symmetrize the adjacency matrices whereby the highest of the two values was adopted as outlined in Ouimet, et al. (2004).

4.3. Measuring nurturing impact of intermediary on network structure

Van der Valk et al. (2011) introduced a social network analysis framework to measure the impact of policy on the innovative performance of networks. The framework evaluates the impact of policy through the study of three network structure characteristics: network

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(Kemp, Schot and Hoogma, 1998; Smith and Raven, 2012; Boon, Moors and Meijer, 2014; Verhees *et al.*, 2015) cohesion, presence of cohesive subgroups and degree of centralisation. This paper combined the framework developed by Van der Valk et al. (2011) with the whole network analysis to evaluate the nurturing effect of a system intermediary on the network.

Network cohesion describes the extent to which network actors are related to one another. Increased network cohesion enables the build-up of social capital (Coleman, 1988). Social capital has been shown to increases the likelihood of shared learning and expectations and therefore the innovative performance of individual network actors (Kilpatrick et al., 1999). Yet, too high a level of cohesion can lead to 'over-embeddedness', which restricts new information from entering the network, thereby reducing the chances of novel combinations of knowledge and the networks ability to adapt to exogenous change (Coleman, 1988). The presence of cohesive subgroups identifies the extent to which the network is made up of separate cohesive subgroups. As the presence of cohesive subgroups increases, local knowledge flow and shared learning increases. Yet, there is a risk of the cohesive subgroups becoming highly 'cliquish', whereby local knowledge lock-in occurs if subgroups are not sufficiently inter-connected.

A balance is therefore required between the formation of subgroups and the connectedness between them. Burt (2000) argues that the most efficient network architecture is likely to happen in the small world typology. Small world networks are networks in which cohesive subgroups are sufficiently interconnected to simultaneously ensure effective knowledge exchange at the local level, whilst preventing knowledge lock-ins. The increase or decrease in the presence of cohesive sub-groups was calculated by comparing the ratios of the clustering coefficient value with the density values, as suggested in Van der Valk et al. (2011), for both before and after the introduction of IBioIC to the network. An increase in the ratio would suggest that the presence of IBioIC has increased the level of cohesive subgroups.

Centralisation is considered as a reflection of the emergence of hubs with above averagely connected central nodes. Networks with a high level of centralisation tend to be more robust and less influenced by the removal or addition of a network member. A clear sense of leadership and shared expectations within the network is also prevalent in centralised networks, and has been shown to be important for innovation (Van der Valk et al., 2011). Yet, highly centralised networks are reliant on the activities of the actors at the centre of these hubs, so that the exiting of these actors can have profound and potentially disruptive effects on the structure of the network.

The presence of cohesive subgroups and centralisation cannot be measured directly, but inferred through the measurement of the structural characteristics of the network as discussed in Van der Valk et al. (2011) and outlined in Table 2. The level of network cohesion was therefore evaluated through the measurement the total number of ties in the network, the network density and average path length. The presence of cohesive subgroups is indicated by the clustering coefficient of the network; and the network centralisation by the centralisation index. This paper used UCINET 6 for the calculation of all such measures.

Table 2: Outline of structural properties measured for the 11 relational attributes outlined in Table 1 and the multiplex relational attribute of total knowledge (adapted from Van der Valk et al.*, (2011))*

Concept	**Measure**	**Calculation**	**Range of Values**	**Meaning of High Value of Measures**
Network Cohesion	Number of Ties	The total number of ties	>0	The network is highly connected
	Density	The total number of present ties divided by the total number of possible ties	0 to 1	The network is densely connected.
	Average Path Length	The average length of all paths between all nodes in the network	>0	The distances between the entities are long

Presence of Cohesive Subgroups	Clustering Coefficient	Mean weighted of the clustering coefficient of all actors	0 to 1	The network comprises of different clusters. To evaluate the level of clustering, the clustering coefficient must be compared to the overall network density.
Degree of Centralisation	Centralisation Index	The degree of inequality or variance in the network as a percentage of that of a perfect star network of the same size	0 to 100%	There are clear hubs among a large number of more limitedly connected others.

The impact of IBioIC was determined by calculating the value of each measure (Table 2) for all relational ties (Table 1) and then comparing the estimated values of the measures prior to IBioIC joining the network. In order to estimate these, the following two assumptions were made. Firstly, any direct ties to and from the intermediary were removed. Secondly, if the frequency of contact between two organizations was identified to be once a month or once every three months, and the tie was formed or highly strengthened by the triple helix-based system intermediary, then it was assumed all relational ties between the two organizations prior to the appearance of IBioIC did not exist (The total number of ties formed or strengthened by IBioIC are listed in Appendix I).

Based on these two assumptions, the value of each measure *before* IBioIC joined the network was calculated for each relational tie; and the percentage change in each measure was determined by the ratios of each relational tie before and after IBioIC joined the network. The structural measures, outlined in Table 2, were calculated using UCINET 6 and plotted in a matrix displaying the percentage changes in the structural measure for all 11 relational ties.

4.4. Measuring impact of intermediary on triple helix interactions within the niche

The impact of the triple helix-based system intermediary on the level of interactions between the groups in the triple helix system was also measured. The triple helix groups were identified as government and government stakeholders; universities; industry and innovation intermediaries. Firstly, the level of interactions for multiple relational attributes were calculated within and between the triple helix groups using the UCINET 6 Group Density function which calculates the sum of ties between triple helix groups and the density of ties.

As per the structural properties of the network, the interactions between triple helix groups were evaluated separately for each relational or multiplex relational attributes. Thus, the level of triple helix interactions for each relational attribute could be compared and contrasted. The impact of the triple helix-based system intermediary on the density of relational ties between the triple helix actors was then calculated. Results of the analysis were visualised using NetDraw.

4.5. Measuring influence and power of intermediary

The data collected in the whole network analysis also allowed for an egocentric network analysis to be undertaken for any network organization. Egocentric analysis is the analysis of the immediate structure and composition of network ties surrounding a single network actor.

Centrality analysis is commonly undertaken in order to identify certain characteristics about specific network actors, such as how well connected they are, the level of control they hold over knowledge and resource flows, or the influence they have on others (Otte and Rousseau, 2002). The four most common measures of centrality, as discussed in Otte and Ronald (2002) and Pilar Latorre, et al. (2017) and outlined in Table 3, are the actors' degree of closeness, betweenness, eigenvector centrality and the number of structural holes bridged, which reflect on the effectiveness of IBioIC in bridging knowledge transfer gaps in the network. Each centrality measure was calculated using UCINET 6 software.

By measuring the varying degrees of centrality, the ability for the intermediary to perform the key nurturing activities of increasing shared expectations, promoting shared learning and building the actor network can be evaluated.

Table 3: Description of egocentric network centralisation attributes selected to measure the level of centrality of IBioIC in the network with respect to the 11 relational attributes outlined in Table 1 and the multiplex relational attribute of total knowledge.

Centrality Measure	**Description**	**High Value**
Degree	The number of relational ties incident on each network actor	The actor is highly connected
Closeness	The average length of the shortest path between the actor and all other actors	The actor is close to many other actors in the network
Betweenness	The number of times an actor acts as a bridge along the shortest path between two other actors	The actor holds a high level of control over knowledge and resource exchange between other network actors
Eigenvector	A measure of the importance of a node in a network	The actor has a high level of influence compared to other network actors
Number of Structural Holes Bridged	The bridging of a gap between two individuals who have complementary sources to information.	The actor bridges a high number of gaps between two individuals who have complementary sources to information

5. Nurturing effect of a triple helix-based system intermediary on a niche network

This section covers the results obtained from both the whole network analysis (impact of nurturing on the structure of the network and on the triple helix interactions) and the egocentric analysis (centrality of IBioIC relative to all other network members).

5.1. Impact on the innovation potential of the network

Table 4 outlines the impact IBioIC had on the network for varying relational attributes. These relational attributes were derived from the SNA based on the survey data. The impact was measured as a percentage change in the relational attribute value due to the presence of IBioIC.

Table 4: An outline of the increase/decrease in structural network values for each relational attribute with respect to the impact of IBioIC showing the significant positive impact of IBioIC on almost all measures of centrality.

	Cohesion			Cohesive Subgroups	Centralisation
Relational Attributes	Δ *Network Density* (Without→With)	Δ *Total Number of Ties* (Without→With) *(%Δ)*	%Δ *Path Length*	%Δ *Ratio between Density and Clustering Coefficient*	%Δ *Centralisation Index*
Frequency of Contact	0.242 →0.315	976→1270 (23)	-11	3	56
Quality of Contact	0.204→0.266	824→1072 (23)	-15	12	53
Tacit Knowledge Transfer	0.101→0.155	406→624 (35)	-13	10	53
Explicit Knowledge Transfer	0.095→0.147	382→594 (36)	-16	2	58
Total Knowledge Transfer	0.110→0.166	442→670 (34)	-9	7	54
Strategic Importance	0.097→0.149	392→600 (35)	-17	3	58
Long Term Relations	0.113→0.168	454→676 (33)	-17	7	60
Collaborative Research Projects	0.060→0.098	242→394 (39)	-13	5	39
Strategic Alliance	0.022→0.040	88→162 (46)	-15	-8	31
Technology Transfer	0.059→0.088	236→356 (34)	-3	-5	33
Cash Transfer	0.049→0.084	196→338 (42)	-14	7	60
IP Transfer	0.015→0.032	60→128 (53)	-21	79	69

Notes:

1. For Network Density and Total Number of Ties: The number to the left of the arrow is the relational attribute value without the presence of IBioIC. The number to the right of the arrow is the relation attribute value including the presence of IBioIC.
2. For Centralization Index: A positive number indicates a % increase in value due to the presence of IBioIC. The % value was calculated by taking the ratio between the structural value including any ties directly formed through IBioIC and the structural value not including any ties formed directly through IBioIC and then converting the ratio to a % change.
3. For Path Length: A negative number indicates that the average path length has reduced between network members
4. Only Frequency of contact scored >2 (once every quarter) were included in the analysis
5. Ratio between Density and Clustering Coefficient: The increase or decrease in presence of cohesive sub-groups was calculated by comparing the ratios of the clustering coefficient value with the density values for both before and after the introduction of IBioIC to the network. If the change in ratio increases the presence of IBioIC increased the level of cohesive subgroups.

5.1.1.Network Cohesion

The results in Table 4 indicate that IBioIC increased the level of cohesion for all types of relational ties. The network density increased for all relational attributes due to the brokering role of IBioIC. The frequency of contact relational attribute demonstrated the highest density value of 0.315. However, as the type of ties gets stronger, the density drops significantly to 0.088 for technology transfer and 0.032 for IP transfer, for example.

The relational attribute that increased the most, with regards to the number of ties, was the existence of frequent contact between actors, in which IBioIC increased the number of frequent contact ties from 976 to 1270 ties. Such an increase suggests IBioIC was effective at broadening the network and increasing the number of weak ties. Weak ties are seen to be necessary within innovation networks for fostering idea generation and introducing new innovation opportunities (Michelfelder and Kratzer 2013).

However, when the percentage increase of the number of ties is considered, the stronger forms of ties, such as strategic alliances, IP transfer and cash transfer increased by 46%, 53% and 42% respectively, compared to the 23% increase in ties for frequent contact. This suggests that IBioIC was more effective at brokering strong relational ties relative to weaker ones. As outlined in Carpenter et al. (2012), increase in strong ties can foster an environment of trust, reciprocity and cooperation throughout the network, whilst constraining the network actors through strong norms and shared expectations. Michelfelder and Kratzer (2013) also found that strong ties are necessary for complex knowledge to be transferred and exploited via technological development.

The introduction of IBioIC into the network also led to the reduction of average path length between actors for all relational attributes. Increase in path length is most evidenced for IP transfer, in which the average path length within the network decreased by 21%. Reduction in average path length builds network cohesion by making it easier for knowledge to be shared between two network actors.

5.1.2. Presence of cohesive subgroups

The increase or decrease in the presence of cohesive sub-groups was calculated by comparing the ratios of clustering coefficient values with network density values for both before and after the introduction of IBioIC to the network. If the change in these ratios increases, this would provide evidence for IBioIC to have increased the presence of cohesive subgroups in the network.

According to the results of our survey, although IBioIC increased the network density for every relational attribute, its impact on clustering varied. Clustering increased for ten relational attributes and decreased for two. With the exception of IP licensing, the increase or decrease in clustering remained roughly equal to or below 10%, suggesting that IBioIC had little impact on clustering. An outlier was IP licensing, whereby the ratio between the density and the clustering coefficients increased by 79% due to the nurturing effect of IBioIC.

Even though IBioIC increased the number of ties - up to 40% for some relational attributes - and reduced the average path length by up to 20%, the impact on the presence of cohesive subgroups appears to be small. This suggests IBioIC was able to enhance the level of network connectedness without significantly increasing the risk of over-embeddedness.

5.1.3.Centralisation

Unlike the variance in the clustering coefficient, the centralisation index for all relational attributes increased. An increase in network centralisation indicates that the immediate network actors, or ‘neighbourhood’ of each network actor, become more connected. The increase in centralisation index was particularly high for long-term relation ties (60%), cash transfer ties (29%) and IP transfer ties (69%). An increase of frequency of contact centralization index of 56% suggests IBioIC to have been an effective mechanism for enhancing both the depth and breadth of the niche network.

The increase in the centralization of strong ties, such as long-term relations or IP, cash and technology transfer, suggests that IBioIC's activities have not only increased the long-term robustness of the network, but have also fostered a sense of shared expectations between network actors, which is critical for the success of the niche.

5.2. Impact on triple helix interactions

In addition to the impact of IBioIC on the network structure, this paper also assessed its impact on the formation of relational ties between and within triple helix groups (academia, government, universities and innovation intermediaries). Figure 1 graphically illustrates the 'frequency of contact' ties formed between the triple helix groups due to the brokering role of IBioIC. Each black line represents a new relational tie formed. It is evident, from Figure 1, that IBioIC not only brokered a large number of relational ties between the triple helix groups but also within each group.

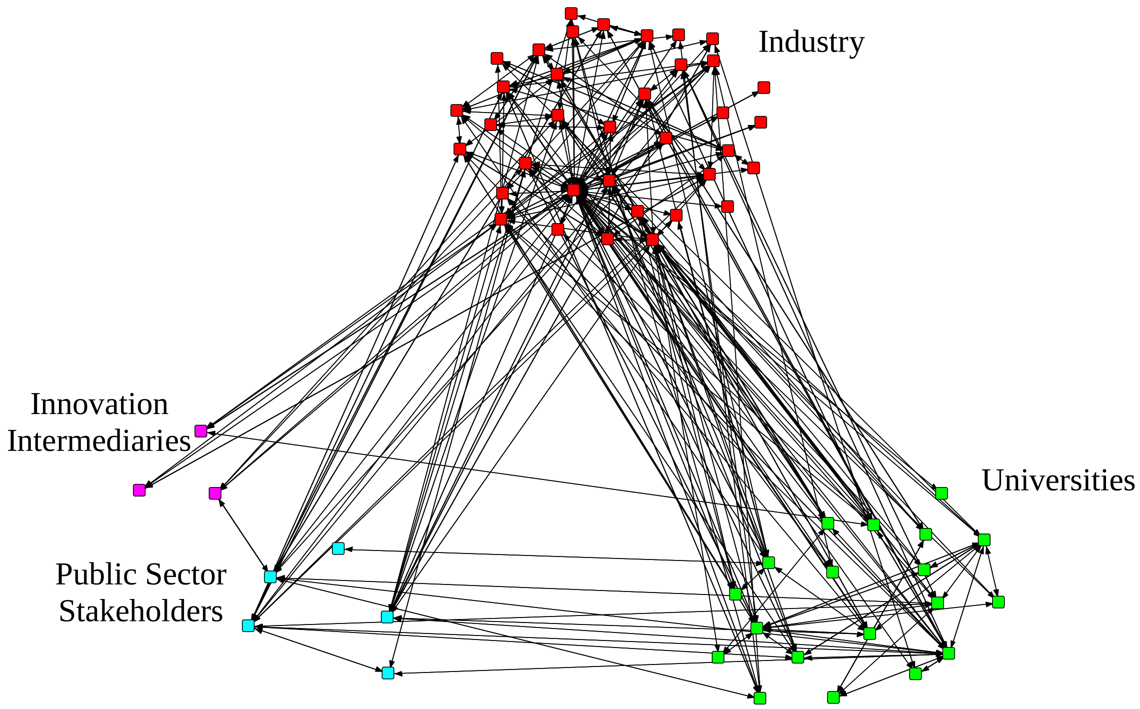

Figure 1: Network Diagram of frequency of contact ties created through IBioIC. Note: This does not include direct ties to IBioIC. Each line represents the formation of a new relational tie between two organizations due to the presence of IBioIC.

Note: The network diagram was produced using the software NetDraw by Borgatti (2002).

Table 5 outlines the impact of IBioIC on triple helix relations for the various types of relational ties. Academia-industry relations experienced the highest increase in relations on average compared to academia-government and industry-government relations. The frequency of contact increased in the academia-industry relations by 17% and by 15% in the academia-government relations, whereas the frequency of contact in the industry-government relations was lower at 5%.

The frequency of contact also increased within each group. Industry-to-industry and government-to-government contact increased by 18% and 25% respectively. The total increase in the quality of interactions was even higher than the frequency of contact between academia and industry, thus demonstrating that IBioIC has played a critical role not only on the formation of new ties and building the network, but also on brokering high quality ties, which are generally likely to increase the chances of shared learning.

Table 5: A measurement of the percentage increase/decrease in the number of ties between and amongst triple helix groups for each relational attribute due to the presence of IBioIC.

	I	A	G	Int.	I	A	G	Int.	I	A	G	Int.
	Frequency of Contact				Quality				Tacit Knowledge			
I	18				21				32			
A	17	8			20	9			36	16		
G	5	15	25		6	19	25		10	29	29	
Int.	66	38	47	75	48	30	50	25	62	35	60	25
	Explicit Knowledge				Total Knowledge				Strategic Importance			
I	31				33				27			
A	36	16			34	16			35	18		
G	8	29	29		8	29	29		9	33	29	
Int.	62	45	75	33	61	34	60	25	58	34	55	33
	Long Term Relations				Collab. Res. Projects				Strategic Alliances			
I	30				38				43			
A	33	17			46	15			41	22		
G	8	33	0		0	56	40		9	67	0	
Int.	60	33	50	25	50	41	100	0	86	80	100	100
	Tech Transfer				Cash Infusion				IP Transfer			
I	18				26				45			
A	35	19			44	20			60	14		
G	0	67	0		0	29	0		0	0	0	
Int.	55	60	100	0	76	59	25	0	50	0	100	0

Notes:

1. A positive number indicates a % increase in value due to the presence of IBioIC. The % value was calculated by taking the ratio between the structural value including any ties directly formed through IBioIC and the structural value not including any ties formed directly through IBioIC and then converting the ratio to a % change.

2. I=Industry, A=Academia, G=Public Sector Stakeholders, Int. = Innovation Intermediary

IBioIC was particularly effective at increasing shared learning among the triple helix groups. Total knowledge exchange was also observed to have increased by 34% between academia and industry; by 29% between academia and government; and by 8% between industry and government. Academia and industry shared relatively equal amounts of both tacit and explicit knowledge, offering a glimpse of the strength of the triple helix governance model of IBioIC with regards to encouraging the formation of a triple helix consensus space[3]. The presence of IBioIC also had a noticeable impact on the level of resource transfer between academia and industry (cash infusion, technology, intellectual property). The level of intellectual property transfer between academia and industry saw a particularly high increase of 60%.

A much greater increase in interactions was observed between academia and industry than between academia and government or industry and government. For example, a 41% increase in strategic alliances was observed between academia and industry, and a 46% and a 33% increase in collaborative research projects and long-term relations respectively.

However, the incidence of knowledge exchange increased much more between academia and government than between industry and government, suggesting an impending challenge for IBioIC in brokering stronger relations between industry and government. Although lower on average, compared to academia-government relational attribute ties, an increase in academia-government interactions was still observed for nearly all relations. For example, strategic importance and long-term relations increased by 33% respectively and strategic alliances increased by 67%.

The results demonstrate the unique network level brokering role of IBioIC, which allowed it to successfully broker relations between innovation intermediaries and other players in the network. The frequency of contact between innovation intermediaries and private sector companies, universities and government stakeholders increased by 66%, 38% and 47%,

[3] Ranga and Etzkowitz (2013, p.20) define the consensus space as “the set of activities that bring together the Triple Helix system components to brainstorm, discuss and evaluate proposals for advancement towards a knowledge-based regime. Through cross-fertilizing diverse perspectives, ideas may be generated and results may be achieved that actors are not likely to have accomplished individually”.

respectively. Moreover, the percentage of collaborative research projects increased by 50%, 41% and 100% respectively for private sector companies, universities and government stakeholders. This highlights the significance of niche managers like IBioIC in coordinating niches at the network level.

A critical task of strategic niche management is enabling the niche to alter the evolutionary trajectory of existing incumbent regimes (Hegger et al., 2007). Industry actors were subdivided into regime and niche actors, as identified by IBioIC; and the density between the two groups was calculated. These actors were identified as regime actors if their main value generation was obtained through incumbent regime value chains. Based on their industry experience, the IBioIC team identified who were regime and who were niche actors. They have a combined industry experience of over 100 years which gives credence to the reliability of their categorisation of regime and niche actors.

The results demonstrated that for most relational attributes, IBioIC doubled the level of interaction between regime and niche actors, particularly for long-term relations, strategic alliances, technology transfer and collaborative research projects. Figures 2 and 3 visually represent the collaborative research project and technology transfer ties directly formed through the presence of IBioIC, clearly demonstrate that strong ties were not only formed between and within the triple helix groups, but also between regime and niche actors.

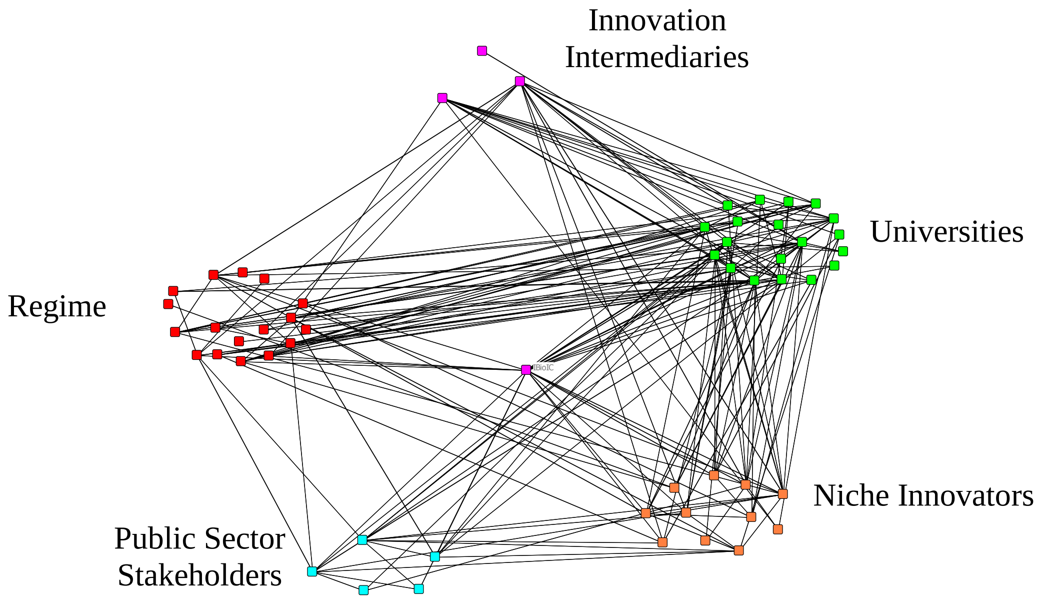

Figure 2: Collaborative research project relational ties formed through the introduction of IBioIC to the network

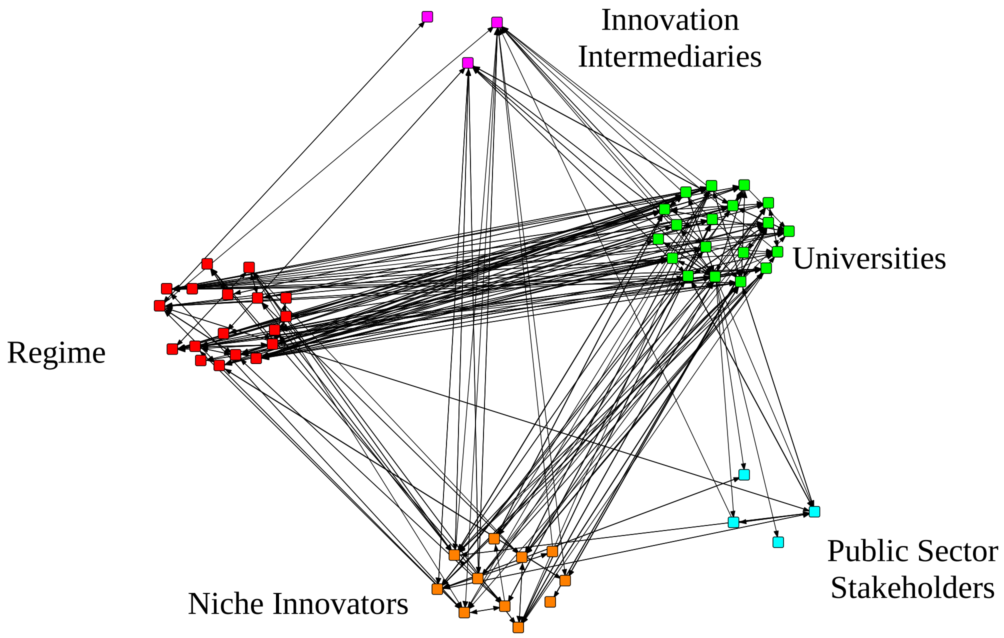

Figure 3: Technology transfer ties formed through the introduction of IBioIC to the network.

Note: The network diagrams in Figures 2 and 3 were produced using the software NetDraw by Borgatti (2002).

5.3. Centrality of the intermediary in the network

In addition to measuring the impact IBioIC had on the overall structure of the network and the relations between triple helix groups, this paper also undertook an egocentric analysis of IBioIC to empirically determine how central it is within the network relative to all other network players. NetDraw was used to produce a network diagram to offer a visual representation of where IBioIC was structurally located in the network relative to other network players.

Figure 4 is a network map of the frequency of contact ties and demonstrates that IBioIC is located near the centre of the network. The size of the actor node was scaled relative to the ‘betweenness’ of all other actors. What is evident is that IBioIC had a higher degree of ‘betweenness’ than any other network actor. This suggests that IBioIC held a high level of power and influence over the flow of knowledge and resources throughout the network, which means it could effectively play the role of a gate keeper to the network.

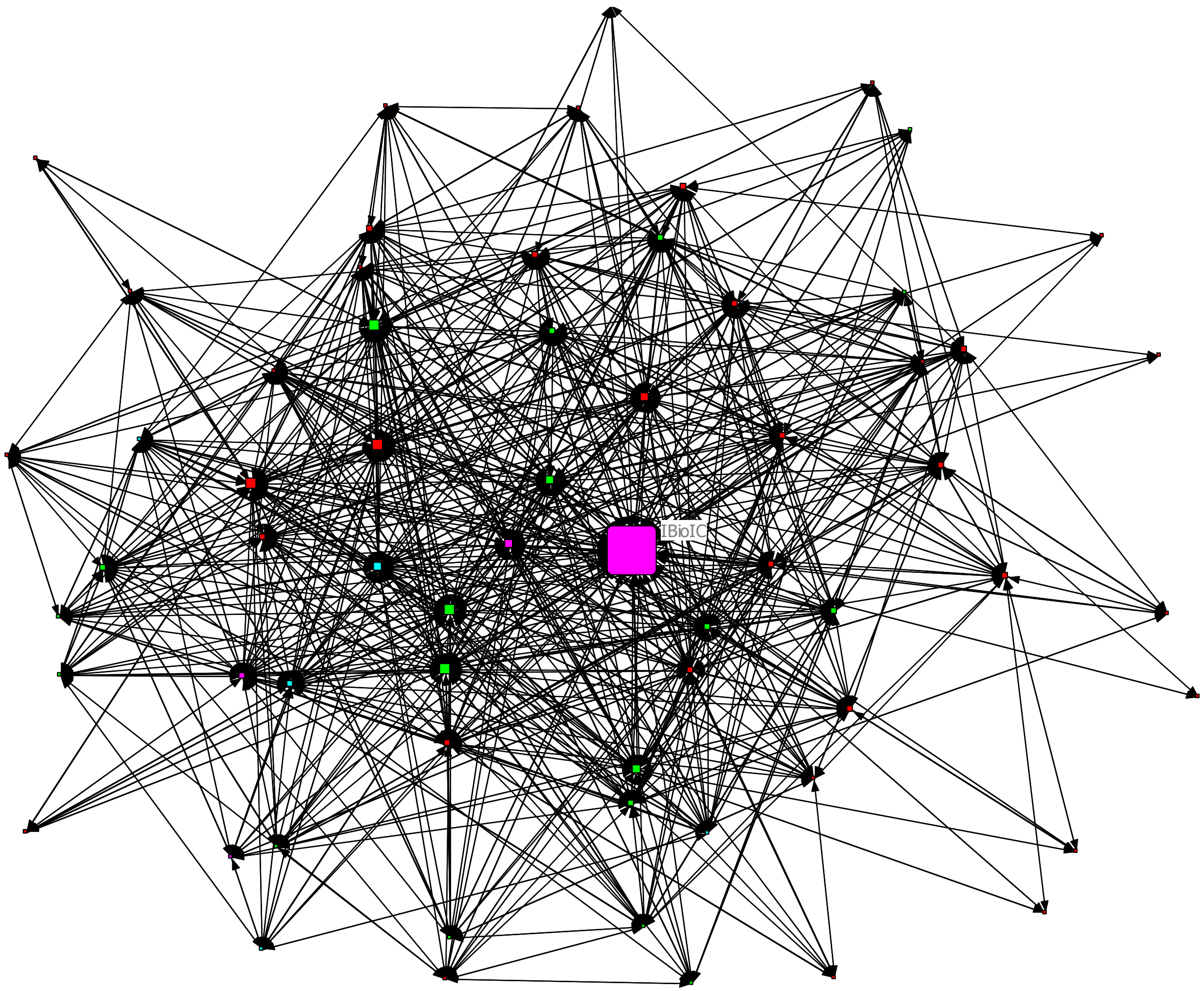

Figure 4: Network diagram of high level of frequency of contact dyadic ties within niche innovation network. Each line represents a connection between two organizations. The size of the actor node was scaled by the value of betweenness of the actor compare to all other network member. IBioIC is the largest node located in the centre of the network demonstrating the high level of centrality relative to all other network actors.

Note: The network diagram was produced using the software NetDraw by Borgatti (2002).

Table 6: Results from egocentric analysis with regards to IBioIC's level of centrality for each relational attribute compared to all 64 other network actors.

	Frequency of Contact				**Quality of Contact**				**Tacit Knowledge Transfer**				**Explicit Knowledge Transfer**				**Total Knowledge Transfer**			
Centrality Measure	IBioIC	Network Average	Network Median	Rank (out of 64)	IBioIC	Network Average	Network Median	Rank (out of 64)	IBioIC	Network Average	Network Median	Rank (out of 64)	IBioIC	Network Average	Network Median	Rank (out of 64)	IBioIC	Network Average	Network Median	Rank (out of 64)
Degree	62	20	20	1	62	17	15	1	45	9.75	9.5	1	43	9	9	1	48	10	10	1
Closeness	64	107	106	1	64	110	111	1	87	143	133	1	89	145	133	1	84	141	130	1
Betweenness	403	22	10	1	552	23.4	8	1	521	32	9.7	1	512	33.2	10.6	1	517	31	9.3	1
Eigenvector	0.273	0.112	-	1	0.298	0.11	0.1	1	0.368	0.1	0.1	1	0.38	0.101	1.101	1	0.368	0.103	0.102	1
Structural Holes Bridged	2644	257	168	1	2840	212	101	1	1560	96	42	1	1434	90	41	1	1760	108	53	1
	Strategic Importance				**Long Term Relations**				**Collaborative Research Projects**				**Strategic Alliance**				**Technology Transfer**			
Degree	45	9	9	1	48	10.6	10.5	1	23	6	5	1	15	2.5	1	1	13	6	5	3
Closeness	93	150.7	136	1	84	140	128.5	1	131	186	167	1	229	327	280	1	161	210	183	6
Betweenness	547	28.5	7.5	1	535	30.76	7.13	1	239	38	6	2	249	24	0	1	107	32	15	4
Eigenvector	0.377	0.103	0.103	1	0.364	0.103	0.1015	1	0.334	0.096	0.09	1	0.418	0.074	0.069	2	0.226	0.098	0.087	7
Structural Holes Bridged	1628	93	39	1	1756	108.6	51	1	412	46	16	1	172	12	0	1	143	41	20	3
	Cash Infusion				**IP Transfer**															
Degree	35	5	4	1	2	2	1	20												
Closeness	116	183	163	1	316	359	315	33												
Betweenness	718	30	8	1	43	36	0	20												
Eigenvector	0.449	0.097	0.095	1	0.033	0.078	0.075	35												
Structural Holes Bridged	1102	43	11	1	2	7	0	21												

Notes:

1. See Table 3 for a full description of centrality measures
2. Median Eigenvector value is not available as a function within UCINET6 software.

Table 6 provides the empirical results of the egocentric analysis with regards to IBioIC's degree of centrality for each relational attribute. It ranks IBioIC relative to the degree of centrality of every other network member. Overall, IBioIC ranked highest among all network members for all centrality indicators of all relational attributes apart from technology and IP transfer. This is to be expected as IBioIC do not directly participate in in technology IP transfer activities.

The number of direct ties IBioIC held for all relational attributes was, on average, five times higher than the average network actor and up to seven times for cash infusions. However, the number of direct ties alone does not fully describe the degree of influence IBioIC held within the network. For that, the centrality measures of closeness, betweenness, eigenvector and bridging of structural holes were measured (see Table 3 for full description).

IBioIC demonstrated lower closeness and higher betweenness values relative to all other actors for nearly all relational attributes. This suggests that in addition to having the shortest path length to all other network actors, thereby aiding knowledge transfer and acquisition, IBioIC was also able to exert a high level of control over knowledge and resource exchange between other network actors. This high level of control was also reflected in the eigenvector centrality in which IBioIC ranked highest for all relational attributes apart from technology and IP transfer. The results therefore suggest that IBioIC held the highest level of influence and control compared to other network actors.

One reason for IBioIC obtaining such a high eigenvector value may be due to the fact that it was able to broker the bridging of higher number of structural holes compared to any other actor in the network (see Table 3 for a definition of a structural hole). IBioIC bridged 14 times the number of structural holes compared to the average network member and 33 times higher than the median.

5.4. Network Member Survey Results

The results from the IBioIC industry network members, outlined in Table 7, demonstrate that 88% of respondents agreed that IBioIC had a positive impact on the industrial biotechnology industry, with 40% strongly agreeing. A total of 91% of respondents agreed that their company directly benefited from IBioIC activities and 85% agreed that IBioIC successfully met the needs of their companies. Finally, 99% of respondents agreed there is a need for IBioIC to exist, with 61% strongly agreeing.

Table 7: Results of network member survey assessing the impact of IBioIC on the network and respective organizations of the respondents

Statement	Organization	Strongly Disagree (%)	Disagree (%)	Neither Agree nor Disagree (%)	Agree (%)	Strongly Agree (%)
IBioIC has made a positive impact to the Industrial Biotechnology industry over the past 3 years	Total (n=121)	1.7	0.0	9.9	47.9	40.5
	Micro & SME (n=84)	0.0	0.0	9.5	41.7	48.8
	Large (n=32)	6.3	0.0	9.4	62.5	21.9
Your company has directly benefited from the activities undertaken by IBioIC	Total (n=121)	0.0	4.1	12.4	52.1	31.4
	Micro & SME (n=84)	0.0	3.6	9.5	50.0	36.9
	Large (n=32)	6.3	6.3	15.6	59.4	18.8
The current format of IBioIC meets your company needs	Total (n=117)	0.0	6.0	8.5	63.2	22.2
	Micro & SME (n=84)	0.0	7.1	8.3	57.1	26.2
	Large (n=30)	0.0	0.0	10.0	80.0	10.0
There is a continued need for IBioIC to exist	Total (n=121)	0.0	0.8	0.0	38.0	61.2
	Micro & SME (n=84)	0.0	1.2	0.0	35.7	63.1
	Large (n=32)	0.0	0.0	0.0	37.5	62.5

Note:

1. Out of a total of 181 responses, only network members (n=121) were included for analysis, any organization that identified as not a member was not included (n=60).

Respondents were also asked whether their interactions with IBioIC contributed to a list of economic benefits to their company, as outlined in Figure 5. The survey results showed that the most influential activity of IBioIC with regards to the economic benefits for both SMEs (and micro) and large organizations were facilitating the creation of industry-to-academia and industry-to-industry strategic relationships, with 65% of the respondents benefiting from the former and 44% from the latter. Overall, the results of the industry network member survey demonstrate a collective agreement within industry on the strategic importance of IBioIC for managing the protected space network.

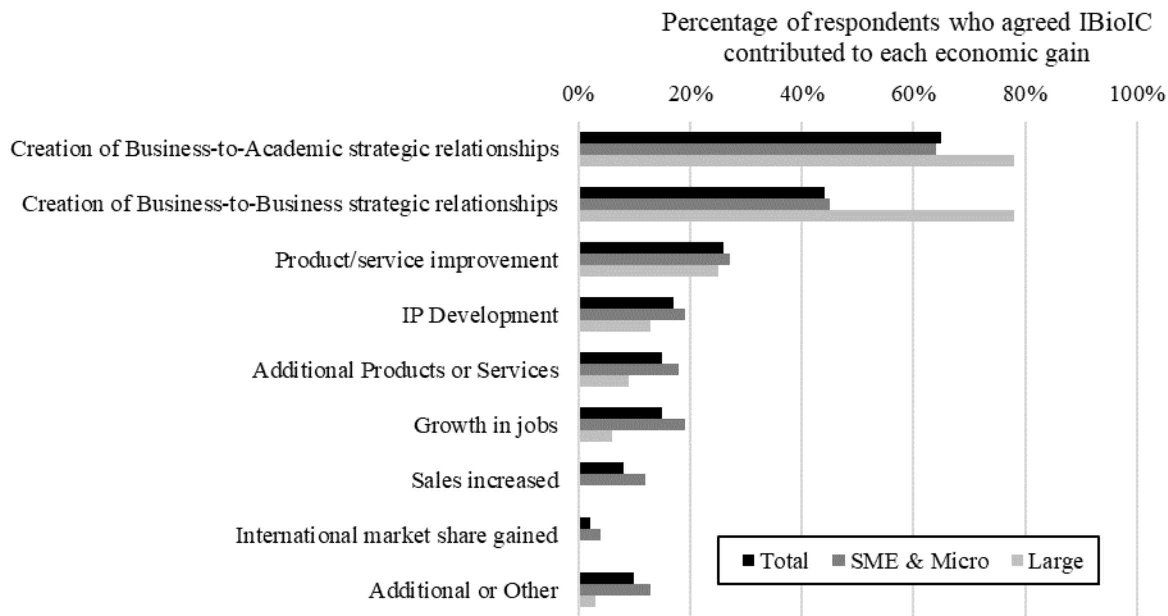

Figure 5: Industry network member opinions on the economic benefits created through IBioIC Activities

Note:

1. Out of 181 total responses, only network members (n=121) were included for analysis, any organization that identified as not a member was not included (n=60). There were 84 SME and Micro organizations and 32 large organizations.
2. Additional/Other benefits suggested by respondents were: (i) raising status and profile of industrial biotechnology in Scotland; (ii) new technology identification; and (iii) raising awareness of opportunities

6. Evaluating the effectiveness of a triple helix-based system intermediary in nurturing a niche innovation network

One of the results of the analysis conducted in this study is that the activities of IBioIC[4] have impacted the structural aspects of the Industrial Biotechnology network by increasing network density; increasing the number of ties; increasing the degree of centralisation and reducing path length (see Table 4). This is suggestive of the effectiveness of IBioIC as niche manager, on the one hand, and the development of trends towards a consensus space within the niche network, on the other. Insofar as IBioIC is bent on to promote adoption of circular economy practices within the network, it can be argued that the conditions on the ground it helped to bring forth can be exploited in favour of the development of technological and market trajectories suited for transition to circular economy. In particular, the extent to which the active participation of the triple helix players is facilitated to promote knowledge generation and knowledge use in line with circular economy principles is critical. The paper validated this hypothesis by demonstrating that the introduction of a triple helix-based system intermediary had a significant positive effect in terms of nurturing the niche by building social networks, facilitating shared learning and promoting shared expectations.

6.1. Building of Social Networks

Unlike traditional SNM managers, the triple helix-based system intermediary in this study was uniquely tasked with the management of the niche at the national level rather than the individual at the experiment level and was co-governed by representatives from public sector stakeholders, universities and industry network members. What makes the structure of governance of IBioIC as a niche intermediary unique is that its basic strategic niche

[4] IBioIC's tasks and activities can be set into three categories: inward facing, outward facing, and both inward and outward facing. The inward facing activities include: provision of technical support; one to one consultations; regular board meetings; PhD sponsorships; introductions; rapid bio-processing and flex bio facilities; rotating board. The outward facing activities include: network integrator role; international partnerships; influencing IB roadmap; informing policy/public sector; Bio-Pilots UK; Bio-Pilots and Bio-based industry; consortium (EU Level); public outreach**;** Influencing public funding. The combined inward and outward facing activities include: IBioIC conference; project group formations/focus groups; hosting European Forum for IB; showcased events; case studies; media releases; newsletters.

management character is augmented by the triple helix governance. This allows the niche intermediary to focus not simply on single experiments but on the much broader system dynamics of triple helix network. As discussed in the paper, the study is based on a synthesis of strategic niche management and the triple helix network. Hence the "uniqueness" of IBioIC governance needs to be seen against the generic SNM mode addressed to single experiments.[5]

The social network analysis and network member survey presented clear evidence of network building by IBioIC. In the period between January 2014 and March 2017, the intermediary was able to double the number of active organizations in the network and increase the number of both weak and strong ties between and within the individual triple helix institutions. The number of frequent contact ties increased by 23% and the number of strategic alliances increased by 46%. In addition to increasing triple helix interactions, the intermediary was able to double the number of collaborative research projects between niche and regime actors, thereby extending the network outwith the immediate niche and increasing the chances of the niche experiments disrupting the current regime configuration. The industrial network member survey, completed approximately a year after the SNA data was collected, demonstrated more than a doubling in the network size, whereby IBioIC contributed to the creation of business-business and business-university strategic relationships by 65% and 44% respectively. This demonstrates that IBioIC has been effective as both expanding the network outwith the initial niche network and has been able to broker a

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[5] The principle underlying the task niche intermediary is essentially the same for IBioIC as it is for the traditional SNM manager in that both seek strategic vantage points to achieve their respective objectives. But compared to the task of the traditional SNM manager which is limited to single experiments, the task of IBioIC as a niche manager is broad in scope involving inward and outward facing activities, complex in nature and systemic in orientation. The wider network IBioIC is tasked to liaise with may expose to the risk of uncertainty, but the resilience in the 'systemness' of its network and the scope for the adoption of innovation deriving from within the niche. This would allow the development of niche-grown technology trajectories, which depending on the underlying selection environment, would be expected to facilitate transition to circular economy. SNM has predominantly been operationalized under the linear lens of managing individual innovation experiments as opposed to re-structuring value chains (Mourik and Raven, 2006; Hoogma et al., 2002). Examples include trialing electric vehicles in a specific location (Weber *et al.*, 1999). However, as outlined in Raven (2005), regime changes do not occur through single experiments. They occur through a long trajectory of numerous niche experiments.

high number of strategic relations between different actors which is necessary to allow shared learning to occur.

By adopting the role of a neutral actor between the triple helix institutions, through the co-governance of all three, the intermediary was able to increase the degree of network centralization between them. A clear sense of leadership and shared expectations within the network tends to be also prevalent in centralised networks, and has been shown to be important for innovation (Van der Valk et al., 2011).

6.2. Facilitating Shared Learning

The success of high scientific technological innovation, such as industrial biotechnology, is dependent on the effective generation, transfer and use of knowledge and resources amongst universities and research institutes and industry (Etzkowitz, 2003). The results of the network analysis demonstrated that a triple helix-based system intermediary is able to increase the level of knowledge and learning exchange within and between the triple helix groups.

Knowledge transfer ties between universities and industry increased by about 34% due to the presence of the intermediary. Technology and IP transfer between the universities and industry increased by 35% and 60% respectively. Asides from brokering knowledge exchange between organizations, the intermediary was also regarded by the network players as a critical sharer of knowledge and was identified in the egocentric analysis as the highest knowledge transferring network actor. The results of the member survey (Figure 5) demonstrated that IBioIC contributed directly to an increase economic benefits such as in product/service improvement, IP development and additional products or services for 27%, 18% and 15% of the respondents respectively. By contributing the increase in such economic benefits, IBioIC has directly contributed to the increase in, and application of, learning within the network.

In addition to stimulating knowledge exchange within the network, the intermediary increased the network cohesion and centralisation for both weak and strong relational ties, whilst maintaining a similar level of network clustering. By increasing network cohesion and centralization whilst maintaining the level of clustering, IBioIC helped lay the important foundations for both tacit and explicit forms of knowledge to be shared more efficiently throughout the network.

Due to the unique governance structure of the intermediary, in which public sector stakeholders were members of the governing board, knowledge transfer between the public sector stakeholders, academia and industry actors was observed to increase. In addition to the increase in knowledge transfer to academia and industry, the number of knowledge transfer ties amongst public sector stakeholders increased by 29%. Such an increase in high quality knowledge transfer both to and amongst public sector stakeholders would be expected to help lay the foundations for improved policy coordination and enforcement, and subsequently, for the introduction and withdrawal of appropriate public sector support, which is a critical objective of SNM.

6.3. Promoting shared expectations

Dedicated intermediating work is needed for expectations to develop within a niche (Raven et al., 2008). This is due to the niche network being comprised of a heterogenous group of stakeholders holding different social interests and perspectives. As such, policy actors are likely to have different expectation profiles compared to a technology developer and the industrial regime actors expectations may contrast with those of the niche innovators.

The work by Raven et al., (2008) found that aligning expectations was challenging for specific local projects. It is therefore logical to argue that upon scaling up the role of niche manager from the project to niche level, the task of promoting and aligning shared expectations is likely too challenging for any one organization to attain.

It is argued in this paper that the role of a niche manager is rather to create the conditions within the network for shared expectations to emerge and evolve organically over time. In particular, Schot and Geels (2008) suggest that expectations are substantiated by on-going collaborative projects. Successful projects confirm initial expectations and new actors are more likely to invest or participate in niche activities thereby strengthening the alignment of expectations (Hermans *et al.*, 2013)

The results of the social network analysis suggest that IBioIC contributed to the establishment of these conditions within the network by brokering strong relational ties between the triple helix niche actors through establishing collaborative research projects and strategic alliances. Perhaps, more importantly, IBioIC was able to bridge structural holes between distant parts of the network and between triple helix institutions. This in turn, increased the network centrality. Increased network centrality, and connectivity, increases the likelihood for expectations to be shared and discussed.

By increasing the number of collaborative ties (such as collaborative research projects, strategic alliances, technology transfer) between the triple helix institutions, as well as bridging structural holes within the network, IBioIC helped to foster the emergence of what Ranga and Etzkowitz (2013, p. 20) call a 'triple helix consensus space'. Ranga and Etzkowitz (2013) argue that it is only when consensus space emerges that shared expectations begin to develop.

Coleman (1988) argues that it is in this institutional overlap that social capital emerges and grows. The efficiency of activities within the network increases with the increase of social capital, which encourages the level of cooperative behaviour required for innovation within networks (Nahapiet and Ghoshal 2017). Increased social capital also enables the emergence of shared expectations and visions and consequently an increase capacity for self-governance within protected space networks (Cai, 2015; Ranga and Etzkowitz, 2013). In addition, building social capital between triple helix institutions is likely to increase the build-up of recombinant knowledge required for successful innovation (Lungeanu and Contractor, 2015).

An important finding of this paper is that, although the intermediary had a somewhat constrained mandate to focus on strengthening academia-industry relations within the network, it was able to double the level of strong ties between regime and niche actors. This increase in niche-regime interactions is not simply an increase in frequency of contact, but also an increase in knowledge and resource flows and the establishment of strategic alliances and collaborative research projects. The latter, in particular, is suggestive of the emergence of shared expectations between niche and regime actors, and of the increasing likelihood of niche innovations being adopted by regime actors. These findings agree with the study by Kivimaa (2014) which argues that the presence of system intermediaries is crucial to trigger regime destabilisation. They also agree with Elzen et al. (2012) which determined that niche-regime hybrid actors, such as innovation intermediaries are critical to technological, network and institutional niche-regime anchoring.

The rather rigid triple helix structure of intermediaries also appears to have prevented the intermediaries from incorporating civil society and third sector actors into the network (otherwise known as the quadruple helix) (Carayannis and Campbell, 2010). This is a crucial omission considering the significance of civil society as integral component in the choice environment for a circular economy-oriented innovation trajectory. SNM researchers have identified that technology users have a critical and active role to play in ensuring the niche innovations are more widely adopted (Weber and Rohracher 2012). Therefore, further investigation needs to be done with regards to exploring how civil society may be incorporated into the development of a niche.

7. Conclusion

This paper argued that the transition to a circular economy requires the establishment of entirely new value chains, which are reliant on the coordinated development, and growth of circular-oriented niche innovation. The paper recognizes the potential role of strategic niche management (SNM) in achieving such systemic re-configuration of the economy but argues that the role of the current SNM network manager must be revised to allow for network level management as opposed to focusing on individual niche experiments.

With this in mind, the paper brings the SNM theory in line with cutting edge practice through an empirical case study of the novel use of a triple helix-based system intermediary as a niche network manager. This was achieved through a complete social network analysis of a national industrial biotechnology innovation network, in which the network manager was innovatively structured as a triple helix-based system intermediary. This allowed for the most comprehensive empirical study to date on the role of system intermediaries in nurturing such networks, facilitating shared learning and raising expectations.

The results of the complete social network analysis demonstrated the positive impact the triple helix-based system intermediary had on the cohesion, the presence of cohesive subgroups and centralization of the niche innovation network. As such, the effectiveness of the intermediary in undertaking the key nurturing activities of building the network, facilitating shared learning and raising expectations were validated. In particular, this paper demonstrated the unique ability of a triple helix-based system intermediary to foster knowledge exchange and collaboration between triple helix institutions and between niche and regime network actors.

From the discussion in this paper, it is apparent that a triple helix-based system intermediary can be leveraged as an effective policy tool for nurturing early stage niche innovation networks, not only in the sense of internally nurturing the network, but also as a channel for governments to steer the network in line with a broader circular economy trajectory.

Although this paper was able to shed light on the impact of a triple helix-based system intermediary on a national niche innovation network, it is not without its limitations. Firstly, by connecting niche actors with regime actors, IBioIC was, to some extent, able to raise awareness, within the network, of external regime expectations and changes. However, additional research is necessary to examine the effectiveness of a triple helix system intermediary in connecting the niche network actors with wider external changes and expectations as well as measuring the effect of processes external to the niche on the niche dynamics.

Secondly, due to the infancy of the Scottish industrial biotechnology network, it was not possible to explicitly identify the impact of IBioIC brokering in terms of creating disruptive changes in the regime. As such, additional longitudinal research is required to explore whether such form of intermediation is capable of creating disruptive changes and regime destabilisation in the long term.

Thirdly, the paper does not categorize the type of learning transferred within the network (such as market, commercial, technical or cultural learning) which would offer valuable insight into the role of a triple helix intermediary in nurturing different forms of learning. However, two types of knowledge transfer were addressed with respect to market, technical and cultural issues: i.e. tacit and explicit knowledge. Explicit knowledge is knowledge which can be easily expressed and recorded as words, numbers, codes, mathematical and scientific formulae. Tacit knowledge is embedded in the human mind through experience and jobs and which is very difficult to extract and codify. By differentiating between explicit and tacit knowledge transfer, the paper partially addresses the challenge of differentiating the different nature of learning. Additionally, by measuring the changes in a range of different types of collaborative relations, that the transfer of different categories of knowledge can be inferred. For example, undertaking joint collaborative R&D projects infer high levels of technical knowledge flow and learning, whereas strategic alliance relational ties infer both market and technical knowledge transfer and learning. This is based on the work by Levinthal and March (1993) who found that the degree to which firms learn about new opportunities is a function of the extent of their participation in interorganizational activities.

Fourthly, although SNA is a useful technique for assessing the structure of an innovation network, it is limited in its ability to explain why such structural changes occur. As such, this analysis could be strengthened through the addition of qualitative methods to explore actor intentions, motivations, frustrations and expectations within the network.

Finally, the paper assessed the impact of a triple helix-based system intermediary on a single circular economy-oriented niche innovation network. In order to gain a broader understanding surrounding the role of a triple helix-based system intermediary as a niche network manager, additional empirical studies should be undertaken on a wide range of circular economy-oriented niche innovation networks such as re-manufacturing, ICT (big data, IoT and blockchain) and renewable energy.

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Appendix I

Table 8: Summary of the number of inter-organisational relationships directly formed or significantly strengthened via IBioIC brokerage.

Organisational ID*	Number of inter-organisational relationships formed directly through IBioIC brokering services	Number of organisational relationships significantly strengthened through IBioIC brokering services
1 (IBioIC)	40	36
2	2	1
3	6	5
4	0	0
5	0	0
6	0	1
7	1	0
8	5	3
9	0	0
10	0	0
11	0	0
12	0	1
13	2	0
14	0	1
15	0	0
16	2	3
17	0	1
18	4	2
19	0	0
20	0	0
21	0	1
22	1	1
23	3	2
24	3	2
25	0	0
26	1	2
27	1	1
28	0	0
29	0	0
30	0	0
31	0	0
32	0	0
33	0	0
34	0	0
35	0	0
36	0	0
37	1	1
38	1	2
39	1	0

40	3	1
41	0	0
42	0	0
43	1	0
44	0	0
45	0	0
46	0	0
47	2	0
48	2	2
49	1	0
50	2	0
51	1	2
52	0	0
53	2	1
54	1	0
55	0	0
56	0	0
57	0	0
58	0	0
59	0	0
60	0	0
61	0	0
62	0	0
63	0	0
64	0	0
Total (Not including IBioIC)	**49**	**36**

Note:

1. *Organisational names have been anonymised due to commercial sensitivity.*