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## Structure and morphology of industrial symbiosis networks: The case of Kalundborg

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### Abstract

Within the field of industrial ecology, Industrial Symbiosis (IS) has emerged as a body of exchange structures to progress to a more eco-efficient industrial system. By establishing a collaborative web of knowledge, material and energy exchanges among different organisational units, IS networks aim to reduce the intake of virgin materials and lower the production of waste by the industrial sector. The aim of this paper is to contribute to the understanding of the operation of IS networks by focussing on the structure and morphology of IS networks and their patterns of interaction and how this influences the outcomes of the collaboration, both in economic and environmental terms. Social Network Analysis (SNA) has been adopted here as the main methodological framework and has been applied to the IS network in Kalundborg (Denmark), proving useful in the analysis of the structural characteristics of the network and the understanding of the role that different actors play. The paper concludes that SNA provides a comprehensive methodological and analytical framework to understand the structural elements of IS networks.

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### 1. Introduction: industrial symbiosis networks

Within the field of industrial ecology, Industrial Symbiosis (IS) has emerged as a body of exchange structures to facilitate progress to a more eco-efficient industrial system. By establishing a collaborative web of knowledge, material and energy exchanges among different organisational units, IS networks aim to reduce the intake of virgin materials and lower the production of waste by the industrial sector. Even though the area has attracted much academic attention and has been reported to lead to economic and environmental benefits (Chertow and Lombardi, 2005), most of the contributions focus on the engineering and technical feasibility of the exchanges and there is still only limited understanding of the social structure and morphology of these networks and the conditions under which they can operate and lead to the reported outcomes. We argue that social network analysis provides a framework for the understanding of the social aspects of IS, offering insights to the structure and interaction of agents within IS networks. IS exchanges cannot be considered in isolation of the social context in which they take place and therefore, the understanding of this context and the patterns of interaction between actors is crucial for the design of policy action to promote IS.

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The aim of this paper is to contribute to the understanding of the operation of IS networks by focussing on the structure and morphology of the networks and their patterns of interaction and how this influences the outcomes of the collaboration, both in economic and environmental terms. Social Network Analysis (SNA) has been adopted here as the main methodological framework and has been applied to the IS network in Kalundborg (Denmark), one of the most relevant examples of IS development, that has been recurrently used as model of IS networks in the literature (Chertow, 2007).

The paper has been structured as follows. Firstly, the application of social network analysis to the understanding of the social aspects of IS is discussed. Secondly, the case study is presented. Thirdly, the core periphery structure of the network, different measures of centrality and aspects such as density, reciprocity or multiplexity are analysed and results discussed. Fourthly, some main findings and conclusions from the case study are drawn about the impact of the structure and morphology in the operation of the network. Finally, the potential of SNA in the understanding of IS networks is discussed and some guidelines for future research are given.

## **2. Understanding the social aspects of industrial symbiosis networks: the contribution of social network analysis**

The emerging field of industrial ecology challenges the traditional idea of the trade off between economic and environmental performance by introducing a new perspective in the organisation of industrial activity that focuses on the improvement of the resource and energy efficiency of the industrial system as a whole through cycling the material and energy flows throughout the system. Industrial Ecology, thus, proposes a new organisation of industrial activities and processes that mirrors the efficient functioning of natural systems, where waste and by-products are subsequently reused and recycled. Within this field, industrial symbiosis is principally concerned with the “cyclical flow of resources through networks of businesses as a means of cooperatively approaching ecologically sustainable industrial activity” (Chertow, 2005). Therefore, the emphasis of industrial symbiosis is on the interfirm interface, focussing on ways of resource optimisation based on collaboration among different industries and activities. It aims to overcome the traditional boundary of the organisation to achieve better environmental collective performance offered by a more global approach to material and energy flows.

A comprehensive definition of industrial symbiosis is that offered by Chertow (2004):

Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchanges of materials, energy, water and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity.

Beyond the technical feasibility of the exchanges, social elements also play a crucial role in the development of IS networks (Domenech and Davies, 2009) and therefore understanding of such elements is essential for the further development of IS.

Social Network Theory provides an theoretical and methodological framework for advancing the understanding of the social aspects surrounding IS networks and can shed some light on issues such as the role of the different members in the network, the processes of information transfer and material exchange negotiation, trust building and alliance formation. The potential to apply SNA to IS has been explored elsewhere (Domenech and Davies, 2009).

## **3. Social network analysis of industrial symbiosis networks: the case study of the industrial symbiosis network of Kalundborg (Denmark)**

### *3.1 Data Sources and Methodology*

The main data for undertaking the analysis of Kalundborg have come from: 1) A site-visit to Kalundborg and in-depth, face-to-face interviews with some of the key actors, and short communications with other relevant agents involved in the network; 2) the examination and analysis of secondary sources such as: company sustainability reports, company environmental policies and programmes, environmental records of emissions, waste and energy (most of this information is accessible through the webpages of the companies participating in the network); 3) Review of the environmental regulatory framework and environmental institutional organisation in the region

through secondary documents and site visits and informal talks with civil servants and governmental officers; and 4) the review of the existing prolific literature on the case.

The methodological strategy has been structured in the following phases: 1) the main participants of the network were identified; 2) dyads were established between the actors, specifying transactional content and intensity, evaluated taking into account the value of the exchanges and frequency of the interaction; 3) a core-periphery structure for the network was proposed and potential local bridges identified; 4) The structural characteristics of the network were analysed. The analysis of the data has been supported by the Social Network software UCINET, version 6.

### 3.2 Introduction

Kalundborg is considered the paradigmatic model of industrial ecology networks (Jacobsen 2006; Chertow, 2007). Over more than four decades the companies in the area have developed a complex web of material and energy exchanges among them that have allowed reducing the environmental impact of the industrial sector by establishing flows of waste materials to be used as raw materials and by the cascading of energy. This industrial ecosystem has led to a significant reduction in the volume of waste generated but also to important economic savings, as shown in Tables X and X. Although the first experiences of cooperation date back to the 60's and are connected to the limited availability of water resources in the area, the number of IS projects has grown to over 22 projects consisting in the exchange and reuse of different types of waste flows. The institutionalisation of the network only took place in 1996 when the companies decided to create the Symbiosis Institute as a platform to diffuse their experience and also contribute to the identification of new potential areas of cooperation.

Table 1. Annual environmental benefits of Kalundborg IS network

Resource/ emission flow	SAVINGS per year
Ground water	2,9 mill m3
Surface water*	1,0 mill m3
Liquid sulphur	20,000 Tn
Biomass	319,000 m3
Biomass (yeast slurry)	42,500 Tn
CO2 emissions**	64, 460 Tn
SO2 emissions***	53 Tn
NOx emissions***	89 Tn
Waste water ****	200,000 m3
Gypsum	170,000 Tn

Data is based on different baseline years, but it is mainly based on calculations made by Christensen in 1998 (personal communication); However, ground water savings incorporates further savings achieved after 2004 by the substitution of ground water by treated surface water at Novozymes. \*Surface water substituted by sea water at Asnaes\*\* Reductions in emissions are calculated as an estimation of the reduction of heavy fuel oil derived from the combined heat and power generation (20,000 tn heavy fuel oil \* 3,223 conversion factor CO<sub>2</sub>). \*\*\* SO<sub>2</sub> and NO<sub>x</sub> are based on 2002 data, Jacobsen (2006). These values are expected to be lower, since unit 5 from Asnaes is no longer fuelled with oil; CO<sub>2</sub> emissions may, on the contrary, be higher, as a result of the fuel substitution (coal for oil); \*\*\*\* This value is calculated as an estimation of waste water recirculation at Asnaes;

Source: Christensen, personal communication 2006; Jacobsen, 2006; Chertow, 2001; Novo nordisk green accounts; Statoil environmental report; Novozymes green accounts; Dong environmental report; Interview data.

Table 2: Economic parameters of the IS network

Investment/ savings	Amount
Investments	US\$ 78.5 mill.
Annual savings	US\$ 15 mill.
Accumulated savings	US\$ 310 mill.

Source: Christensen, 2006, personal communication.

### 3.3 Assumptions

The analysis is based on directed graphs, where ties are not assumed to be reciprocal but having a direction (from node A to node B, but not from B to A, for example). This provides a better representation of the relationships within the network where an IS exchange can be originated in one company but it does not necessarily imply a flow back. Even when IS exchanges generate revenue, money has not been represented as a tie, as the main focus of the research was to study the structure of the IS exchanges and the consideration of money flows in this case might have introduced biases in the morphology of the network. When considering the flows related to knowledge and information, in most cases reciprocity has been assumed (Von Hippel, 1987), even though in some cases the knowledge was originated by a single actor or a pair of actors, the protocols of communication within the companies belonging to the Industrial Symbiosis Institute made it likely for the knowledge to permeate the whole network, leading to innovation and transfer of know-how. However, knowledge and information flows have been considered unidirectional in the case of “external” nodes, as, for example, the flow of fertiliser from Novo industries to the farmers, where the knowledge has been originated by a single actor (Novo industries) with little or no input from the other, in this case, the farmers.

The analysis includes the actors that formally composed the institutionalised network as well as other actors, that although not formally part of it, are playing a role as recipient of flows generated within the network, and have been here referred as “external projects”.

### 3.4 Mapping of actors

The Kalundborg Symbiosis networks is made up of 6 companies, belonging to different sectors of activity: a power station, two major chemical companies, a plaster board manufacturer, a soil remediation company a refinery and the municipality of Kalundborg, that act not as an authority but as supplier/demander of material and energy flows and utilities. There are also some other peripheral actors including farmers from the region, a fishing factory and some material recycling companies that act as recipient of some material flows. The analysis has included all the actors that have at least one exchange with another actor within the network. Other actors, such as Novoren, an urban land field and recycling company, that is formally part of the symbiosis institute but that does not contribute with a tangible exchange, have not been considered in this analysis. The level of commitment and relevance of the role played in the network also varies greatly among the actors. This is examined more closely when analysing the core-periphery structure of the network. In general terms, companies within the Kalundborg network have a high environmental and I+D profile and are medium to large size.

### 3.5 Transactional content

In the IS network of Kalundborg, it is possible to distinguish between four types of transactions: i) exchange of material waste flows; ii) exchange and cascading of water; iii) cascading of energy and iv) exchange of knowledge. While the first three types of contents denote a tangible component, the exchange of knowledge refers to an intangible exchange of know-how, potentially leading to innovation. Different matrices have been elaborated to individually study the different content exchanges. A general matrix has also been generated that encapsulates all the different flows of the network.

The matrix show in Table 3 is a binary matrix, where 1 designs the existence of an exchange flow between a given pair of actors and 0 the absence of link. It corresponds to the general structure of the Kalundborg IS network and therefore considers all the exchange flows taking place among the actors of the network, independently of their transactional content (exchanges of information and knowledge have not been considered in this matrix, as emphasis on the material exchanges is generally stressed in IS; these type of flows would be analysed separately).

**Table 3: Kalundborg IS network Matrix.**

	Novo Nordi	Novozymes	Asnaes Pow	Statoil refin	Gyproc	Soilrem	Municipalit	Farmers	Fish farm	Cement con	Component
Novo Nordisk		1	1	1	0	0	1	1	0	0	0
Novo Enzymes	1		0	0	0	0	1	1	0	0	0
Asnaes Power Station	1	1		1	1	0	1	0	1	1	1
Statoil Refinery	1	1	1		1	0	0	0	0	0	1
Gyproc	0	0	0	0		0	0	0	0	0	0
Soilrem	0	0	0	0	0		0	0	0	0	0
Municipality	0	0	0	0	0	1		0	0	0	0
Farmers	0	0	0	0	0	0	0		0	0	0
Fish Farm	0	0	0	0	0	0	0	0		0	0
Cement companies	0	0	0	0	0	0	0	0	0		0
Component recyclers	0	0	0	0	0	0	0	0	0	0	

Source: Author generated.

Figure 1 shows the graphical representation of the network. It is a directed graph, and hence it is made up by directed arches, that indicate the direction of the link. The graph, as a representation of the structure of the network, already sheds some light upon its properties, offering some approximation to the idea of centrality and density.

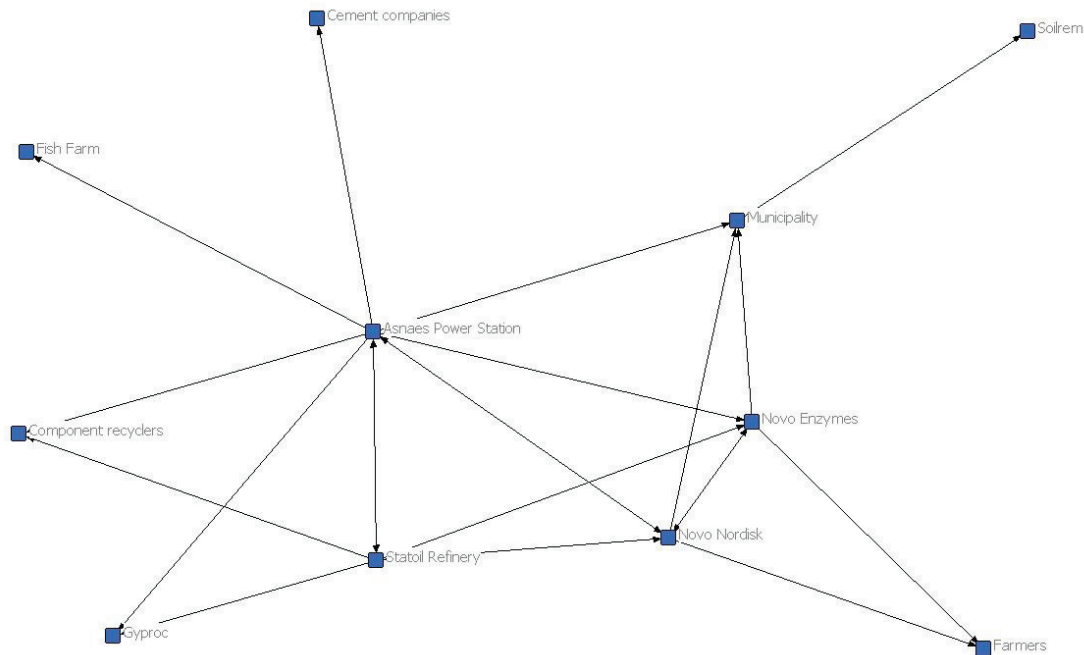


Figure 1: Graphical representation of the Kalundborg IS network

### 3.6 Core-periphery and Size of the Network

As already mentioned, Kalundborg is a small network, made up by six main nodes and a number of secondary nodes, that act as recipients of some of the IS exchanges generated in the network. The network size is a critical element in determining the structure of the network, as it has an impact in aspects such as density and connectivity. In smaller networks, such as the one under study here, actors are more likely to be connected.

The analysis of the core periphery structure of the network defines two core/periphery memberships (class 1 and 2). Class 1 denotes the core of the network, while 2 is composed by the nodes in the periphery:

- 1: Novo Nordisk Novozymes Asnaes Power station Statoil refinery
- 2: Gyproc Soilrem Municipality Farmers Fish farm Cement companies Component recyclers

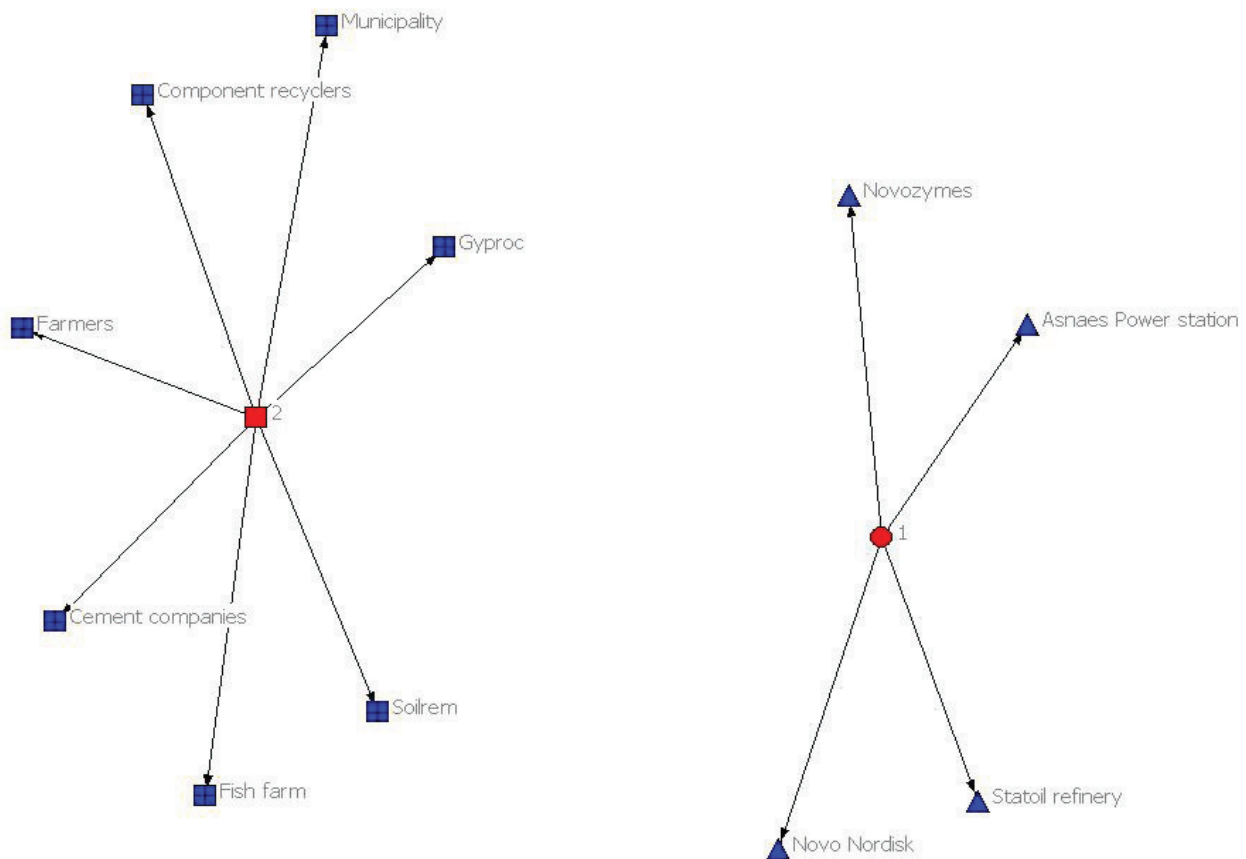


Figure 2: core-periphery structure of the Kalundborg IS network

Similar results are obtained when calculating the coreness values for each node performing a k-core partitioning. The k-core decomposition consists on recursive removing of all the nodes of degree smaller than k, so that larger values of coreness identify with larger degree and more centrally positioned nodes. According to this, the core of the IS network would be composed by all the nodes identified above as core plus the municipality. On the other hand, Soilrem, the fish farm and cement companies present lower coreness values.

Although the calculation of this measure is based on mathematical algorithms, that distinguish between the more densely connected actors from the more loosely class, nodes on the core also share a number of characteristics that may explain this higher density of connections: i) the nodes on the core have frequent formal and informal communication; ii) they were the first members of the network and therefore have a longer history of interaction and



cooperation, which have contributed to the developed of formal and informal protocols of communication and social and emotional linkages among the actors; iii) cooperation over the years has contributed to high levels of reciprocity and trust and iv) in many cases, companies are linked by more than one exchange flow on a continuous basis. On the other hand, some common elements that characterise nodes in the periphery are: i) a less frequent communication among peripheral nodes and with the core; ii) the exchange of information is generally only attached to concrete projects or exchanges; iii) in many cases they act just as recipients of waste flows, and their relations are mainly regulated by market mechanisms leaving no room for embedded relations to develop.

When analysing the core-periphery structure for the different transactional contents of the Kalundborg IS network, only significant changes can be appreciated when considering intangible flows. In the case of the knowledge network, the core is more populated, being composed by the six actors that formally belong to the institutionalised network. This can be explained by the fact that the Symbiosis Institute has contributed to formalise the exchange of information and knowledge among the actors, increasing this way the density of the network.

Due to the small size of the network, local bridges could be relevant for the connection to other potential networks through peripheral actors, increasing the opportunities of creation of new linkages. However, in this case, local bridges have not been identified. This may actually compromise the ability of the network to connect to other nodes and thus may limit its opportunities of exogenous innovation.

### *3.7 Structural equivalence*

The analysis of structural equivalence provides mathematical foundation for identification of the position played by different actors in a network. Structural equivalence refers to the degree to which two nodes have overlapping neighbours, and therefore, may be redundant with regard to adjacency and distance (Bogartti, 2006). Here the measure of structural equivalence is calculated as Euclidean distance (Wasserman and Faust, 2007). The larger the Euclidean distance between two actors, the less structural equivalent the nodes are. Since the content of the transactions in the IS network of Kalundborg varies and they are not mutually interchangeable, the study of structural equivalence needs to be specific to the different types of transactional contents.

For all the content networks, in general terms, Asnaes and Statoil show lower structural equivalence to the other nodes, and therefore, their disconnection would impose a higher risk for the network. Only in the case of the water network, the position of Asnaes and the refinery could be considered structurally equivalent with regard to the IS network, as they play a similar role in terms of adjacency and distance, connecting the same pairs of nodes for the same transactional content. It should be clarified that this analysis only considers the role of the actors with regards to the IS network, and therefore the analysis of structural equivalence aims to understand the position different actors play in this network. Hence, two nodes being structurally equivalent in this analysis refers to their ability to perform a similar role in the IS network, connecting similar pairs of nodes. In the case of IS networks, this requires not only to be able to connect the same pair of nodes but also to generate meaningful material and energy flows for those pairs. Therefore, the analysis has to specifically refer to similar transactional contents. In this context, the results of the structural equivalence analysis need to be evaluated cautiously. In the case of Kalundborg it is difficult to evaluate the consequences of the disconnection of individual nodes, but it seems clear that the position of the power station in the network is crucial for the operation of the whole network and the risks associated with a potential disconnection should not be overlooked. The analysis of the measures of centrality, addressed in the next sections, also contributes to the identification of the key players within the network.

### *3.8 Cliques*

A clique is a subset of nodes, all of which are adjacent to each other. Hence, cliques are cohesive sub-groups of nodes. It should also be noted that it is possible that a node can belong to more than one clique. In the case of the IS network of Kalundborg 5 cliques were identified:

- 1: Novo Nordisk Novozymes Asnaes Power station Statoil refinery
- 2: Asnaes Power station Statoil refinery Gyproc
- 3: Asnaes Power station Statoil refinery Component recyclers
- 4: Novo Nordisk Novozymes Asnaes Power station Municipality
- 5: Novo Nordisk Novozymes Farmers

Asnaes power station belongs to four of the five cliques, while the refinery belongs to three of them. The positions held by these two actors in the network also explains their relevance in the composition of the cliques. Most of the cliques are composed by core actors, which shows a high degree of cohesion at the core of the network. With regards to the composition of the cliques, it is possible to link cliques to specific transactional contents. The first clique seems to be directly related to the cascading of energy and exchange of steam, while the second and third are related to material by-product exchanges. The fourth clique is closely linked to water projects and the fifth one to the fertiliser provision to the farmers by Novo industries.

### 3.9 Structural characteristics of the network

The main structural characteristics of the network have been analysed for the whole network and individually for the content specific sub-networks. General results of the analysis are summarised in Table 4.

Table 4: Structural characteristics of the network.

	Whole network		Materials network		Water network		Energy network		Knowledge network	
Number of ties	22		9		14		6		44	
Density	0.2		0.0818		0.1556		0.0667		0.4889	
Network centralisation	57.78%		18.89%		33.33%		52.78%		33.33%	
Ave. Geodistance	1.585		1.000		1.125		1.143		1.214	
Distance-based cohesion "compactness"	0.279		0.082		0.167		0.072		0.556	
Distance-weighted fragmentation "breadth"	0.721		0.918		0.833		0.928		0.444	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Degree centrality	3.273	2.178	1.455	0.782	1.600	1.685	1.200	1.400	4.600	2.615
Betweenness centrality	2.182	3.0777 999	0.000	0.000	0.200	0.400	0.100	0.300	1.200	2.400
Closeness centrality										
IN	13.407	0.889	9.871	0.713	12.312	2.376	10.788	0.733	23.955	4.737
OUT	29.515	27.922	9.933	1.113	12.606	3.193	11.544	4.273	34.974	16.374

Source: Author generated.



Some key characteristics of the morphology of the network can be derived from the data above. Three different measures of centrality have been used here: degree centrality, betweenness and closeness, as they capture different dimension of the position of an actor in a network. Degree centrality measures the number of direct nodes a node has. This measure assumes that the more direct connections a node has, the stronger is its position in the network. Betweenness centrality, on the other hand, measures the ability of a node to pass information and connect nodes. Therefore, according to this indicator, the identification of key actors will depend on their influence on gaining or cutting access to other nodes in the network. Finally, closeness looks to the distances between nodes in a network. Shorter distances to other nodes result in higher score in closeness.

In general terms, Kalundborg IS network shows a high degree of centralization, which indicates the relevance of central nodes in the operation of the network, as most of the exchanges (or ties) take place among centrally located actors. Also, and partly as a consequence of the level of centralisation and the small size of the network, the average distance among nodes is rather low (1.585), which indicates short paths between companies. This facilitates exchanges and reduces the transactions costs associated with them. The level of centralisation when comparing the different content network is higher in the case of the energy. This seems to point to the relevant role played by the power station in this network, as most of the exchanges are generated by this solely node. This also increases the risk of fragmentation for this content network. In the case of the material network, however, although the level of centralisation is low, the risk of fragmentation is also high, as most of the nodes are just linked to the network by single ties, and therefore, the disconnection of a node, may cause the partition of the network. For example, the disconnection of the refinery would also generate the disconnection of the component recyclers as this is their single tie to the network. The knowledge matrix shows significantly higher density and cohesion as well as degree centrality and betweenness centrality when comparing it with the rest of the content matrices. This seems to point to a well articulated network in terms of information and knowledge transfer. Especially relevant in this case is the relative high mean of betweenness centrality, as the functions of brokerage are essential in the case of the exchange of information and knowledge. Further research needs to be undertaken to understand how these may have an impact on the rest of networks exchanging waste flows.

Although the mean and standard deviation values for the network, as included in Table 4, offer some guidance on the general characteristics of the network, more relevant insights require the analysis of these measures for each of the network nodes, as shown in Table 5, allowing a better understanding of the role played by the different actors in the network.

Table 5: Centrality measure scores by actors.

CENTRALITY NODES	Degree	Betweenness	Closeness	
			IN	OUT
Asnaes power station	8.000	8.667	12.346	83.333
Novozymes	5.000	1.667	12.500	47.619
Novo Nordisk	5.000	7.667	12.500	66.667
Statoil refinery	5.000	2.000	12.346	62.500
Municipality	4.000	4.000	14.085	10.000
Component recyclers	2.000	0.000	13.699	9.091
Gyproc	2.000	0.000	13.699	9.091
Farmers	2.000	0.000	13.889	9.091
Fish Farm	1.000	0.000	13.514	9.091
Cement companies	1.000	0.000	13.514	9.091
Soilrem	1.000	0.000	15.385	9.091

Source: author generated.

The results above confirm the key role of the power station in the Kalundborg IS. It is not only the actor with the highest number of direct ties but also the one that plays the most important role of brokerage in the network. Also

Novo Nordisk proves to be a key actor in the network, especially in its brokerage role, facilitating the connectedness of the network, and therefore its cohesion. In general, as it was expected, actors at the core of the network have higher centrality scores.

### *3.10 Main findings from the network analysis*

The network analysis pointed to distinctive features of the Kalundborg network, which may have an impact on shaping the way it operates and develops. Some main findings of the SNA are summarised here.

The network has a clearly differentiated core and periphery. The core is dense and well articulated, favouring the interaction between the members. This morphology favours the rapid dissemination of ideas and information over the network and therefore, offers the basis for the identification of new IS opportunities among member companies. The periphery, however, is not well structured. Linkages among members located at the periphery have not been found and they do not seem to play a role as local bridges, connecting the network to other networks or potential members. When considering the knowledge and information flows into the general matrix, the core is more populated and well articulated. Further research, however, is necessary to determine whether a well structured knowledge network may have an impact in the way the material based networks operate. The coordination role of the Symbiosis Institute has contributed to institutionalization of the exchange of knowledge and information, however, it is also important to note that most of the projects developed before the institute was created, and therefore in this case informal exchange of knowledge and information seems to have played a more relevant role.

Due to the small size of the network, the path distance is very small, which has contributed to a) reducing the transaction costs associated with the exchanges b) favouring the building of trust and commitment among members. The impact of this on the innovation capacity of the network is another aspect that needs to be further investigated.

In many cases, the linkages are not restricted to a single transactional content but to a combination of them. Companies at the core generally exchange more than one flow within the network. This multiplexity of the linkages contributes to an increase in the density of the network and favours the building of stronger relationships, which could indeed explain the innovation capacity of the network.

The analysis of the centrality measures point to three key players of the networks: the power station, the refinery and Novo industries. Asnaes achieves the highest scores of all measures of centrality. These actors, and especially the power station, are important not only for the number of direct connections they hold with other members of the network, but also for their capacity to connect other nodes, and therefore, to ensure the cohesion of the network. Hence, the disconnection of any of these nodes will cause an important disturbance to the operation of the network, which could lead to defragmentation. However, the analysis of the evolution of the network over the years has shown a strong resilience and capacity of adaptation to the changes operated in the wider economic and regulatory context as well as in the business practices.

## **4. Discussion: the role of SNA for the understanding of IS networks**

As the analysis of the case study demonstrates, SNA provides a comprehensive methodological and analytical framework to understand the structural elements of IS networks. This is of crucial importance for understanding the patterns of the organisation of IS networks and evaluating the impact of network morphology in achieving the expected outcomes. Moreover, the analysis helps to shed some light on the structural elements conditioning the operation of the network and the role different actors play in it. These elements are of extreme importance in a field that still lacks prescriptive frameworks to orientate policy action.

Although IS networks share many of the characteristics of conventional inter-organisational networks, they differ significantly in the content and scope of the cooperation. Therefore, the application of SNA needs to be adapted to the distinctive features of IS networks. As the existence of material exchanges is a key feature of these networks, the understanding of their dynamics required the creation of different content matrices and the separate consideration of knowledge and informational linkages. SNA has proved useful in the analysis of the structural characteristics of IS networks, the identification of the core-periphery of the network and the understanding of the role the different actors play within the network. Further research is needed to understand the factors that drive companies together in the first place and the process of trust building and network development. A homophily analysis could be useful in

the identification of the factors that explain the creation of ties between actors, whether it is related to spatial, social or cognitive proximity. Also relevant for future research is the investigation of the connection between knowledge matrix and the material networks, as this may provide the basis for a better understanding of the adaptation capacity of the network and its ability of innovation.

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