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Uncovering Industrial Symbiosis Opportunities through Social Network Analysis: Case Study of Izmir Ataturk Organised Industrial Zone[1]

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ABSTRACT

Industrial symbiosis (IS) is a novel production system in which firms operating in different industries exchange resources (waste, by-products, energy, water, and information) to enhance resource efficiency and prevent waste. IS applications are primarily based on inter-firm cooperation. An important tool for understanding these collaborations or identifying potential partnerships is social network analysis (SNA). To analyse how SNA can be used in IS practices, the present study identified potential symbiotic relationships and constructed an IS network for firms operating within one organised industrial zone in Türkiye, the İzmir Atatürk Organised Industrial Zone (IAOIZ). In particular, centrality measures were used to reveal which sectors were central to the network and thus played key roles. The findings indicated that these central sectors (metal, cement, glass, and ceramics industries, electricity, chemical, agriculture, paper, plastic, and food sectors) both generate the largest amount of waste and use waste as raw material. The resulting industrial symbiosis network can assist regional policymakers in making decisions. Policymakers can provide support in areas such as legislation, incentives, and the establishment of eco-industrial parks for the sectors identified in this study as having a high ES relationship. Furthermore, such network-based analyses provide a methodological framework for future studies, thereby laying the groundwork for the widespread adoption of industrial symbiosis applications.

Keywords: Industrial symbiosis, social network analysis, circular economy, sustainability

Jel Codes: Q57, P25

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1. Introduction

The technologies and industrial processes that emerged with the Industrial Revolution have greatly increased global production and consumption. However, rapid growth, coupled with natural resource depletion, has led to global overshoot of environmental limits (WWF, 2024). For example, the OECD (2020) predicts that raw material use will double by 2060, in line with increasing global industrialisation and population growth. This massive production and consumption has also created a challenging waste problem that imposes significant costs on national economies. According to the United Nations Environment Programme (UNEP) (2024), for example, cities generate over 2 billion tonnes of solid waste per year, while current waste management practices will impose an additional $640.3 billion in costs by 2050. There are also significant waste problems in sectors like agriculture, construction, health, industry, and trade. The vast majority of the increasing levels of industrial waste is classified as hazardous and causes serious environmental problems due to climate change. In short, current production and consumption processes have caused a significant global waste problem.

Türkiye ranks 140th out of 183 countries in 2024 according to the Environmental Performance Index (EPI) published by the Yale Center for Environmental Law & Policy and the Center for International Earth Science Information Network. This indicates that Türkiye's environmental performance remains at a relatively low level. Moreover, it is evident that the country lags significantly behind European Union and OECD countries in terms of environmental performance. In this context, identifying and developing the potential for industrial symbiosis (IS) in Türkiye is of critical importance. Accordingly, this study focuses on the İzmir Atatürk Organized Industrial Zone (IAOIZ) as the case study area.

Regarding Türkiye specifically, the Turkish Statistical Institute (TSI) estimated that the total waste produced nationally, primarily from Organised Industrial Zones (OIZs) and manufacturing industry workplaces, as well as thermal power plants, mining operations, and households, was 109.2 million tonnes in 2022. Of this, 27% was classified as hazardous. According to the TSI (2022), 28 million tonnes of waste were generated in OIZs and manufacturing industry workplaces, of which 5.4 million tonnes were classified as hazardous. Regarding manufacturing specifically, the primary metal industry and manufacturing accounted for the largest share at 51%, followed by chemicals and plastics at 22%, and the electronics and transport equipment sector at 7% (TSI, 2022). The present study focuses on Izmir, which produces 9% of Türkiye's total waste and a quarter of its hazardous waste (IDA, 2022). The fact that a significant portion of hazardous waste is produced in Izmir was an important reason for choosing this city as the subject of our study. Given the problems outlined above, many countries, including Türkiye, are developing policies to transition from existing production systems to innovative ones to ensure environmental sustainability by increasing resource efficiency and reducing waste. At the forefront are circular economic systems, which can potentially eliminate the current positive correlation between economic growth and waste, increase waste conversion rates, and manage waste safely. To do so, such systems increase resource efficiency by retaining resources within the system as much as possible and significantly reducing waste generation.

IS applications are one of the most important tools for implementing circular economic systems (CEP, 2020). IS is an innovative economic model that has been implemented in many countries as part of sustainability and circular-economy initiatives to address resource efficiency and waste reduction, key themes of environmental sustainability. IS is based on the principle that the waste produced by one factory is used as input by another factory. IS was first introduced by Frosch and Gallopoulos (1989), who defined it as follows: ‘Waste from one industrial process can serve as raw material for another, thereby reducing the industry’s impact on the environment.’

IS applications generally begin by identifying potential waste-raw material exchanges between industries within individual OIZs. The present study has several primary motivations. First, we aim to determine which industries will have greater waste flows and which industry’s waste can be used as raw material for which other industry. Second, we aim to demonstrate that IS can play a key role in developing policies to address waste issues within OIZs. Our study makes a novel contribution by using social network analysis to reveal potential IS applications within a specific OIZ (İzmir Atatürk Organised Industrial Zone-IAOIZ). We identified 120 sectors within IAOIZ and matched producers and users of waste. Social network analysis was then performed using UCINET 6.800. The analysis identified key sectors, which can be used to develop an IS network.

The remainder of the article proceeds as follows: In section 2, after briefly discussing the theoretical framework of IS, section 3 reviews the general literature on information systems and specifically examines studies that use social network analysis methods to investigate information system applications; section 4 explains the dataset and methodology; section 5 presents the findings obtained from social network analysis; and section 6 evaluates the results and findings and includes policy recommendations.

2. Theoretical framework

The acceleration of industrialisation alongside advancing technology and production systems, coupled with the environmental effects of industrial pollution from increasing world population and living standards, has been frequently examined in the literature, leading to a new scientific sub-discipline of “Industrial Ecology and Ecosystems” (Ayres, 1988; Ayres, 1999). Garner and Keoleia (1994) define the fundamental concepts of industrial ecology and guide its application. Focusing on transformation in material and energy flows, they offer a systematic view of interactions between industrial and ecological systems. Chertow (2000) divides industrial ecology into three basic levels: intra-firm, inter-firm, and regional/global. The intra-firm level involves increasing process efficiency by optimising material and energy flows within one facility. The inter-firm level involves increasing efficiency by exchanging materials, energy, water, and by-products between nearby facilities. The regional/global level involves efficiently managing materials and energy flows between distant rather than proximal companies within national and supranational economies.

Chertow (2000) categorises material flows in IS as 'sharing through waste exchange', 'sharing through a company or organisation', 'sharing between companies within a known eco-industrial park', 'sharing between local companies not in a common area', and 'sharing between companies organised virtually across a wide area'. One of the earliest and most successful examples of IS-Kalundborg in Denmark falls under the category of 'sharing between local companies not in a common area'. As the classification suggests, this type of exchange creates space for new companies by starting from the existing flow of materials between companies in different industrial areas. While Kalundborg IS was not initially an eco-industrial park, it enabled companies in the area to benefit from energy, water, and materials flows. Within the industrial ecology literature, numerous studies examining Kalundborg conclude that it is one of the most important examples of industrial symbiosis (Ehrenfeld and Gertler, 1997; Jacobsen, 2006; Valentine, 2016; Gulipac, 2016; Chopra and Khanna, 2014. Beyond Kalundborg IS, numerous initiatives have been conducted in many countries. These include Puerto Rico (Chertow, 2008), the United Kingdom (Mirita, 2004; Gibbs, 2009; Paquin et al., 2015), Sweden (Mirata and Emtairah, 2005), China (Zhu et al., 2007; Guo et al., 2016; Zhang, 2017), Australia (Beers et al., 2008; Golev et al., 2014), South Korea (Park and Behera, 2014), Italy (Taddeo et al., 2017), and Türkiye (Eryılmaz, 2019).

3. Literature Related to Industrial Symbiosis and Social Network Analysis

Within IS, there have been two main groups of SNA-based studies. The first group has investigated relationships within the IS literature the second group has examined IS in specific regions. Given that the present study examines IS relationships within IAOIZ, it belongs to the second group.

We first review SNA-based studies of research articles concerning IS. Huang et al. (2019) combined bibliometrics and SNA to analyse and evaluate the systems, theory, current status, and development trends of IS applications. They concluded that current IS research focuses on four topics: evolution and development, operations, entrepreneurial mechanisms, and efficiency assessment of industrial systems. Vahidzadeh et al. (2021) used SNA and the GEPHI programme to identify the main topics and trends in 112 regional-level IS studies conducted between 1997 and 2019. They identified six main topics: industrial symbiosis and regional learning, waste minimisation, urban IS and life cycle thinking, energy efficiency, operational carriers, and social aspects. Their analysis also revealed a core-periphery structure and identified which topics have become less studied during the recent development of IS research.

We review studies using SNA to identify actual and potential IS. Ashton's (2008) pioneering study of company representatives used SNA and the UCINET programme to investigate how the connections between companies and managers in the Barceloneta Eco-park in Puerto Rico are related to IS connections. Ashton concluded that communication and trust between actors are important factors for achieving IS. In another important study, Domenech and Davies (2011) used SNA to examine the development of IS networks in Kalundborg. Their findings defined the evolutionary stages of IS networks and showed how the network structure changed during these stages. They concluded that SNA provides a comprehensive methodological and analytical framework for understanding the structural elements of IS networks and is one of the most important methods for understanding organisational forms. They argue that SNA is a useful tool for understanding the roles of different actors within an IS network.

Zhang et al. (2016) used SNA to analyse the structural characteristics of various IS networks in China and explain how different structures affect the exchange of materials, energy, and information between network members. Using the fundamental measures of SNA, namely network density and network degree centralisation, they compared eight Chinese IS systems with those in other countries to identify similarities and differences in their structural characteristics. Their analysis determined how particular structures affect resource exchange and identified threats to the stability of these networks.

Song et al. (2018) used SNA to analyze survey data from the Gujiao industrial zone, one of China's mining regions, to assess regional symbiotic relationships among companies. Company representatives within a mining industrial park were interviewed to understand how waste was produced and used. Using SNA centrality measures to evaluate the characteristics and structure of the IS networks, Song et al. revealed that relationships between regional actors affect waste metabolism and presented policy recommendations to managers to develop a more successful IS network.

Regarding SNA studies of IS relationships in Türkiye, most are thesis studies of specific OIZs. For example, Genç (2020) used food network analysis and SNA to assess the sustainability of current and future IS network structures in the construction sector. By identifying potential IS relationships in one industrial zone, he defined the key actors in the industrial network identified four potential waste flow scenarios, and analysed the social relationships that could increase flexibility within the network. Alpar (2023) used SNA to examine IS applications in Eskişehir OIZ from a proximity perspective to identify which sectors were related. The analysis suggested that geographical proximity offered significant opportunities for symbiotic relationships. Şenel (2023) conducted a list study to identify and evaluate NACE codes—the industrial sector codes—of companies operating in Kastamonu OIZ, Tosya OIZ, and Seydiler OIZ in Kastamonu

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province. To identify IS opportunities, Şenel produced a matrix that lists the waste types generated by each company's activity and the NACE codes of the sectors that could use each waste type as a raw material.

This study investigates which sectors in the İzmir Atatürk Organized Industrial Zone (IAOIZ) generate the most waste and how these wastes are used as inputs by other sectors. Unlike the aforementioned studies, this research examines potential industrial symbiosis (IS) applications in IAOIZ through the use of social network analysis (SNA)

4. Data and Method

Here, we specifically review previous studies that use social network analysis (SNA) to examine IS applications. SNA, which is used in various disciplines (e.g., psychology, computer science, education, health sciences), 'examines the relationships and interactions between individuals and groups' (Carrington et al., 2005). SNA is considered a powerful field-appropriate tool for examining and understanding collaborations in IS, particularly, social relationships and connections between organisations or other entities, and the structure of these connections.

SNA not only enables measurement of the connections between actors (nodes) in a network and their relative importance but also enables examination of the characteristics of the entire network of connections (Paquin & Howard-Grenville, 2009). Regarding IS, SNA can be used to identify resource and knowledge flows between businesses, collaboration opportunities, and key players within the network to optimise existing symbiotic relationships and create new collaborations. SNA also helps develop strategies to reduce risks by revealing the network's weak points and fragile structures.

This study used SNA to analyse IS relationships between sectors in IAOIZ in Türkiye based on data obtained from the IAOIZ website and the Waste Declaration System database of the Ministry of Environment, Urbanisation and Climate Change. More specifically, the SNA focused on centrality measures and ego networks.

4.1. Data Sources

One of the largest organised industrial zones in İzmir province, IAOIZ is a major industrial centre. It contains 650 companies across a wide range of industries, including textiles, ready-to-wear clothing, machinery, automotive supplies, metals, plastics, chemicals, food, and electrical and electronics (IAOIZ, 2025). This industrial diversity was a main reason for selecting this zone.

A total of 120 NACE codes (statistical classification of economic activities) for IAOIZ companies were obtained from IAOIZ's official website. Each NACE code represents companies operating in that sector. The waste and waste codes generated by these sectors were then determined from the list (NACE code-waste code) published by the Ministry of Environment, Urbanisation and Climate Change in its Waste Declaration System database for Izmir province in 2022, which includes sectors and wastes. The NACE codes for each company were selected based on the waste type produced the most and the associated codes. Potential symbiotic relationships, i.e., sectors that could use these wastes as raw materials, were identified by matching and database searches in sectoral case studies of IS applications conducted in other countries in which one sector produces waste and another sector receives it. One of these is the MAESTRI database, compiled by the University of Cambridge from various case studies (MAESTRI, 2025). The MAESTRI database is a research project funded by the European Union (EU) and carried out under the IS framework. It combines symbiotic relationships in IS applications implemented in different regions. The database lists, using NACE codes and waste codes, both the wastes from production processes across many sectors and the sectors that use these wastes as raw materials (Genç, 2020). The NACE codes and waste code matches in MAESTRI were examined and the NACE codes identified in IAOIZ were compared against the codes in the waste list published by the Ministry of Environment, Urbanization and Climate Change for İzmir province. In addition, scientific studies (articles, book presentations, etc.) of IS were examined in depth to identify further matches. Finally, symbiotic matches were identified from IS feasibility studies conducted by various institutions and organisations in Türkiye (development agencies, universities, foundations, etc.).

All the obtained matches were listed in an Excel worksheet to create a neighbourhood matrix, with waste producers (sellers) across rows and waste recipients (NACE codes) across columns. Table 1 shows an example of a 120x120 neighbourhood matrix prepared for IAOIZ.

Table 1: Example of a Neighbourhood Matrix for SNA

NACE CODE (NC)	**NC1**	**NC2**	**NC3**	**NC4**	**NC5**
NC1	0	1	1	0	0
NC2	1	0	0	0	1
NC3	1	0	0	1	1
NC4	0	1	1	0	0
NC5	1	0	1	1	0

Source: created by authors

Sectors with a source (waste) relationship between them were assigned a value of ‘1’, while sectors with no relationship were assigned a value of ‘0’. Subsequently, the structural characteristics of the network were analysed using UCINET version 6.800, one of the most commonly used programmes for SNA while the network was visualised using the NetDrawprogramme included in the software.

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Constraints

OIZs are considered advantageous sites for IS research because they represent many different industrial sectors. Symbiotic partnerships encompass diverse alternatives and direct or indirect connections among actors. However, one limitation of the present study is that it disregards legal regulations and directives on waste management in symbiotic partnerships, and instead matches waste generated by one sector with other sectors based on case studies and databases. The aim here is to determine which sectors in the region are more suitable for IS and to provide preliminary work for projects to be implemented or developed in this region.

The second constraint is that it considers inter-sectoral waste-raw material exchange in IS as a technical issue. However, social relationships are very important because strong cooperation between business managers increases the feasibility of IS applications (Ashton, 2008). The present study did not take social relationships between managers into account. Future studies could measure the strength of cooperation between the business managers identified and centralised here.

4.2. Method

The study identified which sectors within IAOIZ can use waste from specific sectors as raw materials to increase resource efficiency and prevent waste within the OIZ. An IS network map between sectors was created using SNA, which examines the relationships among individuals, organisations, and other entities within the same or different groups (Wasserman & Faust, 1994). SNA, which has many applications, is based on graph theory and consists of nodes (actors within the social network; individuals, sectors, managers) and edges (connections between nodes) that represent relationships between nodes (Scott, 2000). SNA uses mathematical models to present data sets containing information about the connections between actors and the connections themselves (Freeman, 2004). Any type of connection between actors allows examination of information such as social, economic, collaborative, and resource-sharing relationships and enables the identification of important actors in the network.

By using SNA, the present study aimed first to identify potential symbiotic relationships based on waste-raw material exchanges between businesses located in IAOIZ. It then aimed to establish an IS network by identifying the sectors at its centre and determining the sectors they are most connected to. The nodes represent the NACE codes of each sectors operating in IAOIZ. The edges, or connections, (i.e., connections between waste producers and receivers).

SNA involves performing various measurement analyses to determine the network's structure and method, and to identify the key actors at its centre. These measurements, particularly centrality measures (Gürsakal, 2009), play an important role in understanding the roles of the nodes (actors) within the network and, through these roles, the structure of the network and the nature of the social relationships.

4.2.1. Centrality measures

Centrality measures are the most fundamental tools for analysing the positions of actors within a network (Yeşilbaş, 2023). The actor positioned closest to the centre within a network is considered to have the most influence and connections. SNA centrality measures are among the most widely used criteria for analyzing sociological and economic issues across many disciplines. They can be used to assess an actor's control over connections within the network, access to resources, and the transfer of these resources to other actors (nodes) (Wasserman & Faust, 1994). The most important centrality measures are degree, betweenness, and closeness.

Degree centrality (DC) measures the number of connections an actor has with other actors in a social network (Gürsakal, 2009). Actors with the highest DC values are those with the most connections and are located at the centre. Inter-company connections are categorized by direction: input degree and output degree. The former indicates the number of connections coming to actors whereas the latter indicates the number of connections going from one actor to other actors (Yeşilbaş, 2023). In the present study, in-degree centrality represents NACE codes for waste-receiving companies; out-degree centrality represents NACE codes for waste-selling companies. Both total in-degree and out-degree centralities were considered to determine the NACE codes (sectors) with the highest values.

Betweenness centrality (BC) measures how much a node acts as a bridge within a social network. In other words, it identifies the actors that control the flow of resources between two other actors. Companies with high BC are the actors that other companies most often turn to reach each other (Song et al., 2018). Within IS, waste flows follow the shortest routes from a cost perspective. Hence, high-BC companies are those approached to identify the shortest waste-flow routes, giving them significant influence and control over waste transfers within a network (Song et al., 2018).

Closeness centrality (CC) measures an actor's direct proximity or distance from other actors. As Wasserman and Faust (1994) put it, 'the closeness centrality measure … measures the shortest distance from a given node to another node, and the shorter the paths between an actor and other actors within the network, the higher the actor's closeness centrality value.' Internal and external closeness measures can be calculated separately, or their sum can be considered and evaluated. In IS applications, this measure indicates the degree to which a company may be affected by other companies (Song et al., 2018).

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Density indicates the frequency of connections between nodes and how closely they are linked. Applied to IS, it expresses the ratio of potential connections in the network to actual connections (Gürsakal, 2009). In networks with high density values, resource sharing occurs more frequently and more rapidly.

5. Research Findings

5.1. Structural Characteristics of the Network

The structural characteristics of the network provide us with basic information about it[4] As Table 2 shows, the SNA for IAOIZ identified 120 nodes (i.e., sectors) and 570 connections (i.e., potential IS connections).

Table 2: Structural Characteristics of IAOIZ Network

Features	IAOIZ Network
Number of Nodes	120
Number of Connections	570
Density	0.040
Standart Deviation	0.196

Source: Created by the authors using the UCINET 6.800 programme

In Table 2, the distribution value was calculated as 0.040 (ss; 0.196). The density value is between 0 and 1, and the closer it is to 1, the denser and more efficient it is (Song, Geng, Dong and Chen, 2018). Our results show that potential waste exchanges in the IAOIZ are not very efficient, but efficiency can be increased by establishing bilateral cooperation.

5.2. General Network Map of Potential Symbiotic Relationships in IAOIZ

A potential network map is created by loading the all-pairs adjacency matrix into the NetDraw add-on within UCINET. Figure 1 shows the potential symbiotic relationships of the sectors within IAOIZ under the IS framework.

In Figure 1, each NACE code represents one sector, while the lines indicate waste flows. Sectors with the highest waste flows are potentially located more centrally while sectors with fewer connections are located more peripherally. More specifically, sectors with NACE codes 24.10, 23.31, 23.65, 35.11, and 01.00 are located more whereas while sectors with NACE codes 14.11 and 33.15, which have no connections, are located outside the network map.

[4] In this study, the relationships between sectors reflect potential relationships rather than existing ones.

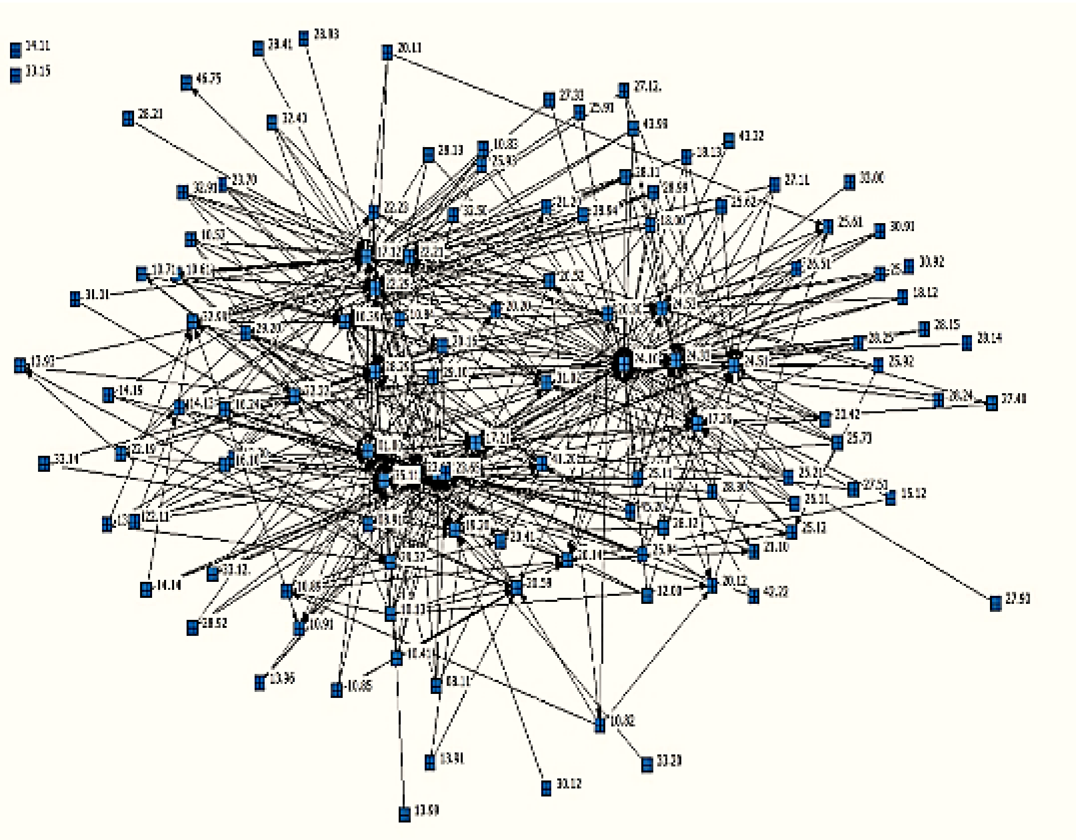
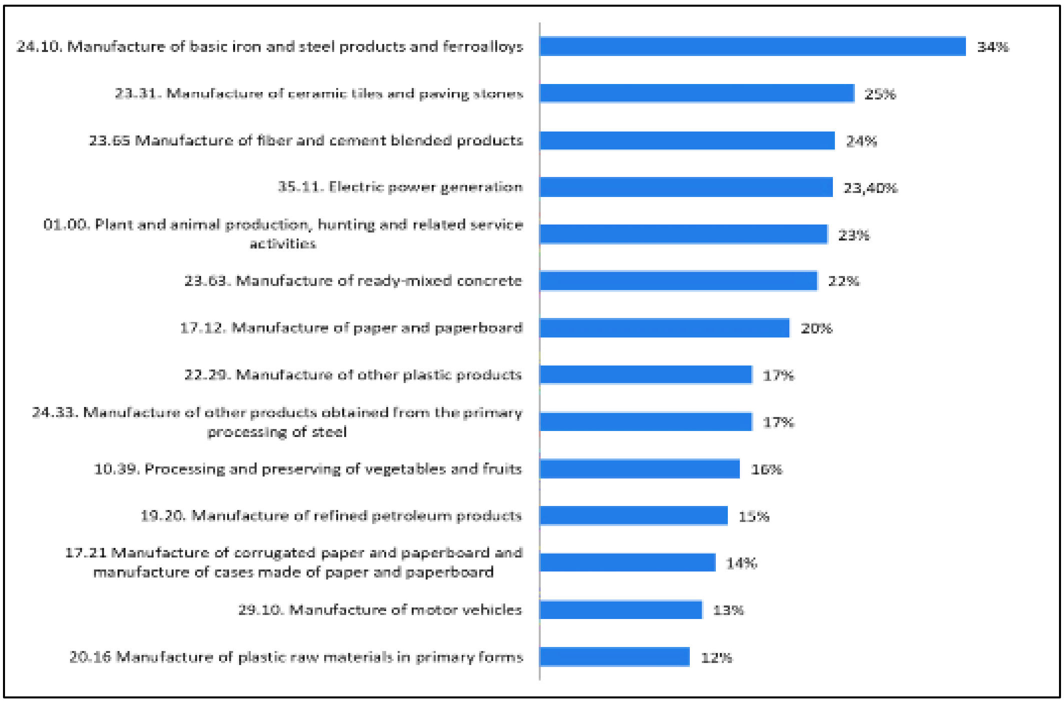


Figure 1: Network Map Showing Potential Symbiotic Relationships in IAOIZ

Graph 1: Key Sectors for Potential IS in IAOIZ



Source: created by authors

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Graph 1 presents the 12 most highly connected sectors, located at the centre of the network map in Figure 1, to illustrate potential symbiotic relationships within IAOIZ. The most highly connected sector is the manufacture of basic iron and steel products (NACE code 24.10), followed by the manufacture of ceramic tiles and paving stones (NACE code 23.31). More generally, the primary metal industry and the manufacture of other non-metallic mineral products (cement, ceramics, lime, glass) produce the most waste and receive the most waste from other sectors for use as raw materials. For example, many primary metal industry companies produce unprocessed slag as waste during manufacturing, which ceramic or cement sector companies can buy to use as a raw material. Thus, the network map makes the flow of resources clear.

5.3. Centrality Measures of Potential Symbiotic Relationships in IAOIZ

5.3.1. Degree Centrality (DC) Analysis

As outlined earlier, an actor with a high DC value occupies a central position in the network and plays an important role (Scott, 2000). Because they produce or receive the most waste potentially, such actors are seen as the most influential in resource flows and significantly influence network formation. For waste-receiving actors, DC is calculated as the input degree and represents the total number of connections (edges) directed towards them in the network. For waste-selling actors, DC is calculated as the output degree and the total number of connections originating from actors with high degrees. Total DC thus indicates the most important waste-producing and waste-receiving sectors within the network potentially (Song et al., 2018). Table 3 presents the DC analysis for IAOIZ, while Figure 2 shows the DC network map.

Table 3: Degree Centrality Analysis for IAOIZ

No	N.K	DC_{IN}	DC_{OUT}	DC_T	No	N.K	DC_{IN}	DC_{OUT}	DCT
1	01.00	26.000	14.000	40.000	**61**	24.51	21.000	3.000	24.000
2	08.11	0.000	5.000	5.000	**62**	24.53	16.000	1.000	17.000
3	08.91	0.000	9.000	9.000	**63**	25.11	1.000	8.000	9.000
4	10.13	0.000	11.000	11.000	**64**	25.12	3.000	3.000	6.000
5	10.39	18.000	9.000	27.000	**65**	25.21	0.000	5.000	5.000
6	10.41	0.000	6.000	6.000	**66**	25.29	0.000	3.000	3.000
7	10.52	0.000	6.000	6.000	**67**	25.61	4.000	3.000	7.000
8	10.61	1.000	6.000	7.000	**68**	25.62	0.000	6.000	6.000
9	10.71	1.000	5.000	6.000	**69**	25.73	0.000	5.000	5.000
10	10.82	1.000	4.000	5.000	**70**	25.91	0.000	2.000	2.000
11	10.83	0.000	5.000	5.000	**71**	25.92	0.000	5.000	5.000
12	10.84	0.000	8.000	8.000	**72**	25.93	0.000	4.000	4.000
13	10.85	0.000	4.000	4.000	**73**	25.94	0.000	8.000	8.000
14	10.89	2.000	8.000	10.000	**74**	26.11	0.000	5.000	5.000
15	10.91	3.000	4.000	7.000	**75**	26.51	0.000	4.000	4.000
16	12.00	0.000	4.000	4.000	**76**	27.11	0.000	4.000	4.000
17	13.30	4.000	10.000	14.000	**77**	27.12.	0.000	4.000	4.000
18	13.91	0.000	2.000	2.000	**78**	27.33	0.000	2.000	2.000
19	13.92	0.000	4.000	4.000	**79**	27.40	0.000	3.000	3.000
20	13.93	3.000	1.000	4.000	**80**	27.51	0.000	2.000	2.000
21	13.96	0.000	3.000	3.000	**81**	27.90	0.000	1.000	1.000
22	13.99	0.000	1.000	1.000	**82**	28.11	0.000	6.000	6.000
23	14.11	0.000	0.000	0	**83**	28.12	0.000	7.000	7.000

24	14.13	6.000	4.000	10.000	**84**	28.13	0.000	3.000	3.000
25	14.14	0.000	4.000	4.000	**85**	28.14	0.000	1.000	1.000
26	14.19	0.000	3.000	3.000	**86**	28.15	0.000	3.000	3.000
27	15.12	0.000	2.000	2.000	**87**	28.21	0.000	1.000	1.000
28	16.10	3.000	4.000	7.000	**88**	28.24	0.000	1.000	1.000
29	16.24	4.000	8.000	12.000	**89**	28.25	0.000	5.000	5.000
30	17.12	37.000	9.000	46.000	**90**	28.29	22.000	4.000	26.000
31	17.21	16.000	8.000	24.000	**91**	28.30	0.000	6.000	6.000
32	17.29	13.000	4.000	17.000	**92**	28.41	0.000	1.000	1.000
33	18.00	0.000	4.000	4.000	**93**	28.92	0.000	3.000	3.000
34	18.12	0.000	3.000	3.000	**94**	28.93	0.000	1.000	1.000
35	18.13	0.000	4.000	4.000	**95**	28.94	0.000	6.000	6.000
36	19.20	11.000	10.000	21.000	**96**	28.99	0.000	6.000	6.000
37	20.11	0.000	3.000	3.000	**97**	29.10	0.000	13.000	13.000
38	20.12	4.000	3.000	7.000	**98**	29.20	2.000	6.000	8.000
39	20.14	9.000	6.000	15.000	**99**	29.32	5.000	8.000	13.000
40	20.16	5.000	9.000	14.000	**100**	30.12	0.000	1.000	1.000
41	20.20	3.000	6.000	9.000	**101**	30.91	0.000	3.000	3.000
42	20.30	3.000	7.000	10.000	**102**	30.92	0.000	3.000	3.000
43	20.41	2.000	8.000	10.000	**103**	31.01	0.000	2.000	2.000
44	20.42	1.000	3.000	4.000	**104**	31.02	8.000	7.000	15.000
45	20.52	1.000	6.000	7.000	**105**	32.40	0.000	4.000	4.000
46	20.59	8.000	5.000	13.000	**106**	32.50	0.000	6.000	6.000
47	21.10	2.000	2.000	4.000	**107**	32.91	0.000	5.000	5.000
48	21.20	1.000	4.000	5.000	**108**	32.99	9.000	3.000	12.000
49	22.11	3.000	4.000	7.000	**109**	33.00	0.000	1.000	1.000
50	22.19	2.000	6.000	8.000	**110**	33.12.	0.000	5.000	5.000
51	22.21	21.000	3.000	24.000	**111**	33.14	0.000	2.000	2.000
52	22.22	4.000	10.000	14.000	**112**	33.15	0.000	0.000	0
53	22.23	3.000	4.000	7.000	**113**	33.20	0.000	1.000	1.000
54	22.29	23.000	9.000	32.000	**114**	35.11	31.000	5.000	36.000
55	23.31	35.000	9.000	44.000	**115**	41.20	9.000	4.000	13.000
56	23.63	31.000	5.000	36.000	**116**	42.22	0.000	2.000	2.000
57	23.65	33.000	6.000	39.000	**117**	43.22	0.000	2.000	2.000
58	23.70	0.000	5.000	5.000	**118**	43.99	0.000	3.000	3.000
59	24.10	63.000	17.000	80.000	**119**	45.20	0.000	7.000	7.000
60	24.33	32.000	5.000	37.000	**120**	46.75	1.000	1.000	2.000

Source: Created by the authors using the UCINET 6.800 programme

Table 3 shows the input degree (DC_{IN}), output degree (DC_{OUT}), and total degree (DC_T) centrality measurements. Sectors with high input degrees, i.e., sectors receiving waste under the ES scope, have NACE codes (01.00, 10.39, 17.12, 22.21, 22.29, 23.31, 23.65, 24.10, 35.11...) The manufacturing of plant and animal products sector, the primary metal industry, chemical product manufacturing, and other non-metallic product manufacturing sub-sectors stand out. Similarly, when looking at sectors with a high output level, i.e., waste-selling sectors with NACE codes (01.00, 10.13, 19.20, 22.22, 24.10, 29.10) show that the food, textile, petroleum products, plastics, and motor vehicle manufacturing sectors stand out. When examining the NACE codes of sectors with high total degree centrality, i.e., those at the center of the network playing a significant role in potential symbiotic relationships, it is seen that, along with the above sectors, the clothing, paper products, electricity, and wood products manufacturing sectors also have high degree centrality.

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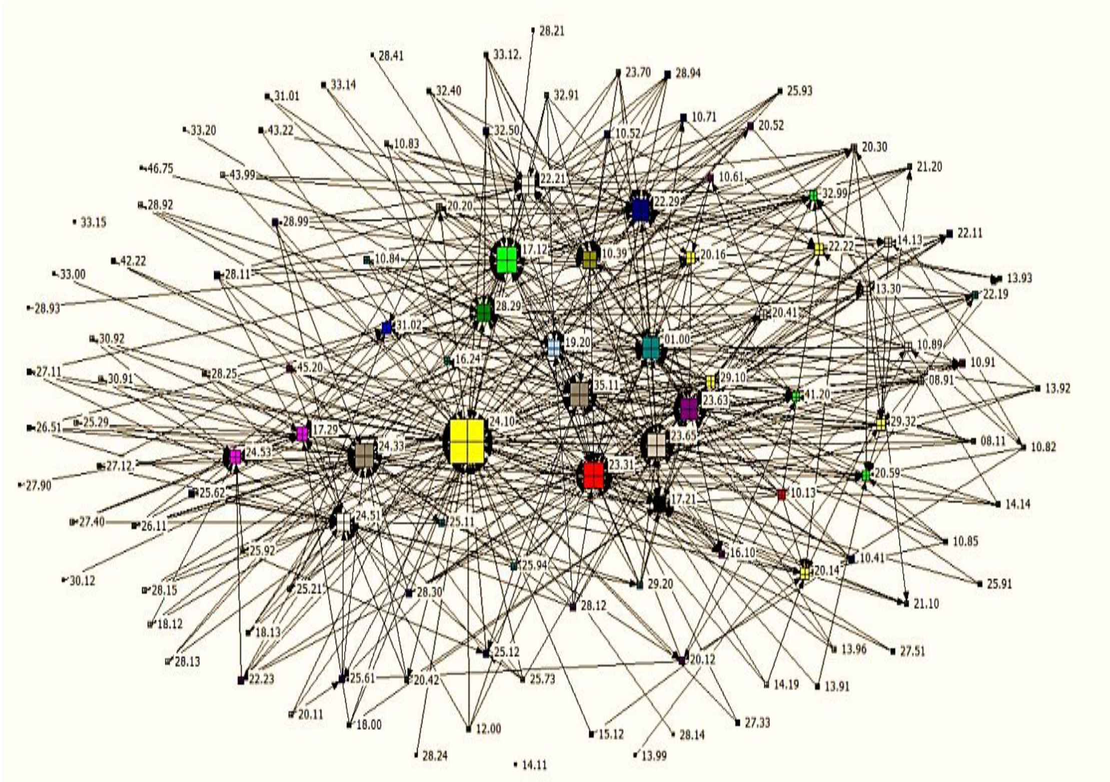

Figure 2: Degree Centrality Network Map for IAOIZ

Figure 2 shows the locations and sizes of the NACE codes (sectors) on the IAOIZ network map based on DC values. NACE codes with high DC values are located more centrally whereas sectors with low values are located more peripherally. The NACE code with the largest node (shown in yellow) on the network map is 24.10 (manufacture of basic iron and steel products and ferro-alloys sector).

5.3.2. Betweenness Centrality (BC) Analysis

As outlined earlier, BC measures the degree to which a connecting actor acts as an intermediary between two other actors. In other words, it measures an actor's ability to provide resource flows and to connect actors to one another (Ataç, 2019). A high value helps identify the actors controlling waste flows. Table 4 shows the BC values of actors who are potential intermediaries in IS applications for IAOIZ.

Table 4: Betweenness Centrality Measurement Analysis for IAIOZ

No	NC	BC	NO	NC	BC	NO	NC	BC
1	01.00	936.287	**41**	20.20	70.574	**81**	27.90	0.000
2	08.11	0.000	**42**	20.30	167.286	**82**	28.11	0.000
3	08.91	0.000	**43**	20.41	134.971	**83**	28.12	0.000
4	10.13	0.000	**44**	20.42	45.916	**84**	28.13	0.000
5	10.39	150.675	**45**	20.52	273.445	**85**	28.14	0.000
6	10.41	0.000	**46**	20.59	50.039	**86**	28.15	0.000
7	10.52	0.000	**47**	21.10	2.352	**87**	28.21	0.000
8	10.61	5.111	**48**	21.20	5.105	**88**	28.24	0.000

9	10.71	47.148	**49**	22.11	29.532	**89**	28.25	0.000
10	10.82	119.889	**50**	22.19	5.976	**90**	28.29	171.61
11	10.83	0.000	**51**	22.21	100.671	**91**	28.30	0.000
12	10.84	0.000	**52**	22.22	28.521	**92**	28.41	0.000
13	10.85	0.000	**53**	22.23	30.178	**93**	28.92	0.000
14	10.89	18.177	**54**	22.29	450.511	**94**	28.93	0.000
15	10.91	1.244	**55**	23.31	475.006	**95**	28.94	0.000
16	12.00	0.000	**56**	23.63	194.224	**96**	28.99	0.000
17	13.30	236.625	**57**	23.65	302.435	**97**	29.10	0.000
18	13.91	0.000	**58**	23.70	0.000	**98**	29.20	6.610
19	13.92	0.000	**59**	24.10	2.251.433	**99**	29.32	235.75
20	13.93	20.806	**60**	24.33	350.864	**100**	30.12	0.000
21	13.96	0.000	**61**	24.51	48.691	**101**	30.91	0.000
22	13.99	0.000	**62**	24.53	24.918	**102**	30.92	0.000
23	14.11	0.000	**63**	25.11	128.051	**103**	31.01	0.000
24	14.13	80.723	**64**	25.12	12.365	**104**	31.02	137.74
25	14.14	0.000	**65**	25.21	0.000	**105**	32.40	0.000
26	14.19	0.000	**66**	25.29	0.000	**106**	32.50	0.000
27	15.12	0.000	**67**	25.61	77.711	**107**	32.91	0.000
28	16.10	15.763	**68**	25.62	0.000	**108**	32.99	112.21
29	16.24	23.817	**69**	25.73	0.000	**109**	33.00	0.000
30	17.12	649.652	**70**	25.91	0.000	**110**	33.12.	0.000
31	17.21	160.322	**71**	25.92	0.000	**111**	33.14	0.000
32	17.29	133.587	**72**	25.93	0.000	**112**	33.15	0.000
33	18.00	0.000	**73**	25.94	0.000	**113**	33.20	0.000
34	18.12	0.000	**74**	26.11	0.000	**114**	35.11	146.90
35	18.13	0.000	**75**	26.51	0.000	**115**	41.20	83.846
36	19.20	195.791	**76**	27.11	0.000	**116**	42.22	0.000
37	20.11	0.000	**77**	27.12.	0.000	**117**	43.22	0.000
38	20.12	17.144	**78**	27.33	0.000	**118**	43.99	0.000
39	20.14	139.235	**79**	27.40	0.000	**119**	45.20	0.000
40	20.16	107.538	**80**	27.51	0.000	**120**	46.75	0.000

Source: Created by the authors using the UCINET 6.800 programme.

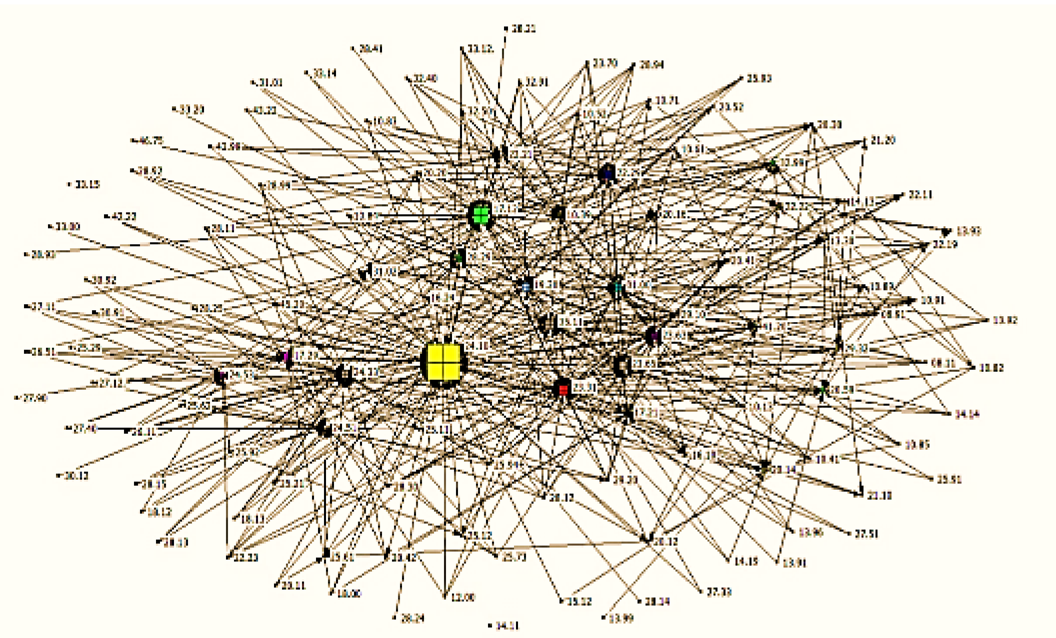

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Figure 3: Betweenness Centrality Network Map for IAOIZ

Table 4 shows that the sectors with the highest BC values have the following NACE codes: 24.10, 01.00, 17.12, 22.29, 23.31, 23.65, and 24.33. That is, regarding IS, these sectors have the highest potential for making connections with other sectors within the network. Sectors with high BC values are located at the centre of the network, indicating that they control waste flows within it.

The similarity between the network maps for DC (Figure 2) and BC (Figure 3) indicates that sectors that play a key role within the network, being located at the centre, also have the most connections with other sectors and thus serve as intermediaries between them.

5.3.3. Closeness Centrality (CC) Analysis

Closeness centrality measures the distance between an actor and other actors in a network, which indicates how quickly they interact (Ataç, 2019). An actor with a high internal closeness value (CC_{IN}) is closer to other actors, while an actor with a high external closeness value (CC_{OUT}) is farther away from other actors and located farther outside the center of the network (Huang, Wang, & Chen, 2019). Since CC includes both indirect and direct connections, the more direct connections there are between two actors within the network, i.e., the fewer intermediary actors there are, the higher these actors' CC value will be, which indicates that they can be more independent and influential within the network (Tüzüntürk, 2012).

Table 5: Closeness Centrality Analysis for IAOIZ

No	N.K	CC_{OUT}	CC_{IN}	CC_T	No	N.K	CC_{OUT}	CC_{IN}	CC_T
1	**01.00**	0.199	0.511	0.710	61	**24.51**	0.187	0.329	0.516
2	**08.11**	0.193	0.143	0.336	62	**24.53**	0.179	0.442	0.621
3	**08.91**	0.201	0.143	0.344	63	**25.11**	0.194	0.331	0.525
4	**10.13**	0.200	0.143	0.343	64	**25.12**	0.196	0.146	0.342
5	**10.39**	0.194	0.389	0.583	65	**25.21**	0.195	0.143	0.338
6	**10.41**	0.194	0.143	0.337	66	**25.29**	0.192	0.143	0.335
7	**10.52**	0.195	0.143	0.338	67	**25.61**	0.190	0.408	0.598
8	**10.61**	0.195	0.286	0.481	68	**25.62**	0.196	0.143	0.339
9	**10.71**	0.192	0.342	0.534	69	**25.73**	0.195	0.143	0.338
10	**10.82**	0.192	0.283	0.475	70	**25.91**	0.191	0.143	0.334
11	**10.83**	0.196	0.143	0.339	71	**25.92**	0.195	0.143	0.338
12	**10.84**	0.199	0.143	0.342	72	**25.93**	0.196	0.143	0.339
13	**10.85**	0.193	0.143	0.336	73	**25.94**	0.197	0.143	0.340
14	**10.89**	0.196	0.225	0.421	74	**26.11**	0.195	0.143	0.338
15	**10.91**	0.187	0.345	0.532	75	**26.51**	0.193	0.143	0.336
16	**12.00**	0.196	0.143	0.339	76	**27.11**	0.194	0.143	0.337
17	**13.30**	0.197	0.367	0.564	77	**27.12.**	0.187	0.143	0.330
18	**13.91**	0.186	0.143	0.329	78	**27.33**	0.191	0.143	0.334
19	**13.92**	0.189	0.143	0.332	79	**27.40**	0.187	0.143	0.330
20	**13.93**	0.183	0.306	0.489	80	**27.51**	0.192	0.143	0.335
21	**13.96**	0.187	0.143	0.330	81	**27.90**	0.183	0.143	0.326
22	**13.99**	0.184	0.143	0.327	82	**28.11**	0.198	0.143	0.341
23	**14.11**	0.143	0.143	0.286	83	**28.12**	0.196	0.143	0.339
24	**14.13**	0.189	0.342	0.531	84	**28.13**	0.192	0.143	0.335
25	**14.14**	0.190	0.143	0.333	85	**28.14**	0.189	0.143	0.332
26	**14.19**	0.190	0.143	0.333	86	**28.15**	0.192	0.143	0.335

27	**15.12**	0.192	0.143	0.335	**87**	**28.21**	0.181	0.143	0.324
28	**16.10**	0.188	0.367	0.555	**88**	**28.24**	0.189	0.143	0.332
29	**16.24**	0.194	0.379	0.573	**89**	**28.25**	0.195	0.143	0.338
30	**17.12**	0.193	0.531	0.724	**90**	**28.29**	0.193	0.500	0.693
31	**17.21**	0.195	0.423	0.618	**91**	**28.30**	0.195	0.143	0.338
32	**17.29**	0.195	0.399	0.594	**92**	**28.41**	0.181	0.143	0.324
33	**18.00**	0.193	0.143	0.336	**93**	**28.92**	0.186	0.143	0.329
34	**18.12**	0.192	0.143	0.335	**94**	**28.93**	0.181	0.143	0.324
35	**18.13**	0.193	0.143	0.336	**95**	**28.94**	0.198	0.143	0.341
36	**19.20**	0.198	0.377	0.575	**96**	**28.99**	0.198	0.143	0.341
37	**20.11**	0.191	0.143	0.334	**97**	**29.10**	0.204	0.143	0.347
38	**20.12**	0.187	0.399	0.586	**98**	**29.20**	0.189	0.252	0.441
39	**20.14**	0.196	0.420	0.616	**99**	**29.32**	0.196	0.285	0.481
40	**20.16**	0.196	0.415	0.611	**100**	**30.12**	0.185	0.143	0.328
41	**20.20**	0.193	0.413	0.606	**101**	**30.91**	0.192	0.143	0.335
42	**20.30**	0.194	0.434	0.628	**102**	**30.92**	0.192	0.143	0.335
43	**20.41**	0.194	0.394	0.588	**103**	**31.01**	0.184	0.143	0.327
44	**20.42**	0.184	0.389	0.573	**104**	**31.02**	0.198	0.386	0.584
45	**20.52**	0.194	0.389	0.583	**105**	**32.40**	0.192	0.143	0.335
46	**20.59**	0.196	0.413	0.609	**106**	**32.50**	0.197	0.143	0.340
47	**21.10**	0.190	0.317	0.507	**107**	**32.91**	0.193	0.143	0.336
48	**21.20**	0.193	0.225	0.418	**108**	**32.99**	0.189	0.409	0.598
49	**22.11**	0.189	0.347	0.536	**109**	**33.00**	0.189	0.143	0.332
50	**22.19**	0.190	0.145	0.335	**110**	**33.12.**	0.193	0.143	0.336
51	**22.21**	0.192	0.416	0.608	**111**	**33.14**	0.187	0.143	0.330
52	**22.22**	0.199	0.274	0.473	**112**	**33.15**	0.143	0.143	0.286
53	**22.23**	0.192	0.305	0.497	**113**	**33.20**	0.185	0.143	0.328
54	**22.29**	0.198	0.422	0.620	**114**	**35.11**	0.192	0.536	0.728
55	**23.31**	0.199	0.556	0.755	**115**	**41.20**	0.193	0.406	0.599
56	**23.63**	0.193	0.546	0.739	**116**	**42.22**	0.192	0.143	0.335
57	**23.65**	0.197	0.551	0.748	**117**	**43.22**	0.191	0.143	0.334
58	**23.70**	0.194	0.143	0.337	**118**	**43.99**	0.193	0.143	0.336
59	**24.10**	0.203	0.623	0.826	**119**	**45.20**	0.195	0.143	0.338
60	**24.33**	0.193	0.488	0.681	**120**	**46.75**	0.179	0.350	0.529

Source: Created by the authors using the UCINET 6.800 programme

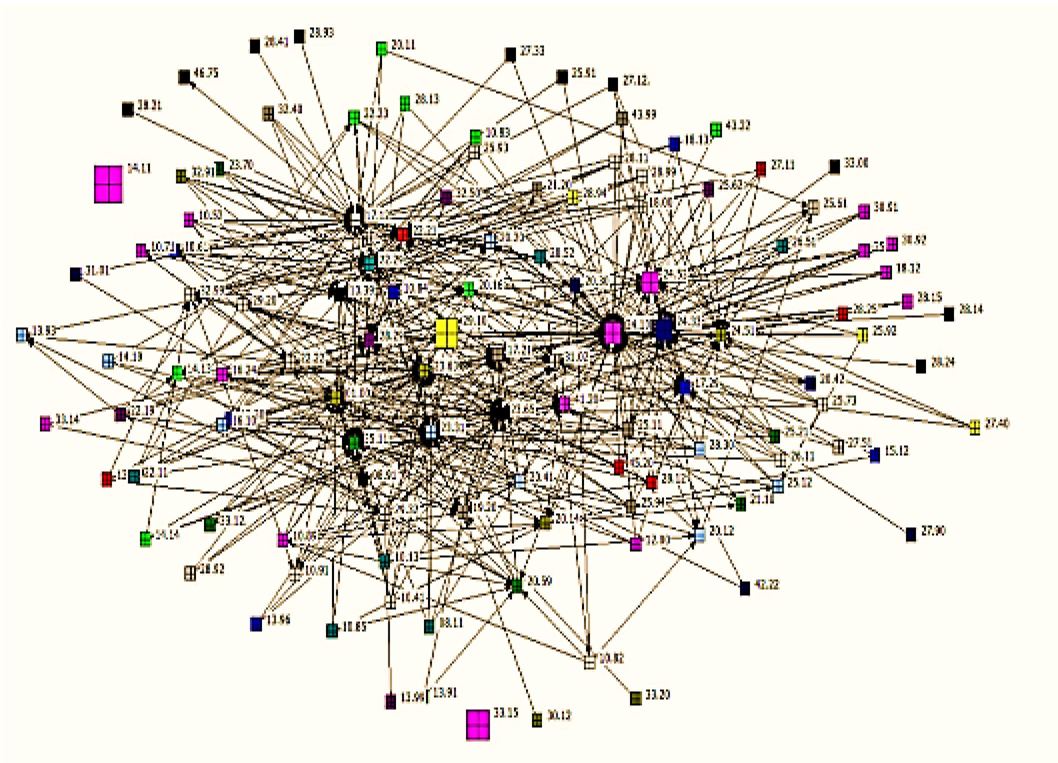

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Figure 4: Closeness Centrality Network Map for IAOIZ

Table 5 shows that sectors with the lowest CC_{OUT} value (0.143), namely those with NACE codes 14.11 and 33.15, are located further away in terms of waste flow within the IS. This indicates that companies in these sectors do not interact with companies in other sectors regarding waste flows. Conversely, sectors with the highest CC_{OUT} value (0.204), with NACE code 29.10, interact indirectly with other sectors. Sectors with high CC_{IN} values, as with other measures, have the highest centrality values.

Figure 4 confirms the closeness measurement results. Sectors with NACE codes 33.15 and 14.11, which are outside the network, are the least proximate sectors and are located outside the network. Sectors with a high CC value are again located at the centre of the network and have many direct and indirect connections.

5.3.4. Ego networks

Ego network analysis provides a social network map for each actor at the centre of the network, helping visualize the connections an actor has established with other actors. Ego networks are particularly important in analyses of multi-actor networks for visualising the connections among actors who play a key role by occupying central positions (Bargotti, Everett, & Johnson, 2013). Figure 5 shows the centrality measurements and the network map of the connections among the 11 actors occupying central positions and playing key roles. These connections between the sectors with the most potential symbiotic relationships within IAOIZ are important for the sustainability of the IS network (Ashton, 2008).

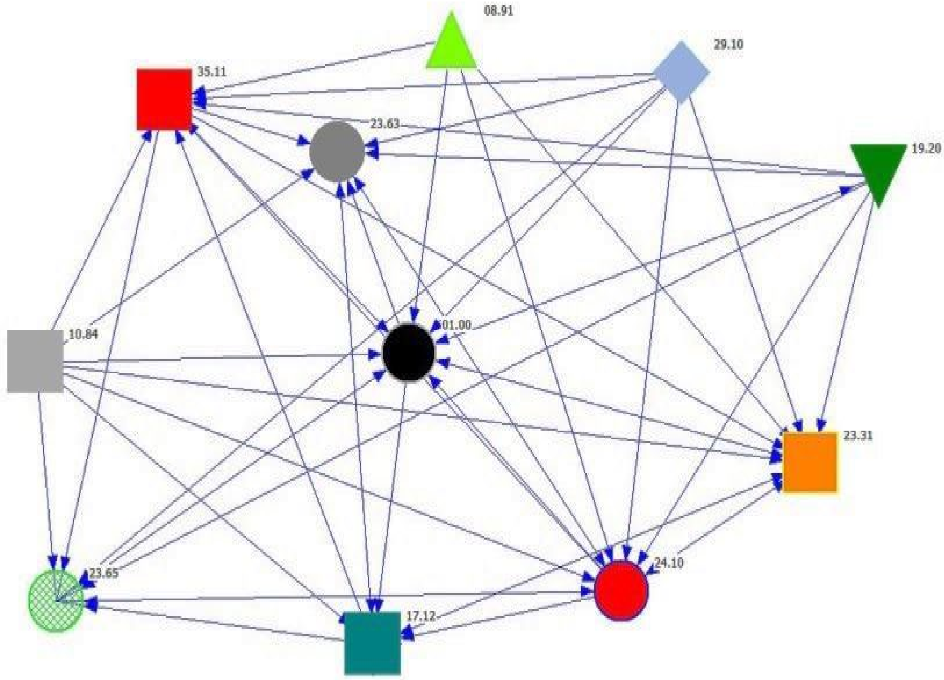

Figure 5: IAOIZ Ego Network Analysis

Figure 5 shows that the sector with NACE code 01.00 (crop and animal production, hunting and related service activities) occupies a central position among the ego networks. In other words, companies operating in this sector are potentially the largest producers and recipients of waste within the ego network.

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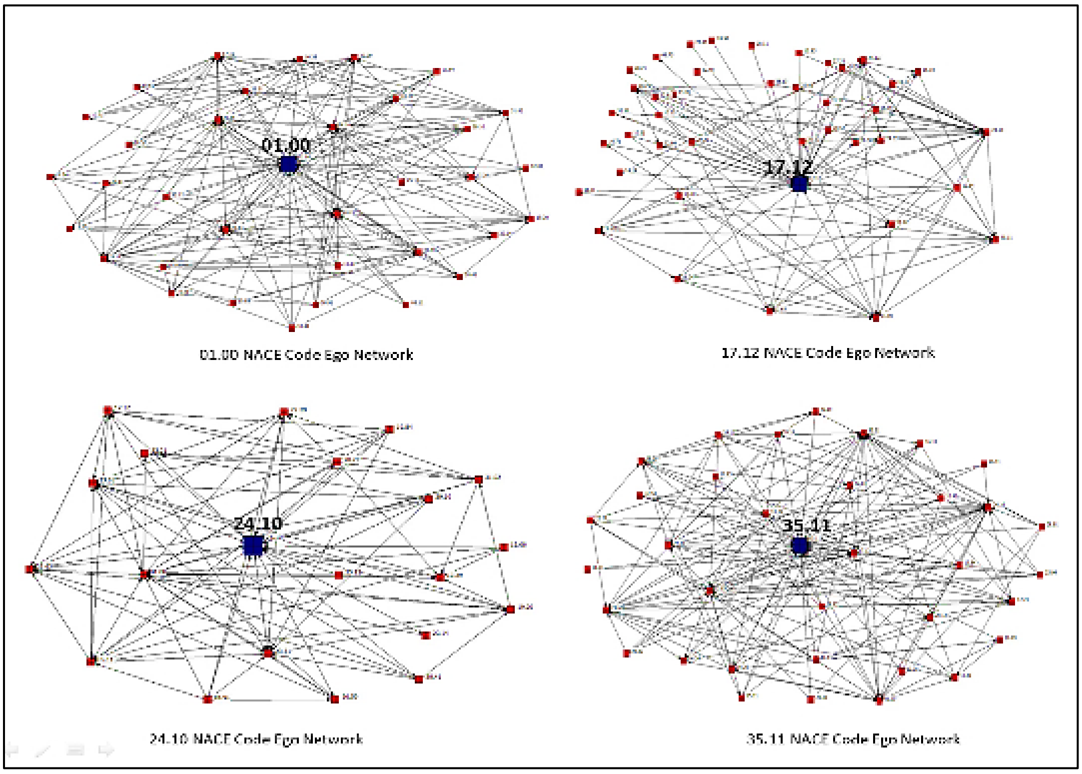

Figure 6: Network Maps for the Ego Networks of Four NACE-Coded Sectors (01.00, 17.12, 24.10, and 35.11).

The UCINET programme allows actors located at the centre of complex, multi-actor, interconnected networks to view their own ego networks based on the centrality measurements (Bargotti, Everett, & Freeman, 2002). This makes it possible to view each actor's connections within highly complex networks. Figure 6 shows the individual ego networks of sectors with NACE codes 01.00, 17.12, 24.10, and 35.11, which are sectors located at the centre based on the centrality measurements. These maps reveal which sectors a sector is most closely related to, thereby identifying potential relationships.

6. Conclusion and Evaluation

The ongoing depletion of natural resources and the generation of waste, which are leading to serious environmental problems, underscore the need for changes in production systems. Different countries have implemented various initiatives to transition from linear production systems to circular economic systems. One such method is IS applications. Based on the simple concept of using waste from one factory as raw material for another these applications provide significant economic returns and environmental benefits in OIZs, which are among the regions that produce the most waste. The present study used SNA to analyse and map potential symbiotic matches (inter-industry waste-raw material exchange) in terms of IS applications for the IAOIZ in Türkiye. Identifying potential symbiotic relationships is important, particularly to determine how inter-sectoral waste flows within a region (Domenech & Davies, 2011). From this perspective, SNA is an important method for identifying which sectors within the network play a key role by being central to resource flows, as well as for determining the structural elements of the IS network. Certain measurement analyses are performed when determining structural elements through SNA, particularly centrality measures such as degree, betweenness, and closeness, as well as ego network analyses.

The present study identified key sectors within the IS framework among businesses operating in IAOIZ, based on centrality measurements of potential symbiotic matches. These sectors represent the companies within the network that either generate the most waste or use it as raw material.

The findings show that IAOIZ sectors operating in the manufacture of basic iron and steel products and ferro-alloys (NACE code 24.10) achieved the highest values in all centrality measures (degree, betweenness, closeness) and played a key role. As well as being located at the centre, they also indirectly connect the sectors they are linked to.

As previously discussed in the introduction section, the Turkish Statistical Institute's (TSI) 2022 report also indicates that the primary metal industry generates the most waste in manufacturing. We determined that this sector not only generates the most waste in IAOIZ, as evidenced by the highest values across all centralisation measurements, but also receives waste from many sectors as raw material and is one of the leading sectors for IS applications in the Industrial Zone of Antalya. Data obtained from databases (MAESTRI) and other case studies revealed that the most common waste code originating from this sector is 100202, unprocessed slag, followed closely by manufacture of ceramic tiles and paving stones (NACE code 23.31, where it can be used as raw material. Similarly, the most common waste produced by sectors operating under NACE code 23.31, namely waste code 101213, (sludges) and waste code 200140 (metals), can be used as raw materials by sectors with NACE codes 01.00 and 24.10. In terms of IS, the most prominent sectors are the basic metal industry sector and the manufacture of other non-metallic mineral products, which covers the manufacture of products such as glass, cement, ceramics, and marble.

This study can contribute to future IS studies conducted by various institutions and policymakers, or by researchers at the Industrial Symbiosis Network, by establishing potential IS networks through cross-sectoral waste-raw material matching and identifying sectors with strategic positions within the network. One of the most important contributions of the present IS study of IAOIZ—where there is a great deal of industrial diversity—is to answer questions like the following: What are the potential symbiotic relationships in the region? Which sectors can be started with when creating an IS network? Which sectors play a key role within the network? Which sectors have the most connections (in waste exchange)? What is the structure and density of IS networks in the region? This will again accelerate and facilitate IS implementation in decision-making processes.

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In this context, various policy recommendations can be presented to policymakers. First, revising the legal framework or waste management regulations governing inter-business waste flows to make them more practical could facilitate the implementation of eco-system (ES) practices. Second, efforts can be made to better inform company managers about ES. Additionally, incentive policies can be implemented for sectors identified in this study as having high potential. Finally, policymakers could provide land allocation for the establishment of eco-industrial parks.

The study has two main limitations. First, legal regulations and legislation regarding waste management in symbiotic partnerships are not taken into account. Second, the social relationships among firm managers are not considered. These limitations can be regarded as potential barriers to the realization of prospective symbiotic relationships. Future studies may identify potential industrial symbiosis (IS) relationships by taking these constraints into consideration.

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