A Network Approach to the Digital Innovation Hub as an Ecosystem Supporting the Digital Transformation of Enterprises in a Region

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Abstract: The study aims to examine the two-mode network of digital innovation hubs (DIH) operating in Poland, understood as ecosystems and competence centers, to support the digital transformation of enterprises in a region. Digital Innovation Hub is also one of the S3 Smart Specialization Platform mapping tools and identifying areas of economic specialization of regions, aimed at facilitating interregional cooperation and creating partnerships between different actors across Europe. While the functions and goals of DIH are more and more often presented in national and regional development documents, little is known about the network structure of DIHs operating in a given country (region) and in the European Union. The study used structured and secondary Smart Specialization Platform data, which allows the creation of two-mode relationship networks and shows how interrelated the studied DIHs and digital technologies they use are. Based on the social network analysis and network metrics (centrality, density, and network projection) integrated into programs such as UCINET and ORA-PRO, the visualization and measurement of the network structure of two-mode networks (actor x technology AT_{ij}) as well as its projection into actor x actor (AA_{ij}) and technology x technology (TT_{ij}) networks were created. The results show 15 DIHs or actors (A) and 29 technologies (T), each of which a given DIH offers to show primarily influential DIHs and digital technologies as well as the areas of cooperation. DIHs are a promising and still little explored area of interest for researchers worldwide. The article is the first attempt to investigate the network structure of DIHs operating in Poland and their relations to technologies.

Keywords: digital innovation hub, DIH, two-mode network, digital transformation, enterprises, social network analysis, density, technology, cooperation, region

1. Introduction

Network approach, in the sense of identifying, assessing and measuring relations, interdependencies and interactions between entities within technology parks (Martin-Rios, 2014; Padilla-Meléndez et al., 2013), industrial clusters (Biggeri et al., 2021), regional or national innovation systems (Arranz et al., 2020; Pinto et al., 2021) is one of the most interesting approaches to the functioning of enterprises[1] in connection with the emerging network paradigm (Capello, 1996; Cooke and Morgan, 1993; Cravens et al., 1996). This paradigm distinguishes the applied research approach, including collecting and managing network data, features of network data, the level of analysis, and network variables taking the form of a matrix. The network approach allows you to look at entities from a multimodal (meta-network) perspective, including not only social actors (organizations, enterprises, institutions, research units, etc.) but also the acquisition and use of knowledge and skills, technologies, or resources that are decisive for their competitiveness (Ashworth and Carley, 2006; Ujwary-Gil, 2020). The meta-network allows for the simultaneous analysis of enterprises' heterogeneous and interrelated elements. However, this is not a commonly used approach because it requires the construction of the so-called two-mode networks and their projections (Borgatti and Everett, 1997; Everett and Borgatti, 2013). While the parks, as mentioned above, clusters and innovation systems have gained the interest of researchers, a relatively new concept - digital innovation hub (DIH) - is currently in the exploration phase. To the knowledge of the article's authors, the network approach to study and measure DIHs of a given region has not been applied so far.

The network is made up of a group of interconnected enterprises and their stakeholders based on formal and informal types of relationships between them within a defined network boundary. The boundary may be a technology park, an industrial cluster, or a region where DIHs operate. The network approach focuses on relationships, interaction patterns and not on the individual characteristics of individual enterprises (Barnes and Harary, 1983). The network approach allows you to model the structure of the network of inter-organizational relations, examine the impact of this structure on the functioning of enterprises and the possibilities or

[1] In the article, enterprises will be referred to interchangeably as actors, digital innovation hubs, or DIHs.

limitations of individual activities in the network (Ujwary-Gil et al., 2022). The network understood in this way is one-mode. Two-mode networks called affiliation networks (Everett, 2016; Jasny, 2012; Ujwary-Gil, 2017) take place in the case of relationships between two different sets of nodes. The network theory should be seen as the basis for interpreting the behavior of social actors and understanding the interdependencies occurring in the network of relations (Borgatti and Halgin, 2011; Salancik, 1995). In line with the assumptions of network theory, the actor's position in the network determines its limitations and possibilities in terms of its achievements or behavior (Borgatti et al., 2013). The creation of technologies, key practices and processes, the services offered depend on the individual actions of social actors, however, conditioned by the actions of others in a given ecosystem. Thus, enterprises are embedded in relationships that influence the behavior of actors and their similarities or differences.

The Digital Innovation Hub (DIH) is a relatively new area of research and a concept of the European Commission. It is designed to build an ecosystem of digital innovation by uniting different environments and sectors, exchanging knowledge, experiences, and technologies (Hervas-Oliver et al., 2021). The European Union dedicated the Digital Europe Program's (DEP) financial perspective for 2021-2027 to the digital competences, making enterprises' digital transformation towards Industry 4.0 a reality (Florek-Paszkowska et al., 2021; Gancarczyk and Ujwary-Gil, 2021). The DEP intends to provide DIHs with access to technological knowledge and experiments to better assess digital transformation projects' viability. The testing and experiment services provided by DIHs may also include other enabling technologies contributing to the implementation of new solutions. The DEP focuses on several priorities: 1) building and strengthening EU capabilities in the field of High-Performance Computing; 2) research and development of artificial intelligence; 3) strengthening cybersecurity due to its importance for European democracy and the EU economy; 4) developing digital competences so that the knowledge and skills to use the latest digital technologies become more and more common; 5) implementing interoperable solutions in areas of public interest and facilitating entrepreneurs, especially small and medium-sized enterprises, to access digital technologies and specialist knowledge (Mărcuț, 2020).

The idea of DIH is to support and improve the competitiveness of enterprises using digital technologies dedicated to the digital development of activities, business models, production, services, and business processes. DIH's offer is addressed to enterprises where the level of digital technology applications is low and whose potential currently does not allow them to meet the challenges posed by the rapid technological development based on the use of microelectronics, photonics, and digitization (Georgescu et al., 2021; Ujwary-Gil and Potoczek, 2020). Therefore, the Digital Innovation Hub is a one-stop shop where start-ups can get help in improving their business, manufacturing processes, products, business models, and services through digital technologies.

There is currently no systematic analysis of DIHs related to digital technologies. In this study, a two-mode social network model was used to examine the impact of enterprises (DIHs) operating in Poland on digital technologies that DIHs use in the products and services they provide. Analyzing the impact of DIHs acting through a network of relationships is crucial as it can differentiate the importance of DIHs in a given region. So far, no research has been conducted that would allow the identification of influential DIHs and technologies in the region. To establish effective collaboration, it is imperative to explore the power of DIHs in controlling the impact of technology.

Three research goals (RG) were formulated:

RG1) Defining the network boundary, DIHs, and digital technologies.
RG2) Developing a two-mode network describing the relationship of DIHs with digital technologies and its projections.
RG3) Examining the DIHs network structure and digital technologies in the region.

This research contributes to the management of digital technologies by identifying potential areas for collaboration, revealing the complex relationships between DIHs that are interconnected through technologies understood as a common area of activity.

2. Methodological approach

2.1 Network boundary and population

The research subject is digital innovation hubs operating in Poland and digital technologies that Polish DIHs offer to enterprises for their digital transformation dedicated to services, products, or the reinvention of business models. Data on DIHs was obtained thanks to the Smart Specialization Platform tools (S3 Tools and Data Sources, accessed in March 2022). The network elements are formed by the following nodes: 15 actors (A), i.e. DIHs, and 29 technologies (T) (Table 1).

Table 1: DIHs operating in Poland and digital technologies (sorted alphabetically)

ID	DIH name (A)	ID	Technology (T)	ID	Technology (T)
A01	Centre for Advanced Manufacturing Technologies, Wroclaw University of Science and Technology	T01	Additive manufacturing	T16	Logistics
A02	CYBERSEC HUB	T02	Advanced, or high performance computing	T17	Micro/nano electronics
A03	DIH4.AI	T03	Artificial intelligence	T18	Mobility & location based technologies
A04	Emerging Transactional and Financial Technology Hub (ETFTH)	T04	Big data, data analytics, data handling	T19	Nanotechnology
A05	HPC4Poland	T05	Cloud computing	T20	New media technologies
A06	Institute of Electron Technology (ITE)	T06	Communication networks	T21	Organic and large area electronics
A07	IoT Poland Foundation Hub	T07	Cyber physical systems	T22	Photonics and imaging technologies
A08	IT and Expert Hub Supporting Biomedical Research, Technology and Education (BioMedHub)	T08	Cyber security	T23	Quantum computing
A09	Krakow Technology Park	T09	Distributed ledger technology	T24	Robotics
A10	Lublin Medicine Cluster	T10	Gamification	T25	Screens and display technologies
A11	NASK National Research Institute	T11	Industrial biotechnology	T26	Sensory systems
A12	PIAP HUB	T12	Interaction technologies	T27	Simulation, modelling and digital twins
A13	Poznan Science and Technology Park of Adam Mickiewicz University Foundation	T13	Internet of things	T28	Software as a service and service architectures
A14	Regional Digital Innovation Hub related to Internet of Things (IoT North Poland HuB)	T14	Internet services	T29	Virtual, augmented and extended reality
A15	Silesia Smart Systems	T15	Laser based manufacturing		

Source: Based on S3 Tools and Data Sources: Digital Innovation Hubs (accessed 29 March 2022).

The DIHs listed have the following attributes (S3 Tools and Data Sources, accessed March 2022). The oldest DIH was established in 1965 (A12). Industrial Research Institute for Automation and Measurements (PIAP), from the very beginning, research work on new technologies carried out at the Institute is usually combined with designing equipment and production lines to enable direct implementation of research achievements in industry. The youngest DIH was founded in 2019 (A03) in Gdańsk. DIHs locations are the main national metropolises, such as Warsaw (A04, A08, A11, A12), Kraków (A02, A09), Wrocław (A01), Gdańsk (A03), Poznań (A05, A13), Lublin (A07, A10), Toruń (A14), and Gliwice (A15). The turnover of DIHs ranges from 0-250.000 (A02, A04, A07, A14, A15), 250.000-500.000 (A08), 1.000.000-5.000.000 (A01, A03, A05, A09, A12, A13) up to over 5.000 .000 (A06, A10, A11). Such DIHs employ the number of employees in the range of 1-9 as A02, A03, A04, A07, A14, A15. In the range of 10-25 employees - A08; 50-100 (A01, A09), and over 100 employees - A05, A06, A10, A11, A12, A13. The geographical scope of DIHs is mostly national (A02, A03, A05, A06, A07, A08, A10, A11, A12, A13); European (A01); regional (A04, A09, A14, A15).

2.2 Social network analysis techniques and visualization

The methodology of network research was used based on the fundamental assumption, which is the interdependence of the analyzed elements of the two-mode DIHs approach, which distinguishes this approach from other methods used in social research, where the observations are independent of each other. The main premise for undertaking this research is to understand the functioning of enterprises that play the digital innovation hub role in the region, connected with a set of interdependent networks of technological relations. For this purpose, we used the inner-dot product where the matrix is multiplied by its transposition, also known as a projection, and obtained the two one-mode matrices: technology similarity shared by actors and actors similarity shared by technology. We transformed the two-mode matrix analogically to Jasny (2012) into the following one-mode projection P (1) of network G and its transposition G^T in which rows (n) and columns (m) are replaced, creating a network $G_{ij} = G_{ji}^{T}$ for each pair of actors (A) $_{ij}$. The projection creates a new network whose links record the commonalities of nodes. It means a two-mode valued network where relation (i,j) is the number of neighbors that nodes i and j have in common.

$$G = \begin{bmatrix} A_{11} & \cdots & A_{1m} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nm} \end{bmatrix},\ G^T = \begin{bmatrix} A_{11} & \cdots & A_{n1} \\ \vdots & \ddots & \vdots \\ A_{1m} & \cdots & A_{mn} \end{bmatrix},\ P = G \times G^T = \begin{bmatrix} P_{11} & \cdots & P_{n1} \\ \vdots & \ddots & \vdots \\ P_{1n} & \cdots & P_{nn} \end{bmatrix} \quad (1)$$

For this purpose, two network programs were used: UCINET (Borgatti et al., 2002) and ORA PRO (Altman et al., 2017). The network approach allows for associating a given DIH with the technology (c.f., Ujwary-Gil, 2019). In the ATij two-mode network (actor x technology), the actor i is related to technology j if the actor i uses or offers technology j. Then the cell in the matrix between the elements ij = 1. Otherwise ij = 0, which means no relation (Table 2). Figure 1 is a visualization of the ATij two-mode matrix shown in Table 2. In the case of a two-mode matrix projection using the formula (1), at the intersection of rows and columns is the number of technologies shared by DIHs in the case of row-by-row projection (Table 3) and the number of actors shared by technologies when projecting through columns (Table 4).

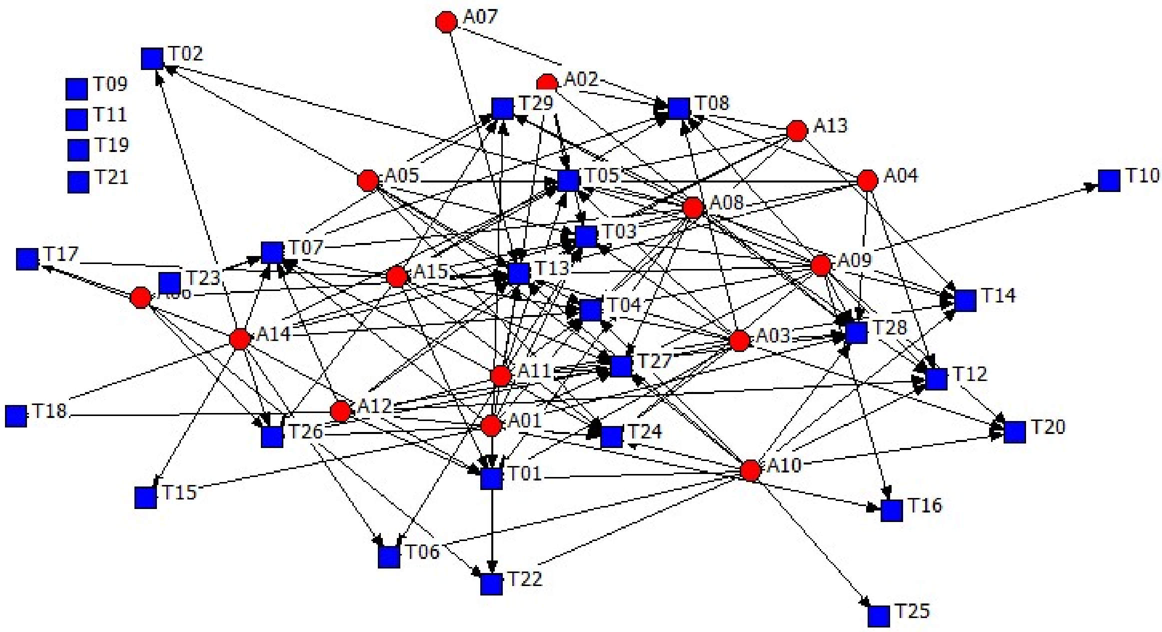

Figure 1: Two-mode network of DIHs and digital technologies

3. Results and data analysis

Table 2 shows the two-mode and affiliation network (actor x technology). On the one hand, the sum of each line represents the number of technologies that the DIH uses to provide services or products. On the other hand, the sum of the columns determines the number of actors associated with the given technologies. The degree of centrality of a node in one set (actor) corresponds to the ratio of the number of links to the total number of nodes in the other set (technology). Hence, in a network of actors, a given DIH with a high degree of centrality has greater authority to deal with the technologies, and the technologies with high centrality may be provided by more DIHs. The results show that the technologies are offered by 0 - 14 DIHs, thus showing the potential of cooperation in the field of technology development. Actors A01, A09, A10, A14, and A15 are the most influential DIHs with the highest degree of centrality (number of technologies used between 12-14). The least influential DIH is A07 (2 technologies).

Table 2: Actor x technology matrix

	T01	T02	T03	T04	T05	T06	T07	T08	T09	T10	T11	T12	T13	T14	T15
A01	1		1	1			1						1		1
A02			1		1		1	1					1		
A03	1		1	1	1			1					1		
A04			1		1			1				1	1		
A05		1	1	1	1								1		
A06							1	1					1		
A07								1					1		
A08	1	1	1	1	1		1					1		1	
A09			1	1	1			1		1		1	1	1	
A10	1			1		1						1	1	1	
A11			1	1	1	1	1						1	1	
A12	1		1				1					1	1		
A13			1	1	1			1					1	1	
A14	1	1	1	1	1	1	1						1		1
A15	1		1	1	1		1	1					1		
SUM (A01-A15)	**7**	**3**	**12**	**10**	**10**	**3**	**8**	**8**	**0**	**1**	**0**	**5**	**14**	**5**	**2**

Table 2: Actor x technology matrix (continued)

	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29	SUM (T01-T29)
A01	1						1		1		1	1	1	1	13
A02													1		6
A03					1				1		1		1		10
A04													1		6
A05									1			1		1	8
A06		1					1				1				6
A07															2
A08												1	1	1	11
A09	1				1				1			1	1	1	14
A10					1		1		1	1		1	1		12
A11									1		1	1	1		11
A12			1						1			1			8
A13															6
A14		1	1								1				12
A15		1							1		1	1		1	12
SUM (A01-A15)	**2**	**3**	**2**	**0**	**3**	**0**	**3**	**0**	**8**	**1**	**6**	**8**	**8**	**5**	

In turn, artificial intelligence (T03), big data, data analytics, data handling (T04), cloud computing (T05), and internet of things (T13) are the most influential technologies offered by DIHs. With an interaction density of 0.315, actors (A01, A09, A10, A14, A15) and technologies (T03, T04, T05, T13) have intense relationships, which may suggest potential cooperation between these actors (DIHs) for technology development. The most central DIHs in the network are more capable of digital technology because they have the potential to work with a broader range of actors (DIHs) and identified digital technologies.

In Table 3, the horizontal and vertical dimensions refer to technology, which means that if a given technology (T) can be supported by a given DIH, then at the intersection of rows and columns there is a number of actors offering a specific technology. For example, two DIHs (A08 and A14) offer T02 and T07. Thus, at the intersection of the row and column, the entry is 2. Interestingly, many cells in the technology matrix are 0, which means that out of all 29 technologies offered by DIHs in a given region, as many as five are not provided by any DIH. They are T09 (distributed ledger technology), T11 (industrial biotechnology), T19 (nanotechnology), T21 (organic and large area electronics), and T23 (quantum computing).

Conversely, the technologies of T13 (internet of things) and T03 (artificial intelligence) have the greatest similarity of resources because they can be addressed by the largest number of actors (11 DIHs). Wherever the number in the cells is 1, then the selected two technologies (dyad) are supported by one DIH. Accordingly, it has the least similarity of resources with others. To deal with this problem, it is possible to initiate closer cooperation between DIHs in the area of identified digital technologies.

Table 3: Technology x technology matrix

	T01	T02	T03	T04	T05	T06	T07	T08	T09	T10	T11	T12	T13	T14
T01	7													
T02	2	3												
T03	6	3	12											
T04	6	3	9	10										
T05	4	3	10	8	10									
T06	2	1	2	3	2	3								
T07	5	2	7	5	5	2	8							
T08	2	0	6	4	6	0	3	8						
T09	0	0	0	0	0	0	0	0	0					
T10	0	0	1	1	1	0	0	1	0	1				
T11	0	0	0	0	0	0	0	0	0	0	0			
T12	3	1	4	3	3	1	2	2	0	1	0	5		
T13	6	2	11	9	9	3	7	8	0	1	0	4	14	
T14	2	1	4	5	4	2	2	2	0	1	0	3	4	5
T15	2	1	2	2	1	1	2	0	0	0	0	0	2	0
T16	1	0	2	2	1	0	1	1	0	1	0	1	2	1
T17	2	1	2	2	2	1	3	2	0	0	0	0	3	0
T18	2	1	2	1	1	1	2	0	0	0	0	1	2	0
T19	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T20	2	0	2	3	2	1	0	2	0	1	0	2	3	2
T21	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T22	2	0	1	2	0	1	2	1	0	0	0	1	3	1
T23	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T24	5	1	7	7	5	2	4	3	0	1	0	3	8	3
T25	1	0	0	1	0	1	0	0	0	0	0	1	1	1
T26	4	1	5	5	4	2	5	3	0	0	0	0	6	1
T27	5	2	7	7	5	2	5	2	0	1	0	4	7	4
T28	4	1	7	6	6	2	4	4	0	1	0	4	7	4
T29	3	2	5	5	4	0	3	2	0	1	0	2	4	2

Table 3: Technology x technology matrix (continued)

T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29
2														

T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29
1	2													
1	0	3												
1	0	1	2											
0	0	0	0	0										
0	1	0	0	0	3									
0	0	0	0	0	0	0								
1	1	1	0	0	1	0	3							
0	0	0	0	0	0	0	0	0						
1	2	1	1	0	3	0	2	0	8					
0	0	0	0	0	1	0	1	0	1	1				
2	1	3	1	0	1	0	2	0	4	0	6			
1	2	1	1	0	2	0	2	0	7	1	3	8		
1	2	0	0	0	3	0	2	0	5	1	3	5	8	
1	2	1	0	0	1	0	1	0	4	0	2	5	3	5

Figures 2 and 3 show Tables 3 and 4 respectively.

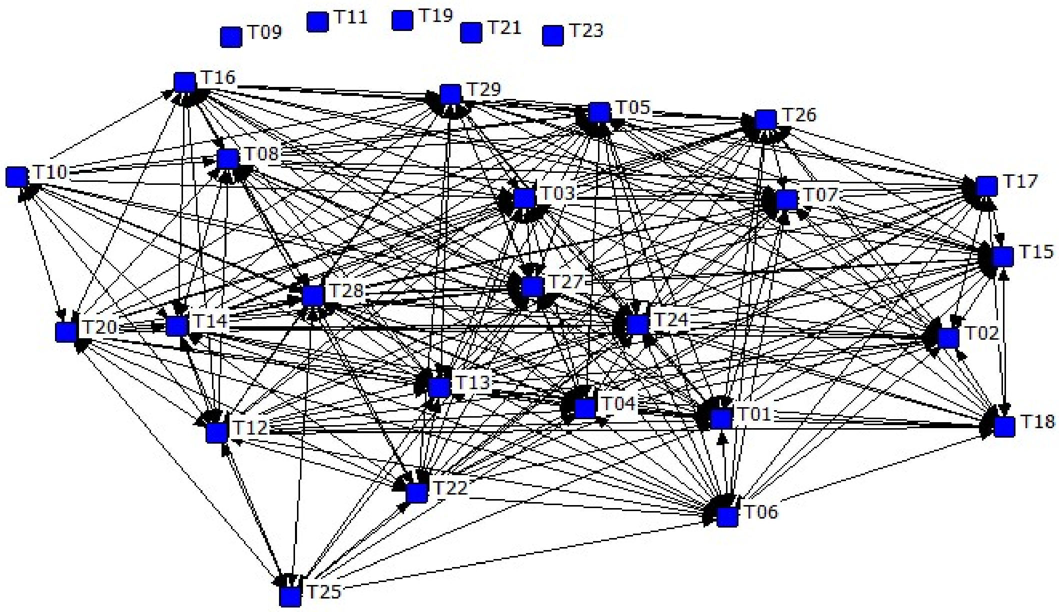

Figure 2: Technology x technology network

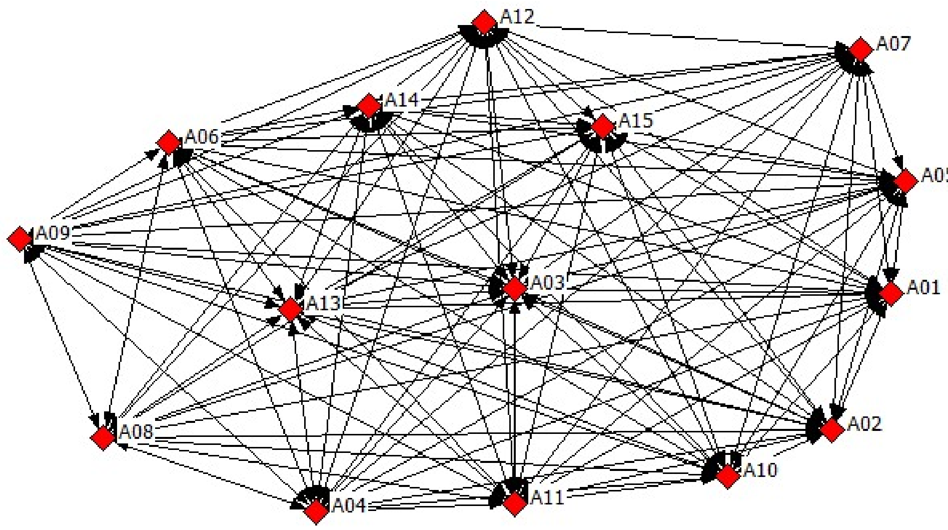

Figure 3: Actor x actor network

The matrix actor x actor indicates the number of technologies each pair of DIHs can offer together (Table 4). The horizontal and vertical dimensions indicate the actors (DIHs). The number on the diagonal of the adjacency matrix indicates how many technologies are offered by DIHs. The matrix shows the dyad A01 and A15, i.e. the DIH pair with the greatest similarity in the power of 31% (i.e., 9/29 technologies). An actor with greater access to digital technology can have more influence by offering competing services and products. All DIHs must pay attention to a minimum of 1 technology, a maximum of 9. High centrality technologies tend to target critical actors and have a high network impact.

Table 4: Actor x actor matrix

	A01	A02	A03	A04	A05	A06	A07	A08	A09	A10	A11	A12	A13	A14	A15
A01	13														
A02	4	6													
A03	7	5	10												
A04	3	5	5	6											
A05	6	3	5	3	8										
A06	4	3	3	2	1	6									
A07	1	2	2	2	1	2	2								
A08	7	4	5	4	6	1	0	11							
A09	8	5	8	6	7	2	2	8	14						
A10	7	2	6	3	4	2	1	6	8	12					
A11	8	5	7	4	6	3	1	7	8	7	11				
A12	6	3	4	3	4	2	1	5	5	5	5	8			
A13	3	4	5	4	4	2	2	4	6	3	5	2	6		
A14	7	4	6	3	5	4	1	6	4	4	7	5	4	12	
A15	9	5	8	4	7	5	2	7	8	5	8	6	5	8	12

4. Conclusion

A network approach was used to analyze digital innovation hubs understood as an ecosystem supporting the digital transformation of enterprises in a given region. In the Introduction section, three research goals (RG) were set, which were achieved as follows:

RG1) The boundary of the network was determined, which is a given region (in this case Poland as one of the European Union countries), in which at least 15 DIHs are located. The DIHs are listed in Table 1, as well as 29 advanced digital technologies that have been identified for all regions. The technologies a given DIH creates and uses depend on its specialization, investment conditions, and demand for services or products.

RG2) A two-mode relationship network was developed based on the linkages between DIHs and digital technologies. The network analysis shows that the network density in this two-mode network was 0.315 (137 links out of 435 possible). So DIHs are associated with technologies in approx. 32%. A projection was performed, transforming a two-mode matrix (also known as a network) into a one-mode matrix containing respectively shared technologies or actors (DIHs). The projection made it possible to indicate the similarity in terms of resources (technology) and subject (organization), showing the potential for institutional and technological cooperation and pointing to technological gaps in a given region. All relationship matrices are graphically presented in Figures 1, 2, and 3.

RG3) The structure of the two-mode network indicates the average level of the density (with reservations, which will be discussed below in the research limitations), which may mean the unused technological potential offered by Polish DIHs. A deeper analysis would determine the resource (technological) similarity of each DIH. In general, the greater the number of shared technologies, the greater the similarity between the DIH pair. Also, the greater the number of shared actors, the more technologies each DIH pair can offer together. The analysis of all three matrices allows for initial recognition of the distribution of DIHs and technologies in relationship networks, indicating a technological gap and the least influential (in terms of connections) DIHs. All the above mentioned technologies can be developed and used by one or more DIHs, showing the potential of cooperation in the field of digital technology management in the region. The two-mode matrix and its variances developed as part of this study provide guidance on where to pay more attention to the cooperation of DIHs and what is the technological potential of the region.

This study is the first to use a two-mode network approach to analyzing DIHs and digital technologies. Hence, no unequivocal conclusions can be drawn, as there is no reference to other similar studies in this area. The relationship density in different European regions is not known to indicate the level of cross-linking of DIHs and technologies. This is the first attempt and, at the same time, a promising start to further research, much more advanced, using DIH attributes (i.e., year of establishment, turnover, number of employees, or organizational form), exploring existing network dependencies as well as much more advanced social network analysis techniques.

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