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The Legacy of Loet Leydesdorff to the Triple Helix as a Theory of Innovation

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Abstract

This paper is an *in memoriam* tribute to the distinguished scholar Loet Leydesdorff written by some of his academic collaborators, including the editors of the Triple Helix journal and representatives of the Triple Helix Association. The paper revisits Loet Leydesdorff's seminal contributions and legacy in innovation studies, particularly

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his work on the Triple Helix model and the measurement of Triple Helix synergies. Additionally, we highlight that Loet was not only a prolific author and outstanding scholar but also a humble person who played a crucial role in the community formed around Triple Helix ideas. The paper also serves as the editorial for the special issue of *Triple Helix* journal, titled "Legacy of Leydesdorff and the Triple Helix".

Keywords

innovation – measurement – redundancy scientometrics – triple helix

1 Introduction

Loet Leydesdorff was a Dutch sociologist, cyberneticist, and professor emeritus of the chair of Dynamics of Scientific Communication and Technological Innovation at the University of Amsterdam. With around 650 scientific publications since 1984, he has more than 73,000 Google Scholar citations and an H-index of 117 (November 2023). Unfortunately, he passed away last March 11, leaving an unfillable space in our minds and hearts.

Over the recent years, Loet has received several homages in conference series and publications that discussed his contribution to several fields of science. One most recent example of this was the series of online workshops during 2021 and 2022, organized by professors Mark Johnson and Jaimi Hendrix, discussing Loet's last book, "The Evolutionary Dynamics of Discursive Knowledge: Communication-Theoretical Perspectives on an Empirical Philosophy of Science" released in 2021, which make wrap-up of this trajectory. Also, the Triple Helix – A Journal of University-Industry-Government Innovation and Entrepreneurship, organized a special issue with the publication of Leydesdorff and Lawton Smith's (2022) paper "Triple, Quadruple, and Higher-Order Helices: Historical Phenomena and (Neo-)Evolutionary Models", based on a keynote speech presented in the Triple Helix Conference in 2021, as well as five invited contributions that intend to respond to the arguments expressed in their paper.

Also, during the XXI Triple Helix Conference, held in Barcelona at La Salle – Ramon Llull University on June 2023, Loet's family received the deep condolences from the TH community and the formal recognition from Triple Helix Association (THA) about Loet's relevance by awarding him the Triple Helix Life Achievement Award. From now, the Triple Helix Life Achievement Award will be named Loet Leydesdorff Award.

Throughout his career, he has made numerous remarkable achievements and significant contributions to scholarship. As we take a moment to reflect on Loet's legacy, we would like to emphasize some of his most notable accomplishments in the field of science and innovation, particularly in relation to the Triple Helix model.

2 About the Man and the Researcher

Louis André (Loet) Leydesdorff was born in Jakarta (Netherlands Indies, now Indonesia) on August 21, 1948. He received his undergraduate degree in social science from the University of Amsterdam in 1971 and his Ph.D. in communication science from the same university in 1983. Before completing his Ph.D., he worked as a researcher at the Netherlands Organization for Scientific Research (NWO) from 1973 to 1983.

Over the years, his research has focused on the dynamics of scientific communication and the use of scientometric indicators to study the structure and evolution of scientific fields. It is worth noticing here his contributions over the years with the journal Social Science Information (SSI – Sage Publications) and, particularly, his article in the Special Issue "Half a century of social science publishing". In this publication "Meaning as a sociological concept: a review of the modeling, mapping and simulation of the communication of knowledge and meaning" (vol. 50, issue 3–4, pp. 391–413, 2011) he examined how the communication of meaning and knowledge – which clearly is analytically different from the communication of information – has been central to Niklas Luhmann's attempts to make the theory of autopoiesis relevant for sociology, and interestingly applied analytical techniques such as semantic maps to the content of articles published in SSI in the years 2005–2009 as well as to that of the literature citing the journal in the same period. He has significantly contributed to developing various scientometric indicators, including the citation impact factor, the Hirsch index, and the degree of specialization.

Also, Loet Leydesdorff has made significant contributions to the study of science communication, particularly on the internet and social media context. He has developed several novel approaches for studying the structure and dynamics of scientific communication on social media platforms, including Twitter and Wikipedia. His work in this area has shed light on how social media are transforming the dissemination and consumption of scientific information.

His book, "A Sociological Theory of Communication: The Self-Organization of the Knowledge-Based Society", published in 2001, is considered a seminal

academic contribution in the field of communication studies. In this book, he presents a theoretical framework for understanding the dynamics of scientific communication in the context of a knowledge-based society. He argues that the interaction between different levels of social organization, including individuals, organizations, and societal structures, drives the self-organization of knowledge production and dissemination.

One of Leydesdorff's most influential contributions was developing the "Triple Helix" model of university-industry-government relations. According to this model, innovation and economic development are driven by interactions between these three sectors or spheres, each of which contributes unique knowledge and resources to the innovation process. His contribution to the Triple Helix has been widely cited and has influenced policy decisions related to science and innovation, as we will explore in the next section.

In addition to his research, Loet has played an active role in the scientific community, serving on numerous editorial boards, scientific committees, and entities, particularly as the vice president of the Triple Helix Association from 2009 to 2013.

He has also been recognized with several prestigious awards for his contributions to the field of scientometrics, including the Derek de Solla Price Medal, in 2003, and the Eugene Garfield Award for Innovation in Citation Analysis, in 2013.

3 Triple Helix: Etzkowitz & Leydesdorff's Collaboration[1]

The exchange of ideas and collaboration between Loet Leydesdorff and Henry Etzkowitz began in 1994, leading to a legacy of research on innovation systems. They co-organized the International Triple Helix Conference (THC) starting in 1996, which brought researchers together to form an international movement and conduct collaborative research. The Triple Helix model proposed in 1995 (Etzkowitz and Leydesdorff, 1995) explains the dynamics of technological innovation as an interaction between the spheres university, industry, and government, forming a recursive process represented by a spiral (Leydesdorff; Etzkowitz, 1998; Etzkowitz; Leydesdorff, 2000). In a nutshell, the Triple Helix concept provides an analogy or metaphor to comprehend the dynamic interactions among actors from different spheres: knowledge generation (university), knowledge application (company), and economic regulation (government). Its primary objective is to foster the generation and dissemination of scientific

1 This part was originally written in Portuguese for the chapter 1 and 2 of the book "As Hélices da Inovação" (Amaral, Mineiro & Ferreira, 2022).

and technological knowledge, enabling companies to innovate and societies to achieve economic and social development. This discussion encompasses various areas including entrepreneurship, innovation, public policies, and business strategies, all of which contribute to the economic growth and prosperity of nations and societies. Moreover, the Triple Helix concept is intertwined with topics such as technology transfer, academic management, regional development models, and the discourse surrounding urban and regional planning, among many others.

The authors published seminal papers on the Triple Helix concept from 1995 to 2003, which involves modeling economic actors in three superimposed spheres and discussing their interactions' effects. The model is appealing due to its simplicity and elaboration, which are easily understood in non-academic circles. Also, the Triple Helix model gained acceptance due to its suitability for explaining the rapid transformation of society at the end of the 20th century. Innovation becomes the basis for wealth creation and economic development, and scientific and technological research gives companies a competitive advantage.

Regarding to the collaborative works, the duo's most relevant papers, published in 1996 and 1997, were "*The Future Location of Research: A Triple Helix of University-Industry-Government"* (Leydesdorff; Etzkowitz, 1996a), "*Emergence of a Triple Helix of University-Industry-Government Relations"* (Leydesdorff; Etzkowitz, 1996b) and *"The Triple Helix: Academic–Industry–Government Relations: Implications for The New York Regional Innovation Environment"* (Leydesdorff; Etzkowitz, 1996c), and *"Introduction to Special Issue on Science Policy Dimensions of the Triple Helix of University-Industry-Government Relations"* (Etzkowitz; Leydesdorff, 1997). Combined with *"The Triple Helix: Academic–Industry–Government Relations: Implications for The New York Regional Innovation Environment"* (Etzkowitz, 1996a) and "*From Knowledge Flows to the Triple Helix: The Transformation of Academic-Industry Relations in the USA"* (Etzkowitz, 1996b), they constitute a genesis Triple Helix concept and a theoretical effort of main authors to advance and disseminate their ideas.

These articles share the same concept: modeling economic actors in three superimposed spheres, like a Venn diagram, and discussing the effects of interactions between them, that is, to analyze the influence that an actor from one sphere has on an actor from the other sphere and how much he is influenced. A good example is a professor who makes consulting services for companies. It takes scientific knowledge to solve practical problems, influencing the company's corpus of knowledge, and brings experiences and needs from the business world to feed its class content and its strategies and research focus (Amaral, Mineiro & Faria, 2022).

Etzkowitz and Leydesdorff (2000) and Leydesdorff (2003) point out that these interactions do not need to be linear but can be multiple, configuring new mutual agreements between institutions. Institutional configurations can be organized into four subdynamics: 1) the economic dynamics of generating wealth arising from exchange; 2) the dynamics based on the reconstruction of knowledge and innovation over time; 3) the political and managerial need that demands a normative control in the interfaces (Etzkowitz, 2003); and 4) improving the role of the university in the transition from an industrial society to knowledge-based society (Cai; Etzkowitz, 2020). Etzkowitz and Leydesdorff (2000) and Leydesdorff, Dolfsma, and Van Der Panne (2006) argue that there is an overlap of relationships between these actors.

Significant new contributions appear in 1998 with the articles *"The Triple Helix as a Model for Innovation Studies*" (Leydesdorff; Etzkowitz, 1998) and *"The Endless Transition: A "Triple Helix" of University-Industry Government Relations*" (Etzkowitz; Leydesdorff, 1998). These works reinforce the central concepts and applicability to understand a new knowledge economy that was emerging and, in attributing the main role in the model to the university, something that will be discussed later. Amaral, Mineiro and Faria (2022) argue that Triple Helix differs from the Sabato Triangle (Sábato; Botana, 1968), which emphasizes the role of government as an articulator, regulator, and executor. Also, Triple Helix differs from the National/Local Innovation Systems approach (Lundvall, 1992; Cooke, 2001), which emphasized the role of the company as the central locus of innovation. Now, the most relevant aspect is where the knowledge comes from.

In 1999 and 2000, there was a comprehensive production between Etzkowitz and Leydesdorff and individually with partners that culminated in the articles *"The Future of the University and the University of the Future: Evolution of Ivory Tower to Entrepreneurial Paradigm"* (Etzkowitz et al., 2000) and in *"The Dynamics of Innovation: From National Systems and "Mode 2" to a Triple Helix of University-Industry–Government Relations"* (Etzkowitz; Leydesdorff, 2000), among others. These two articles present and represent the maturity of the Triple Helix discussion and a synthesis of previous years' production. Possibly because of this, they are among the most cited, having received 4,526 and 13,270 citations over these twenty-two years (November 2023).

According to Leydesdorff (2005) "the different metaphors in the study of knowledge-based innovation systems can be considered theoretical assessments of complex dynamics from different perspectives and with potentially different objectives." Triple Helix is the sociological metaphor for the study of innovation. It is developed in the wake of Merton's sociology of science, Parsons and Luhmann's sociological systems theory, and social studies of science and technology (FE, 2009).

In 2001, the collaborative production has a new chapter, which occurs individually, together, and with partners. The articles *"The Transformation of University-Industry-Government Relations"* (Leydesdorff; Etzkowitz, 2001) and *"The Second Academic Revolution and the Rise of Entrepreneurial Science"* (Etzkowitz, 2001) and *"A Triple Helix of University-Industry-Government Relations": "Mode 2" and the Globalization of "National" Systems of Innovation"* (Leydesdorff; Etzkowitz, 2001), deepen the ideas launched between 1998 and 2000.

In 2002, a collection book is organized under the title *"Universities and the global knowledge economy: A Triple Helix of University-Industry-Government Relations."* From then on, collaborations began to dwindle. There was no formal break, but the growth of the Triple Helix movement led them to explore different paths with different partners, as in an open marriage.

The last significant collaboration between them took place in 2003, with the article *"Can 'the public' be considered as a fourth helix in university-industry-government relations?"*. This article is even little referenced despite dealing with a relevant topic: the "anchoring" of the model in society (Leydesdorff; Etzkowitz, 2003).

Etzkowitz and Leydesdorff only returned to writing together in 2015 (Leydesdorff; Etzkowitz; Kushnir, 2016). Although they expanded Simmel's analysis of dyads and triads from the micro-level to the meso level when developing the Triple Helix model (Cai and Etzkowitz, 2020), they have different perspectives on the core of Triple Helix interactions: Etzkowitz' neo-institutional perspective focusing on the relations between university, industry, and government, and Leydesdorff's neo-evolutionary perspective regarding the helices as selection mechanisms. Cai (2022) has provided a comprehensive analysis of the similarities and differences between the two Triple Helix approaches, which can be summarized as follows.

Etzkowitz proposed the concepts of knowledge, consensus, and innovation spaces to better account for the mechanisms of university-industry-government interactions. On the other hand, Leydesdorff provoked the Triple Helix functions of knowledge production, wealth creation, and normative control as mutual selections that shape a trajectory as in a coevolution. Despite the differences, Etzkowitz's concept of triple spaces and Leydesdorff's concept of triple functions share similarities in understanding the roles of university, industry and government in innovation processes. Triple Helix spaces are created through interactions between the three spheres, while Triple Helix synergy is measured by the overlapping of functions. In such, both approaches complement each other. For instance, Leydesdorff's indicator based on Triple Helix functions provides a better operationalization of the mechanism of 'taking on the role of the other' proposed by Etzkowitz (Cai, 2022).

4 A Bibliometric Analysis

The analysis using scientific statistics (bibliometrics) seeks to deconstruct the complex body of Leydesdorff's scholarly contributions within the Triple Helix framework. By meticulously examining the subtleties of his academic output and tracing its evolutionary path, the objective is to shed light on the intellectual terrain to which he has actively contributed to the context of Triple Helix approaches. This scrutiny will facilitate the evaluation of the broader repercussions of his research within the scientific community and its significance in furthering the comprehension of innovation systems framework. Subtopics to be explored are as follows:

A. Loet Leydesdorff Scientific Work Analysis – Main Information: A detailed exploration of the core concepts, methodologies, and findings from Leydesdorff's seminal works, serving as an academic nexus for ensuing discussions and analyses within the article.
B. Sources' Production:
    i. Sources Scientific Production over time: Investigating the trajectory of Leydesdorff's scholarly output over the years, providing insights into the evolution of his research focus, methodologies, and contributions to the field of Triple Helix Science and Technology Studies.
C. Conceptual Structure:
    i. Co-occurrence Network: A discussion on the intricate web of interconnected ideas, themes, and concepts identified within Leydesdorff's Triple Helix body of work, illustrating the synergistic relationships and mutual influences amongst them.
    ii. Thematic Map: The construction and interpretation of a thematic map based on Leydesdorff's work, visualizing the convergence and divergence of themes, the emergence of new research territories, and the interconnectedness of scientific domains, offering a spatial representation of his intellectual landscape.
D. Social Structure:
    i. Collaboration Network: This analysis conducted here illuminated the global reach and collaborative nature of research in the Triple Helix theory, showcasing international cooperation among scholars. It demonstrated Loet Leydesdorff's central role in fostering interdisciplinary connections and knowledge exchange, further solidifying his influential position in the field of innovation and technology policy.

4.1 *Main Information*

This analysis dives deep into his academic pursuits, spanning 26 years from 1996 to 2022. Examining a vast array of 63 documents across 31 sources, it underscores his significant influence, reflected in an impressive citation rate. Beyond sheer numbers, Leydesdorff's versatility shines through his varied document types and keyword themes. Additionally, his collaborative spirit, evident in both domestic and international partnerships, further establishes his monumental role in advancing the Triple Helix discourse. Table 1 presents the most cited papers and Figure 1 organizes relevant information.

TABLE 1 Most cited papers

ID	Reference	Number of citations
1	Etzkowitz, H., Leydesdorff, L. The dynamics of innovation: From National Systems and "mode 2" to a Triple Helix of university-industry-government relations. Research Policy, 29 (2), pp. 109–123, 2000.	4,254
2	Leydesdorff, L., Etzkowitz, H. Emergence of a Triple Helix of university-industry-government relations. Science and Public Policy, 23 (5), pp. 279–286, 1996.	280
3	Leydesdorff, L., Etzkowitz, H. The Triple Helix as a model for innovation studies. Science and Public Policy, 25 (3), pp. 195–203, 1998.	517
4	Leydesdorff, L. The Triple Helix, Quadruple Helix, …, and an N-Tuple of Helices: Explanatory Models for Analyzing the Knowledge-Based Economy? Journal of the Knowledge Economy, 3 (1), pp. 25–35, 2012.	394
5	Leydesdorff, L., Deakin, M. The triple-helix model of smart cities: A neo-evolutionary perspective. Journal of Urban Technology, 18 (2), pp. 53–63, 2011.	258
6	Leydesdorff, L. The triple helix: An evolutionary model of innovations. Research Policy, 29 (2), pp. 243–255, 2000.	250
7	Leydesdorff, L., Meyer, M. Triple Helix indicators of knowledge-based innovation systems. Introduction to the special issue. Research Policy, 35 (10), pp. 1441–1449, 2006.	230
8	Park, H.W., Leydesdorff, L. Longitudinal trends in networks of university-industry-government relations in South Korea: The role of programmatic incentives. Research Policy, 39 (5), pp. 640–649, 2010.	154

TABLE 1 Most cited papers (*cont.*)

ID	Reference	Number of citations
9	Leydesdorff, L., Meyer, M. The Triple Helix of university-industry-government relations. Scientometrics, 58 (2), pp. 191–203, 2003.	151
10	Leydesdorff, L., Fritsch, M. Measuring the knowledge base of regional innovation systems in Germany in terms of a Triple Helix dynamics. Research Policy, 35 (10), pp. 1538–1553, 2006.	150
11	Leydesdorff, L. The mutual information of university-industry-government relations: An indicator of the Triple Helix dynamics. Scientometrics, 58 (2), pp. 445–467, 2003.	132
12	Leydesdorff, L., Dolfsma, W., Van Der Panne, G. Measuring the knowledge base of an economy in terms of triple-helix relations among 'technology, organization, and territory'. Research Policy, 35 (2), pp. 181–199, 2006.	127
13	Etzkowitz, H., Leydesdorff, L. The future location of research and technology transfer. Journal of Technology Transfer, 24 (2–3), pp. 111–123, 1999.	111
14	Leydesdorff, L., Sun, Y. National and international dimensions of the Triple Helix in Japan: University-industry-government versus international coauthorship relations. Journal of the American Society for Information Science and Technology, 60 (4), pp. 778–788, 2009.	108
15	Leydesdorff, L., Ivanova, I. "Open innovation" and "triple helix" models of innovation: Can synergy in innovation systems be measured? Journal of Open Innovation: Technology, Market, and Complexity, 2 (3), art. no. 11, 2016.	100
16	Park, H.W., Hong, H.D., Leydesdorff, L. A comparison of the knowledge-based innovation systems in the economies of South Korea and the Netherlands using Triple Helix indicators. Scientometrics, 65 (1), pp. 3–27, 2005.	98
17	Ivanova, I.A., Leydesdorff, L. Rotational symmetry and the transformation of innovation systems in a Triple Helix of university-industry-government relations. Technological Forecasting and Social Change, 86, pp. 143–156, 2014.	96
18	Etzkowitz, H., Leydesdorff, L. Introduction to special issue on science policy dimensions of the Triple Helix of university-industry-government relations. Science and Public Policy, 24 (1), pp. 2–5, 1997.	96

TABLE 1 Most cited papers (*cont.*)

ID	Reference	Number of citations
19	Leydesdorff, L., Etzkowitz, H. Can 'the public' be considered as a fourth helix in university-industry-government relations? Report on the Fourth Triple Helix Conference, 2002. Science and Public Policy, 30 (1), pp. 55–61, 2003.	95
20	Leydesdorff, L., Meyer, M. The decline of university patenting and the end of the Bayh-Dole effect. Scientometrics, 83 (2), pp. 355–362, 2010.	93

Source: developed by the authors with Scopus data (November 2023).

FIGURE 1 Scientific Work Analysis – Main Information
SOURCE: SCOPUS (1996–2023)

The research papers cover a timespan from 1996 to 2022, indicating that Loet Leydesdorff has been actively contributing to the field for more than two decades. There are 63 documents in total, which indicates a substantial body of work on this topic. These documents were found in 31 sources that have been used for these papers, which suggests a diverse range of literature and references that contribute to the development of the Triple Helix theory. The annual growth rate of 2.7% suggests a steady and consistent publication output over the years, which is a positive sign of continued interest and research in the field.

The average age of the documents is 12.5 years, which could be an indicator of the enduring relevance of the research conducted by Loet Leydesdorff in the Triple Helix theory. An average of 146.4 citations per document is a strong indicator of the impact and influence of Loet Leydesdorff's work in the field, showcasing the significance of the Triple Helix theory in the scientific community.

Regarding to references it's mentioned that there is an average of 1 reference per document, but it would be helpful to have more information on the references to understand the sources and literature that have influenced Loet Leydesdorff's work. While about keywords, there are a total of 188 Keywords Plus and 124 Author's Keywords, which can be analyzed to identify the key concepts and themes that have been explored in the papers.

Loet Leydesdorff has collaborated with 39 other authors, indicating a network of researchers contributing to the development and application of the Triple Helix theory. Most of the documents are articles (54), but there are also book chapters, conference papers, editorials, and reviews. Analyzing the distribution of document types can provide insights into the variety of contributions made by Loet Leydesdorff in different contexts. There are 10 single-authored documents, which suggest that Loet has also published research independently. The average of 2.21 co-authors per document indicates a collaborative approach to research. It's interesting to note that there is no international co-authorship mentioned. Further investigation into the geographic distribution of collaborators could provide insights into the global reach of the Triple Helix theory.

4.2 *Sources*

The analysis of academic publications provides invaluable insights into the evolution and impact of scientific theories and research areas over time. In this study, the production of scholarly articles in selected journals related to the field of science and innovation is analysed, spanning a timespan from 1996 to 2022. The aim is to shed light on the growth and trends in academic contributions to these journals and, by extension, the research landscape in these areas.

The journals under examination encompass "Scientometrics," "Research Policy," "Science and Public Policy," "Technological Forecasting and Social Change," and the "Journal of the American Society for Information Science and Technology." Encompassing various subjects in scientometrics, innovation, technology, and information science, the analysis centers on annual publication counts within these journals to observe patterns of growth, influence, and research activity.

Exploring the data presented in the subsequent sections reveals the trajectory of scholarly output, allowing us to identify pivotal years of growth and examine the relative prominence of each journal in the academic discourse (see Figure 2). In Scientometrics, the number of papers published remains constant at 0 until 2003, after which it gradually increases, reaching 6 by 2013 and then steadily rising to 9 by 2014. It remains at 9 until 2022. The number of

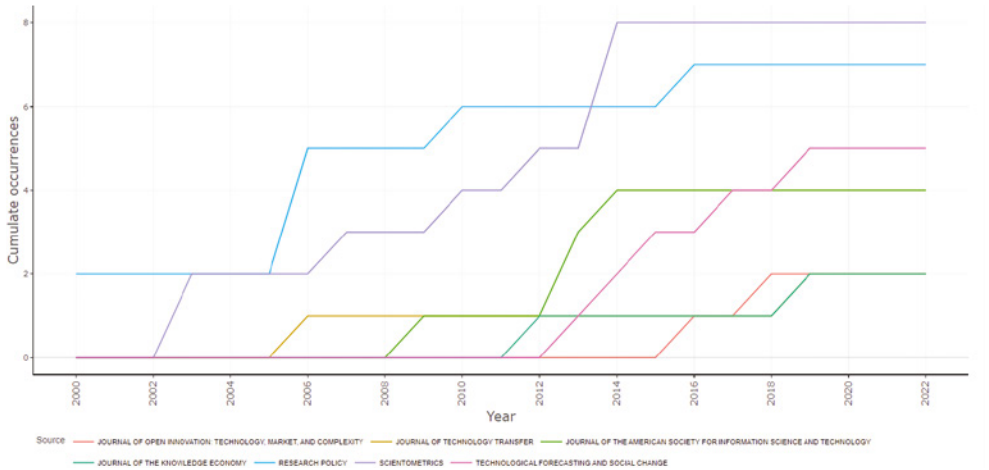

FIGURE 2 Scientific Work Analysis – Sources' Production over Time
SOURCE: SCOPUS (1996–2023)

papers published in "Research Policy" starts at 0 in 1996 and gradually increases over the years. In 2000 when it reaches 2. The count remains at 2 until 2002 and then gradually increases to 7 by 2017. It remains at 7 until 2022. At last, In the "Science and Public Policy" journal, the number of papers published starts at 1 in 1996 and increases steadily, reaching 5 by 1999. It remains at 5 until 2022.

4.3 *Conceptual Structure*

4.3.1 Co-occurrence Network

In this analysis, an exploration is undertaken of a co-occurrence network involving key terms and concepts extracted from a corpus of scholarly literature. These terms serve as the foundational themes and subjects within the domains of the Triple Helix approach, knowledge-based systems, innovation, mutual information, government relations, mathematical models, and technological development. Through the examination of the interconnections among these terms, as determined by centrality measures, the primary objective is to reveal the inherent conceptual structure underpinning research within these spheres. The ensuing network analysis yields valuable insights into the thematic groupings and central elements within the knowledge landscape, affording a comprehensive perspective on the interconnected nature of ideas within these academic domains (see Figure 3).

The subsequent section outlines these prominent clusters and pinpoints the central nodes within each cluster, as determined by the Betweenness, Closeness, and PageRank centrality metrics:

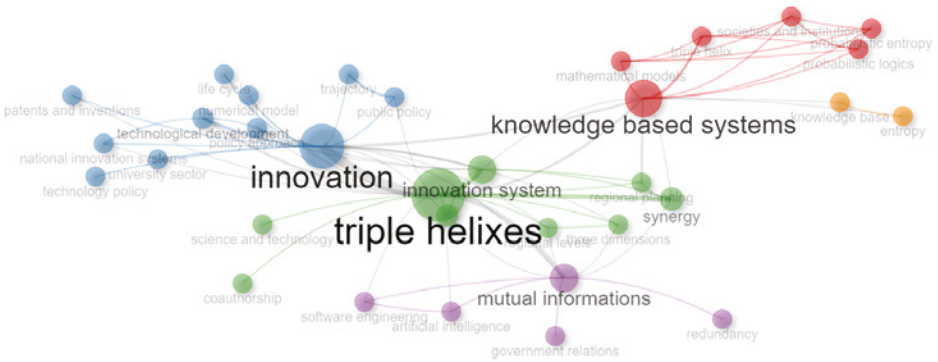

FIGURE 3 Scientific Work Analysis – Co-occurrence Network
SOURCE: SCOPUS (1996–2023)

Cluster 1: Knowledge and systems (node group 1):

- Knowledge-based Systems: This node exhibits a high level of betweenness centrality (187.35) within its cluster, suggesting its importance in connecting various aspects of knowledge-based systems research.
- Mathematical Models, Triple Helix, Probabilistic Entropy, Probabilistic Logics, Societies and Institutions: These nodes, while having lower betweenness centrality, contribute to the overall cohesion of the cluster.

Cluster 2: Innovation and policy (node group 2):

- Innovation: With a substantial PageRank (0.119), the "innovation" node emerges as influential, indicating its prominence in the network and its role in disseminating information related to innovation.
- Public Policy, Technological Development, University Sector, Life Cycle, National Innovation Systems, Numerical Model, Patents and Inventions, Policy Approach, Technology Policy, Trajectory: These nodes, with varying centrality measures, collectively contribute to the discourse on innovation and policy within the cluster.

Cluster 3: Triple Helix and systems (node group 3):

- Triple Helices: This node exhibits the highest betweenness centrality (206.12) within its cluster, signifying its role as a critical connector and bridge in discussions related to the Triple Helix theory.
- Innovation System, Synergy, Information Theory, Regional Planning, Science and Technology, Coauthorship, Regional Levels, Three Dimensions: These nodes complement the discourse on innovation, synergy, and regional aspects within the context of the Triple Helix theory.

Cluster 4: Information and government relations (node group 4):

- Mutual Information: This node, with a substantial betweenness centrality (69.13), plays a pivotal role in connecting discussions related to mutual information, a key concept in information theory.

– Government Relations, Redundancy, Artificial Intelligence, Software Engineering: These nodes contribute to discussions on government relations, redundancy, and artificial intelligence, albeit with varying levels of centrality.

Cluster 5: Entropy and knowledge base (node group 5):

– Entropy: While not exhibiting high centrality, the "entropy" node plays a role in discussions related to entropy in information theory.
– Knowledge Base: Similar to entropy, the "knowledge base" node contributes to the understanding of knowledge repositories but does not dominate the network.

This network analysis provides insights into the interconnectedness and centrality of specific nodes within their respective clusters. It helps us understand which concepts and terms are central to the scholarly discourse in these research areas, highlighting their significance in shaping discussions and knowledge dissemination.

4.3.2 Thematic Map

In this exploration, a thematic map is presented, revealing the interconnected network of concepts found within a body of scholarly literature. This map is structured into discrete clusters, each denoting a thematic domain distinguished by the frequent occurrence of terms. Spanning Triple Helix, innovation, knowledge mutual information, mathematical models, and government relations, this analysis exposes the intricate web of ideas and subjects that have garnered scholarly focus. Through the identification of these thematic clusters and their central nodes, valuable insights are garnered into the prevailing research themes and their interactions, providing a comprehensive perspective on the intellectual landscape within these academic domains (see Figure 4).

Here's a summary of the key themes and clusters identified in the dataset:

Cluster 1: Triple Helix and innovation:

– Triple Helixes: This node, with the highest betweenness centrality (5279) and PageRank centrality (0.036), plays a central role in discussions surrounding the Triple Helix theory. It suggests that the Triple Helix model is a pivotal concept that bridges various aspects of innovation, technology, and policy. This centrality implies that research on the Triple Helix theory holds a significant position within the scholarly discourse, indicating its enduring relevance and influence.
– Innovation: The "innovation" node, with notable betweenness centrality (2448) and PageRank centrality (0.029), is integral to Cluster 1. Its centrality

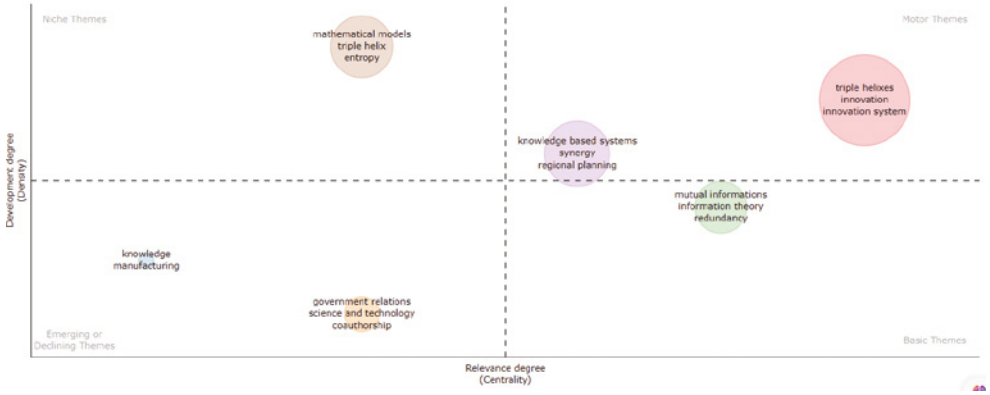

FIGURE 4 TH Scientific Work Analysis – Thematic Map
SOURCE: SCOPUS (1996–2023)

highlights the importance of innovation as a fundamental driver of research in scientometrics, innovation, and technology policy. This finding suggests that innovation remains a central and influential theme in academic discussions, with implications for policy development and technological advancement.

Cluster 2: Knowledge and manufacturing:

– Knowledge: Within Cluster 2, the "knowledge" node exhibits notable betweenness centrality (414) and PageRank centrality (0.006), signifying its role as a central concept in discussions related to knowledge. This centrality implies that knowledge is a core element of the conceptual framework, indicating its critical role in shaping research in this cluster. It suggests that knowledge plays a pivotal role in understanding the interplay between knowledge-based systems and manufacturing processes.

Cluster 3: Mutual information and information theory:

– Mutual Information: This node is the central hub within Cluster 3, boasting the highest betweenness centrality (1357) and PageRank centrality (0.019). It plays a pivotal role in discussions on mutual information and information theory. This centrality indicates that mutual information is a fundamental concept in information theory and data analysis. Its prominence suggests that researchers are actively engaged in exploring information theory's applications, particularly in understanding the relationships between variables.
– Information Theory, Redundancy, Artificial Intelligence, Software Engineering: These nodes contribute to the understanding of information theory

and related concepts within Cluster 3. The presence of artificial intelligence and software engineering suggests that these fields are closely connected to information theory, hinting at the growing significance of data science and computational methods in this domain.

Cluster 4: Knowledge-based systems and regional planning:

- Knowledge-Based Systems: The "knowledge-based systems" node is central to Cluster 4, with substantial betweenness centrality (1706) and PageRank centrality (0.021). It stands as a cornerstone concept in discussions surrounding knowledge-based systems. This centrality implies that knowledge-based systems are at the heart of research in this cluster, suggesting their vital role in decision support, expert systems, and knowledge management.
- Synergy, Regional Planning, Region, Regional Levels, Research and Development, Three Dimensions: These nodes complement the discourse on knowledge-based systems, regional planning, and research and development within Cluster 4. The presence of these concepts indicates that research in this cluster encompasses a diverse range of topics related to knowledge application, regional development, and innovation strategies.

Cluster 5: Government relations and science & technology:

- Government Relations: This node, with a significant betweenness centrality (1122) and PageRank centrality (0.012), holds a central position within Cluster 5, signifying its importance in discussions related to government relations. Its centrality suggests that the interface between government policies and scientific and technological advancements is a focal point of research within this cluster. This finding has implications for policymakers and researchers seeking to understand the dynamics of government support for innovation and technology.
- Science and Technology, Coauthorship: These nodes contribute to the discourse on science and technology policies and collaborative authorship within Cluster 5. The presence of "coauthorship" highlights the collaborative nature of scientific research, indicating that partnerships and collaborations play a central role in advancing science and technology.

Cluster 6: Mathematical models and concepts:

- Mathematical Models: The "mathematical models" node exhibits significant betweenness centrality (398) and PageRank centrality (0.010) within Cluster 6, underscoring its role in discussions related to modeling. This centrality implies that mathematical modeling is fundamental to research within this cluster, reflecting its importance in understanding complex

systems and phenomena. It suggests that researchers in this cluster rely heavily on mathematical modeling techniques to explore various concepts and phenomena.

– Triple Helix, Entropy, Germany, Knowledge Base, Probabilistic Entropy, Probabilistic Logics, Societies and Institutions, Technology Transfer: These nodes contribute to the broader discourse on mathematical modeling, the Triple Helix theory, and related concepts within Cluster 6. The presence of these concepts highlights the interdisciplinary nature of research in this cluster, suggesting that mathematical modeling techniques are applied to diverse areas, including the Triple Helix theory, entropy, knowledge management, and technology transfer.

This in-depth analysis of each cluster provides a nuanced understanding of the meaning and implications of the key concepts and their centrality within their respective thematic areas. It offers valuable insights into the core themes and their interconnectedness within the scholarly discourse on scientometrics, innovation, technology policy, and related research domains.

4.3.3 Social Structure

In this section, delving into the examination of key contributors within the scholarly network analysis involves analyzing the centrality measures of notable authors. This approach provides insights into their significance and influence in the field of research related to the Triple Helix theory and innovation (see Figure 5).

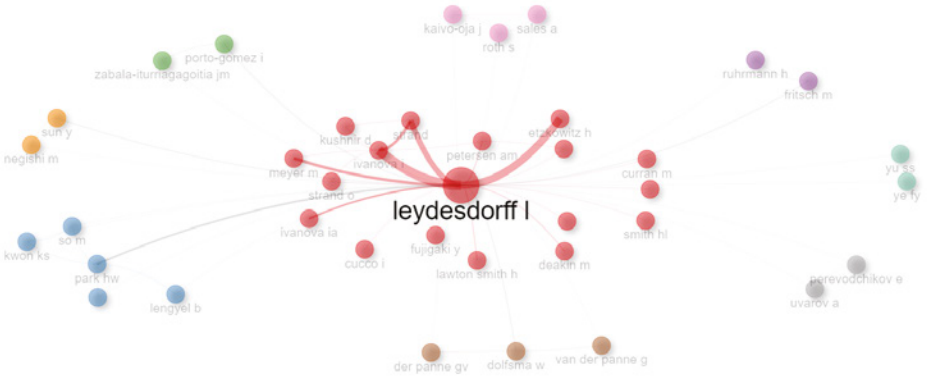

FIGURE 5 Scientific Work Analysis – Collaboration Network
SOURCE: SCOPUS (1996–2023)

Cluster 1: Prominent figures in Triple Helix research

Cluster 1 is characterized by its focus on the Triple Helix theory, and the following authors have emerged as central figures within this cluster:

– Inga Ivanova (ivanova i): Inga Ivanova holds a notable position in Cluster 1 with a moderate betweenness centrality (2.40) and PageRank centrality (0.071). Her presence implies her active participation in discussions and research related to the Triple Helix theory, contributing to the network's diversity and knowledge exchange.
– Henry Etzkowitz (etzkowitz h): While Henry Etzkowitz has a lower betweenness centrality, his presence (PageRank centrality of 0.034) suggests his contribution to the cluster's knowledge dissemination. Etzkowitz's work may focus on specific aspects of the Triple Helix theory or related topics.

These central figures in Cluster 1 have likely significantly impacted the scholarly discourse on the Triple Helix theory and innovation, and their work continues to influence research and discussions in this domain.

Cluster 2: Notable researchers in technology policy

Cluster 2 centers around technology policy, and while there are not as many central figures as in Cluster 1, the following authors are notable:

– Han W. Park (park hw): Han W. Park exhibits a moderate betweenness centrality (2.50) and a PageRank centrality of 0.038. His presence suggests active involvement in research related to technology policy, implying a role in shaping discussions and contributing to the network's knowledge diffusion in this area.
– Hyo Dong Hong (hong hd): Hyo Dong Hong, with a PageRank centrality of 0.0117, has contributed to discussions on technology policy within the cluster.
– Kwang Sun Kwon (kwon ks): Kwon Sun Kwon's presence (PageRank centrality of 0.016) indicates an involvement in the network's discussions on technology policy.

Clusters 3–9: Emerging scholars and collaborators

Clusters 3 to 9 feature various authors who, while not as central as those in Cluster 1 or 2, contribute to the diverse landscape of research. Their participation suggests a collaborative effort to expand the knowledge boundaries in their respective areas of study.

These emerging scholars and their collaborative efforts are vital in enriching the scholarly discourse, fostering interdisciplinary connections, and furthering research in innovation, technology policy, and related fields.

Overall, this analysis of key contributors and their centrality within the scholarly network provides valuable insights into the researchers' roles and influences in shaping discussions, advancing knowledge, and contributing to the vibrant ecosystem of ideas in the field of Triple Helix theory, innovation, and technology policy.

In this comprehensive analysis, the remarkable influence of Loet Leydesdorff's pioneering work in the fields of Triple Helix theory and innovation research becomes evident. His scholarly contributions have not only endured the test of time but have also significantly shaped the trajectory of these fields. Over the years, Leydesdorff's work has facilitated consistent annual growth in related scientific documents and fostered international collaboration among scholars, transcending geographical boundaries to enrich the discourse with diverse perspectives.

The thematic analysis highlighted the enduring relevance of key concepts like "Triple Helix" and "Innovation" within Leydesdorff's research, emphasizing their pivotal roles in advancing the comprehension of innovation dynamics. Furthermore, network analysis showcased the centrality of his work, as evidenced by high betweenness centrality and PageRank centrality, underscoring the profound impact of his research in bridging various aspects of the Triple Helix framework. As we consider the implications of his work, it becomes evident that Leydesdorff's legacy will persist in guiding and inspiring future generations of scholars, policymakers, and practitioners, offering an invaluable foundation for addressing complex challenges and promoting collaborative solutions in the realms of innovation and technology policy.

5 Content Analysis

Although most of Leydesdorff's contribution to the Triple Helix model is in collaboration with Etzkowitz and various other co-authors, we identified at least three significant Leydesdorff contributions to the Triple Helix model.

5.1 *Evolutionist Aspect of University-Industry-Government Interaction*

There are many examples of Triple Helix initiatives around the world (Etzkowitz & Zhou, 2017). However, they often end up limiting the understanding of it to the so-called neo-institutional side, where actors and spheres or helices participate in an initiative (like regional development projects or science and technology parks). Of course, it is essential that the actors exist and that they interact, but this does not explain how they do it. At this point, the neo-Schumpeterian or evolutionist discussion arises, which is more complex

and related to the process of creation, encoding/decoding, transmission, and use of knowledge, called technology transfer in the literature.[2]

Leydesdorff has an important contribution because he had the perception of the limitation of the institutional side to describe the complex dynamics that happen between the actors from their interaction overtime. Individual and collective learning processes, institutional strategies, individual interests, and regulatory and/or economic issues affect relationships, making the process fully dynamic with substantial historical, cultural, and even rooted local aspects.

He emphasizes the neo-evolutionary aspect (or neo-Schumpeterian) in which helices are selection mechanisms that influence each other asymmetrically, outlining a co-evolutionary trajectory for creating wealth, knowledge, and norms (Leydesdorff, 2012). Based on his trajectory dealing with dynamic and complex systems, Leydesdorff has started to discuss how to measure the interaction among actors. In his mind, Triple Helix is a theory that explains the relations in a knowledge-based economy.

5.2 *Measuring Triple Helix Linkages*

Leydesdorff made academic efforts to measure the interaction between the actors, which would be the way to understand and apply Triple Helix, transforming the concept form a metaphor in a theory. He seeks concepts from biology and chemistry, such as entropy, redundancy, and synergy, which he applies using patent information and other input and output indicators from science, technology and innovation (Leydesdorff, 2008; Leydesdorff; Ivanova, 2016; Ivanova et al., 2016).

Leydesdorff played a key role in the development of Triple Helix indicators (Park & Leydesdorff, 2010; Leydesdorff & Park, 2014). These indicators originated from Leydesdorff's earlier work (Leydesdorff, 2003; Leydesdorff & Meyer, 2003), where he introduced a scientometric approach to measuring Triple Helix dynamics from a neo-evolutionary perspective.

Leydesdorff's Triple Helix Indicators, which can be accessed at https://leydesdorff.net/, have been applied in various contexts through collaborative publications involving Leydesdorff. These contexts include Germany (Leydesdorff & Fritsch, 2006), Russia (Leydesdorff, Perevodchikov, & Uvarov, 2015),

2 The neo institutional approach is based on authors such as Ronald Coase, Kenneth Arrow, Douglas North, and Oliver Williamson. The neo-Schumpeterian or evolutionist discussion is based on the works of Christopher Freeman, Richard Nelson, Giovani Dosi, Sidney Winter, Keith Pavitt, among others.

China (Leydesdorff & Zhou, 2014), South Korea (Kwon, Park, So, & Leydesdorff, 2012), as well as cross-country analyses (F. Y. Ye, Yu, & Leydesdorff, 2013).

Jovanović, Savić, Cai, and Levi-Jakšić (2022) highlighted three important aspects of Triple Helix measurements. Firstly, these measurements serve as a control mechanism to assess the efficiency and effectiveness of policy implementation. Secondly, performance evaluation is crucial for enhancing Triple Helix interactions by identifying weak links and exemplary practices within the observed systems. Lastly, measuring Triple Helix efficiency can contribute to the development of ranking tools that gauge innovation competitiveness on a global scale.

5.3 *How Many Helices in a Model Are Better?*

Another Leydesdorff's contribution concerns the debate on the number of helices in the innovation model. Since Etzkowitz and Leydesdorff (1995) introduced the Triple Helix model of hybrid relationships to explain structural evolution in knowledge-based economies, many scholars, entrepreneurs, and managers have tried to extend it by including additional helices. It has been argued that the Triple Helix model is insufficient to explain systemic innovation's contemporaneity (Nordberg, 2015; Galvão et al., 2017; Yoon; Yang; Park, 2017). As such, new proposals have emerged over the years by extending the Triple Helix with inclusion of various elements, such as:

- a user of innovation (Arnkil et al., 2010; Carayannis; Cherepovitsyn; Ilinova, 2017)
- financial organizations (Colapinto; Porlezza, 2012)
- non-governmental organizations (NGOs) or associations (Nordberg, 2015; Grundel; Dahlstrom, 2016)
- intermediary organizations (Van Horne; Dutot, 2017)
- citizens and workers (Grundel; Dahlstrom, 2016; Campanella et al., 2017)
- creative class (Nordberg, 2015)
- international dimension (Lew; Khan; Cozzio, 2018)
- sustainable society (Grundel; Dahlstrom, 2016)
- something broader than the family, the state, companies, where people come together with a common interest or objective (Grundel; Dahlstrom, 2016)
- collectives (Mineiro; Castro; Amaral, 2023)
- an arena with multiple actors (Hasche; Hölund; Linton, 2019).

Among these initiatives, two most well-known models are the Quadruple and Quintuple Helix models. The Quadruple Helix model, introduced by Carayannis and Campbell (2009), essentially incorporates public or civil society as the fourth helix. On the other hand, the Quintuple Helix model,

proposed by Carayannis and Campbell (2010, 2013), adds a fifth helix representing the natural environments. Additionally, there are other proposals in the literature, such as the Penta Helix model (Hardianto et al., 2019; Shyafary; Pristanti; Cahyadi, 2020) and the Triple Helix Twins (Zhou; Etzkowitz, 2021).

Leydesdorff, along with Etzkowitz, aimed to defend their positions on the Triple Helix model based on the principle of Occam's razor. According to this principle, unnecessary complexity or new constructs should not be introduced in an explanation if not required. They believed that the triad of university, industry, and government actors and spheres, in terms of both their spheres and functions, is adequate to explain the creation and use of knowledge, as well as the resulting technological innovation and economic development (Leydesdorff, 2021).

Leydesdorff took the discussion further by introducing the concept of n-tuple helix in his seminal work (Leydesdorff, 2012). This theoretical exploration is significant for the model and provides insight into the dynamic relationships among the actors and spheres. Loet argues that the helix model represents the actors of the knowledge society and, therefore, there is no limitation to working solely with the three original actors. If there is a contribution to knowledge generation, one can model that society or set of relationships with as many spheres as desired. In this way, Leydesdorff expands the model, suggesting that there can be an infinite number of blades in the helix. However, according to him, the crucial question lies not in the number of blades, helices or actors, but rather in how to analyze the relationships among them. Leydesdorff argues that the triad or three-helix model is the most suitable, considering the better understanding of three-dimensional systems and the computational capacity required for analyzing such relationships. Introducing additional blades or helices, such as a model with four, five, or more helices, would entail four-dimensional, five-dimensional, and so on, relationships. Consequently, this would lead to a significant increase in complexity without commensurate analytical benefits (Leydesdorff, 2012).

More recently, Leydesdorff reinforced his argument that the dynamics of innovation primarily arise from the Triple Helix model, in a paper co-authored with Lawton Smith titled "Triple, Quadruple, and Higher-Order Helices: Historical Phenomena and (Neo-)Evolutionary Models" (Leydesdorff and Lawton Smith, 2022). In this work, the authors contended that Quadruple, Quintuple, and N-tuple helices can be deconstructed into various combinations of interacting triple helices. Leydesdorff and Lawton Smith provide justifications for their arguments from both theoretical and methodological standpoints.

6 Final Considerations

Loet Leydesdorff left us in March 2023 as a person, but his knowledge and contribution will be with us as an inspiration to our path on academy. This paper tried to analyze his contributions to the Triple Helix as a theory and keep it relevant for future studies in this field.

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