THESIS SUMMARY

Gravity Models and Machine Learning Approaches for Understanding Corporate Investment Flows and Framework Programme Collaborations in Europe

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Introduction

The complex structure of economic and research interactions that define the European Union presents significant analytical challenges. Understanding the structure and dynamics of these interactions is crucial for policymakers, regulators, national governments, and economic actors, such as companies from the smallest to the largest. This dissertation addresses two fundamental types of networks within this context: corporate ownership networks, which reveal the flow of investments and control, and research collaboration networks, which underpin innovation and knowledge transfer. European economic integration and research collaboration patterns require systematic analysis to understand underlying network formation mechanisms and predict future developments. The investigation of ownership networks and collaboration networks within the context of the European Union has emerged as a critical research domain, as these networks fundamentally shape economic flows, innovation patterns, and regional development between member states.

The investigation of ownership networks is driven by several critical motivations that intersect with economic, regulatory, and societal factors. An analysis of ownership networks sheds light on hierarchical structures within corporations and their interlinkages, thus elucidating the control dynamics over assets and decision-making processes. A deeper understanding of these structures is fundamental for stakeholders, including policymakers, as it informs regulatory frameworks aimed at enhancing transparency and accountability within corporate governance (Lidth Jeude et al., 2019; Takes et al., 2018). Furthermore, ownership networks can reveal complex interdependencies that may lead to monopolistic behavior or anticompetitive practices, with significant implications for market efficiency and economic equity (Nakamoto et al., 2019; Villamil et al., 2024). Methodologically, network science techniques have been used to explore these structures, leading to innovative frameworks that capture the layered nature of corporate hierarchies and improve the ability to analyze the complexity embedded in ownership relationships (Babić et al., 2019; Rungi et al., 2017).

Similarly, the investigation of collaboration networks in research is motivated by the need to enhance knowledge transfer, foster innovation, and understand the social dynamics within scientific communities. These networks facilitate interactions between researchers, influencing their collaboration choices and overall productivity. A critical motivation for analyzing these networks is the desire to understand and potentially rectify social and epistemic inequalities in science (Li et al., 2022). The structural configurations of collaboration networks also influence the dissemination of innovation, with external collaborators playing an important role in network dynamics (Katerndahl, 2011). One of the primary motivations is to enhance R&D productivity and innovation performance, as large networks can facilitate faster mobilization of resources and knowledge, which is essential for rapid innovation (Laufs et al., 2024).

This dissertation aims to contribute to both fields by developing and applying advanced modeling techniques. For ownership networks, a novel gravity-based

model is proposed to explain and predict investment flows. For collaboration networks, a comprehensive machine learning framework is developed to predict the formation of partnerships within the Horizon 2020 Framework Programme. By integrating large-scale heterogeneous datasets, this work seeks to provide a deeper and more nuanced understanding of the factors that shape these critical European networks.

This study is guided by two primary objectives, each corresponding to one of the types of network analyzed.

The first ultimate objective of the study is to understand and model the European ownership network to derive valuable information on how investment flows within the European Union and what factors influence the formation of this network. The goal is to improve link prediction and the network parameters derived for which a gravity-based null model is proposed. This involves identifying the main investment communities and assessing their temporal stability. Achieving this goal provides a deeper understanding of the factors that play a role in network formation, and this information can be beneficial to decision makers and government representatives in supporting regional and national economic decision-making processes.

The second main goal is to gain a deeper understanding of the collaboration network of the H2020 Framework Programme. The aim is to provide an accurate model that can predict collaboration links between firms based on measurable numeric information and to identify the influential parameters that play a role in the formation of the network. The construction of an accurate link prediction model is regarded as advantageous for decision makers seeking to forecast future consortia within the Framework Programmes. Identifying key influential factors enables the facilitation and support of future collaborations. Furthermore, outlier collaboration communities — characterized by links that are either stronger or weaker than predicted — are also identified, providing relevant insights for the management and regulation of collaboration formation.

1.1 Research Questions

Taking into account the above objectives and their relevance, the current study seeks to answer the following research questions.

> **RQ1:** Can the proposed gravity-based economic null model improve link prediction and network coefficient estimation, identify stable Emergent Innovation Communities, and provide insights into their spatial and temporal dynamics?
>
> **RQ2:** To what extent do administrative borders influence investment flows, and how do these effects change when controlling for geographical distance?
>
> **RQ3:** Can the proposed model, applied to a comprehensive dataset, enhance our understanding and predictive accuracy of organizational collaboration and community structures in Framework Programmes beyond current benchmarks?

These research questions encompass the dual objectives of improving predictive accuracy for both ownership and collaboration networks while identifying the underlying mechanisms that drive network formation in European contexts.

Related Studies and Research Assumptions

2.1 Theoretical Foundations in Network Science

Network science provides the foundational context for this dissertation. Early influential models, such as the Erdős-Rényi (ER-model) model, defined random graphs based on a fixed number of nodes and a uniform edge probability (Erdős and Rényi, 1959). While fundamental, the ER-model fails to capture key properties of real-world networks, such as power-law degree distributions. The small world network model, formally described by Watts and Strogatz (1998), introduced networks with high clustering and short path lengths, a structure observed in systems ranging from social interactions to brain networks (Bullmore and Sporns, 2009). A significant advancement was the Barabási-Albert (BA-model), which incorporated network growth and preferential attachment to explain the emergence of scale-free networks with highly connected hubs (Barabási and Albert, 1999). These foundational models have been integrated into broader analytical frameworks, including community detection and dynamic network models, to better capture the complexity of real-world systems (Farzaneh and Coon, 2022; Rinaldo et al., 2013).

2.2 Corporate Ownership Network Analysis

The exploration of ownership networks within corporate governance has gained significant traction as scholars attempt to discern intricate relationships between ownership structures and various corporate performance metrics. Ownership concentration has been shown to have considerable impact on earnings informativeness, as demonstrated by Sharifi and Jafari (2016), who found that concentrated ownership relates to low earnings information. The control exercised by certain owners significantly shapes governance structures, which affects business ethics and corporate behavior (Zattoni, 2011).

Several studies have used network science techniques to explore ownership structures, leading to the development of innovative frameworks that capture the layered nature of corporate hierarchies (Babić et al., 2019; Rungi et al., 2017). This complexity is crucial to understanding how power is concentrated within a small number of corporations, thus shaping competitive dynamics on a global scale (Vitali et al., 2011). The investigation of ownership networks serves multiple critical motivations that intersect with economic, regulatory, and societal factors, including the elucidation of hierarchical structures and the revelation of complex interdependencies among corporations.

Despite advances in link prediction methodologies, prediction accuracy remains a persistent challenge in ownership network analysis. Two primary factors contributing to suboptimal accuracy have been identified: limitations inherent to the

models and constraints associated with the datasets. From a model-based perspective, traditional approaches such as the configuration model introduced by Newman and Girvan (2004) assume random network structures without accounting for spatial constraints or economic factors that influence link formation.

2.3 Collaboration Network Analysis

Collaboration network analysis plays a key role in understanding the intricate dynamics of partnerships in various fields, serving not only as a pathway to knowledge sharing but also as a mechanism to address complex global challenges. The investigation of collaboration networks in research is driven by several motivations, mainly centered on enhancing knowledge transfer, fostering innovation, understanding social dynamics within scientific communities, and maximizing research impact (Li et al., 2022).

The critical motivation for analyzing these networks stems from the desire to understand and potentially rectify social and epistemic inequalities in science. Collaboration networks provide insights into how researchers associate with each other, which is crucial to address disparities in access to resources and opportunities. The structural configurations of collaboration networks can influence the dissemination of innovation Katerndahl (2011), and international collaboration networks can generate more precise outcomes in various contexts (Vanni et al., 2014).

Link prediction in collaboration networks has been addressed through various methodological approaches. Similarity-based techniques leverage local structures around the nodes when predicting potential links, with well-known examples including the Common Neighbors (CN) method, the Jaccard coefficient and the Adamic-Adar index (Ahmad et al., 2020; Zhang et al., 2016). Machine learning methods have gained prominence due to their ability to model complex relationships and patterns that simple similarity metrics might miss (Sulaimany et al., 2017; Wang et al., 2020).

The analysis of H2020 collaboration networks has revealed that prediction accuracy remains a persistent challenge. Previous studies have shown that prediction precision between multiple algorithms plateaued near 0.75 Chen et al. (2021), indicating the need for more sophisticated approaches that can capture the complex dynamics of research collaboration formation.

2.4 Research Assumptions

Based on the literature review and the identified research gaps, the following research assumptions were formulated.

> **RA1:** Gravity-driven economic principles dominate ownership network formation, with gravity-based economic null model predictions reflecting real-world investment flows more accurately than topology-only models.
>
> **RA2:** Administrative borders create structural breaks in ownership networks independent of geographic proximity, persisting across temporal layers.
>
> **RA3:** Machine learning techniques including generic and non-generic approaches can be beneficial for improving the prediction of the connections in the collaboration network of the Horizon 2020 Programme and with the proper model, the influential factors can also be identified.

These assumptions form the theoretical foundation for the methodological approaches developed in this dissertation and guide the empirical investigations conducted on both ownership and collaboration networks.

Results

3.1 Ownership Network Analysis: The Gravity-Based Economic Null Model

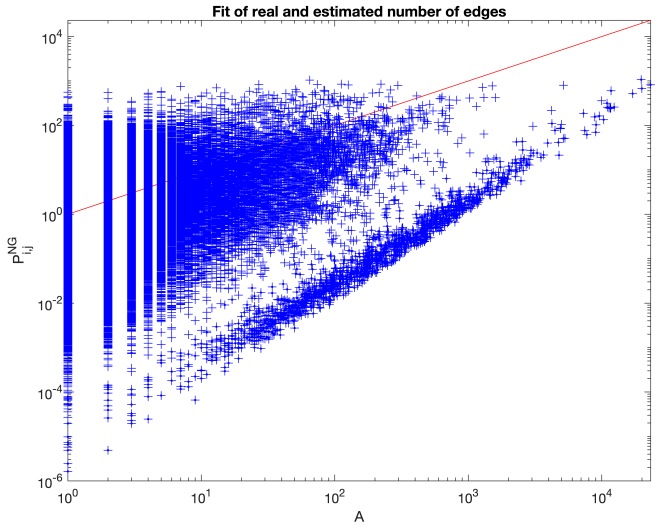
To analyze the European corporate ownership network, a novel Gravity-Based Economic Null (GEN) model was developed. This model predicts the number of ownership links between NUTS 3 regions based on spatial, economic, technological, and corporate financial indicators, without relying on pre-existing network topology information. The performance of the GEN model was compared with two established null models: the random configuration model of Newman and Girvan (2004) and the distance-dependent spatial model of (Expert et al., 2011).

The GEN model demonstrated a better fit to the observed data, achieving the lowest link prediction error ($\epsilon^{grav} = 0.0080$) compared to the spatial model ($\epsilon^{spa} = 0.0112$) and the random model ($\epsilon^{NG} = 0.0191$), as illustrated in Figure 3.1.

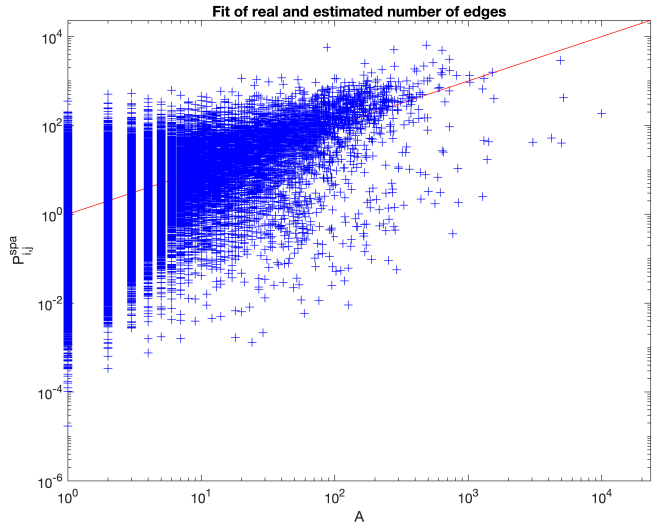
The regression coefficients of the GEN model revealed that subsidiary formations are driven by technological and economic disparities, with capital flowing from more developed to less developed regions. For example, subsidiaries tend to be located in NUTS 3 regions with lower GDP levels and fewer patent applications relative to their parent companies.

The improved link prediction of the GEN model also led to more accurate estimations of the properties of the derived network, such as centrality. Figure 3.2 shows the in-degree centrality across European regions, highlighting that the GEN model's prediction more closely resembles the original network structure compared to other models. It correctly identifies that investment attractiveness is concentrated in core European nations, while other models overestimate investment in Southern and Central Europe.

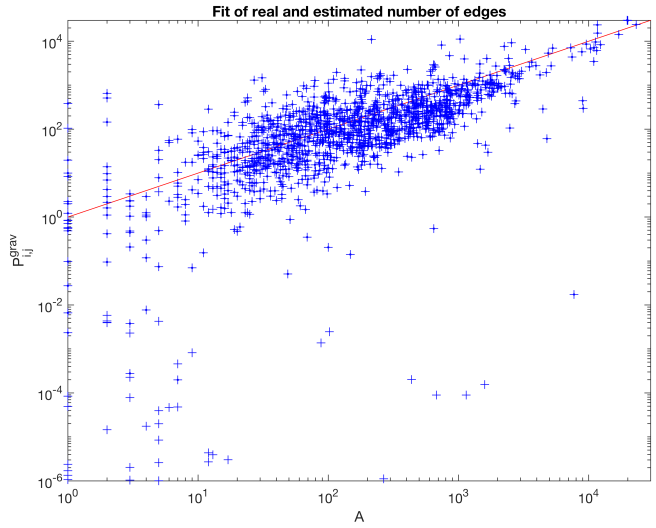
By integrating the GEN model with community detection algorithms, Economic-Investment Communities (EICs) were identified. These are groups of regions where the intensity of investment exceeds the expected levels based solely on economic, financial, and technological factors. The analysis revealed that these EICs are predominantly structured within national borders, indicating that administrative boundaries remain a powerful force shaping investment patterns, as shown in Figure 3.3. The temporal analysis of these communities from 2010 to 2018 further showed that these national-level structures are highly stable over time (Figure 3.4).



(a) Newman and Girvan (2004)'s model: $||\mathbf{A} - \mathbf{P}^{\text{NG}}|| = \epsilon^{NG} = 0.0191$

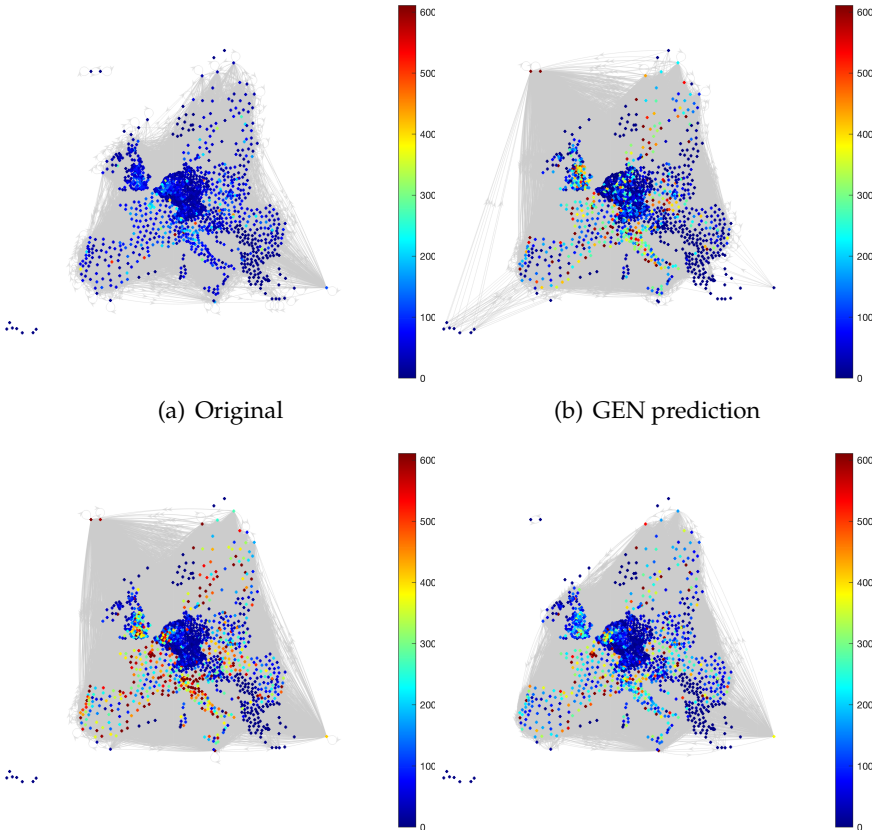


(b) Expert et al. (2011)'s model: $||\mathbf{A} - \mathbf{P}^{\text{spa}}|| = \epsilon^{spa} = 0.0112$



(c) GEN model: $||\mathbf{A} - \mathbf{P}^{\text{grav}}|| = \epsilon^{grav} = 0.0080$

FIGURE 3.1: Fits of the different null models (2018)



(a) Original (b) GEN prediction

(c) Random network (d) Spatial network

FIGURE 3.2: The in-degree centralities for the predicted network structures (2018)

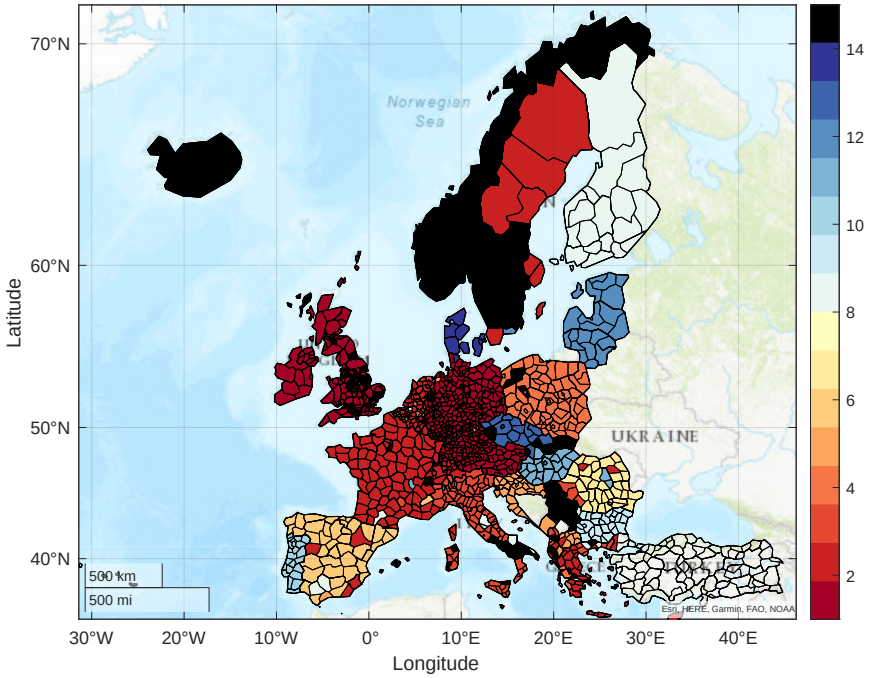
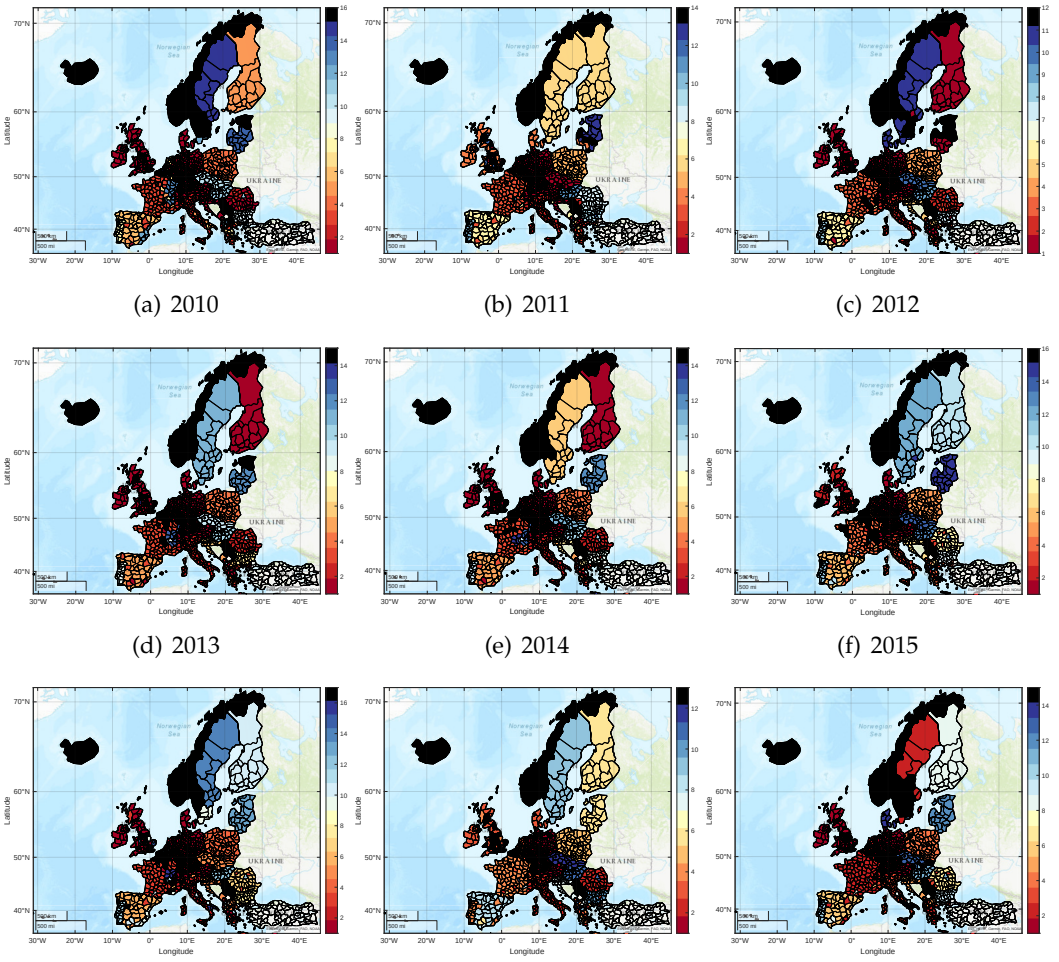


FIGURE 3.3: Economic-Investment Communities identified using the GEN model (2018). Modules (differentiated by color) largely align with national administrative boundaries.



(a) 2010 (b) 2011 (c) 2012

(d) 2013 (e) 2014 (f) 2015

(g) 2016 (h) 2017 (i) 2018

FIGURE 3.4: Layers as years (2010-2018) of the found economic modules

3.2 Horizon 2020 Collaboration Network Analysis

For the analysis of the H2020 collaboration network, a comprehensive research database was constructed by integrating data from the CORDIS, Orbis, Patstat, and Eurostat databases. A set of machine learning models was applied to predict collaborative links between organizations.

The feature importance analysis, conducted using the Boruta algorithm and the Random Forest models, yielded one of the most significant findings of this study. As shown in Figure 3.5, collaboration-related variables were identified as the most powerful predictors of link formation. Specifically, the earned contribution (EC) and the average rate of parallel project completion (MULTI) were the most influential factors, surpassing even the geographical distance. This suggests a strong preferential attachment mechanism, where organizations with extensive connections and a history of managing multiple projects are more likely to attract new collaborations.

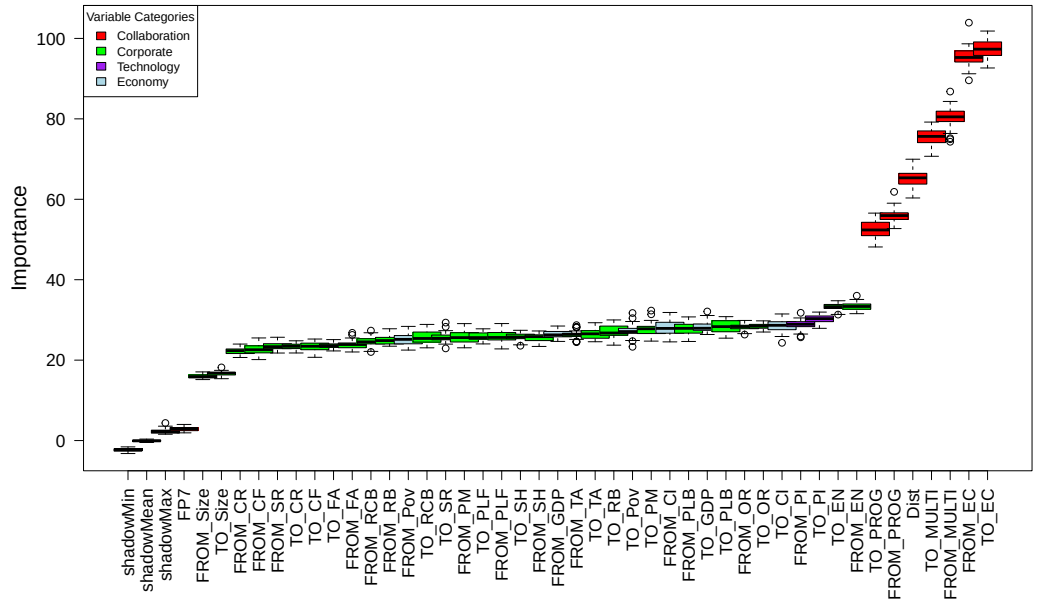


FIGURE 3.5: Feature importance as determined by the Boruta algorithm. Collaboration-related variables are ranked as the most important predictors.

The predictive performance of various machine learning algorithms was evaluated. Non-generic, black-box methods like Random Forest (RF) and XGBoost outperformed generic methods like Linear Discriminant Analysis (LDA) and Logistic Regression (LogR), indicating the presence of significant nonlinear relationships in the data. The tuned XGBoost model achieved the highest accuracy (0.863) and F1 score (0.911) in the test data set. When applied to the entire network, the RF and XGBoost models demonstrated high overall accuracy (higher than 0.96) and minimal structural discrepancies between the original and predicted networks.

The link prediction model was then used as a null model to identify outlier collaboration communities — groups of organizations where the observed number of collaborations significantly exceeded the model's predictions. These communities, depicted in Figure 3.6, were found to be geographically concentrated in core EU

nations, particularly Germany and the UK. This finding highlights the existence of strong self-reinforcing collaborative clusters that are not fully explained by the extensive set of corporate, economic, and technological variables included in the model.

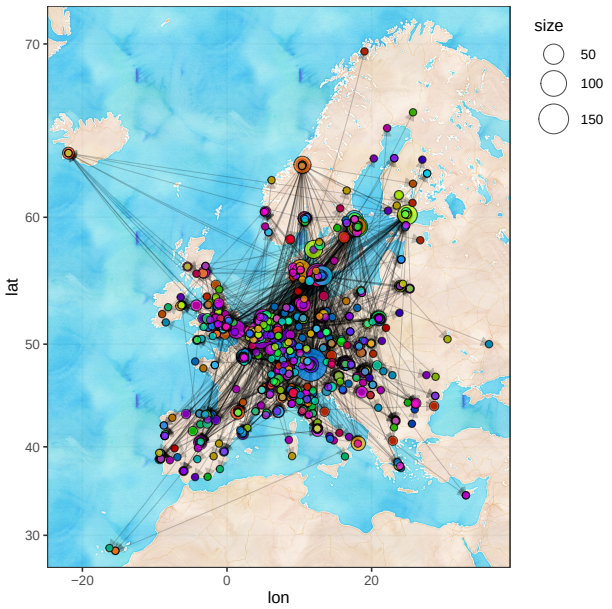


FIGURE 3.6: Economic collaboration communities. Nodes represent organizations, and edges represent underestimated collaborations. The communities are geographically concentrated in Western Europe.

Research Theses

Based on the comprehensive analysis and the results obtained, the following research theses are established.

RT1: In this dissertation, it has been demonstrated that the gravity-based economic null model reduces link prediction error in comparison to the Newman-Girvan and Expert models, while also enabling the identification of economic-investment communities and providing superior estimation of derived network parameters relative to the aforementioned models. The model has indicated that company establishments within the European Union are influenced by technological and economic disparities, with investment flows directed from more developed regions toward less developed ones.

RT2: The gravity-based economic null model proposed in this work has revealed that primary investment flows are strongly shaped by administrative boundaries (country borders), as investments are predominantly established within national borders, resulting in capital largely remaining domestic. Although the European Union seeks to enhance integration and promote economic equality across all member states, administrative boundaries continue to exert a significant effect on the formation of the European ownership network.

RT2.1: The proposed annual model introduced in this study, has the capability to identify temporal changes in economic-investment communities.

RT3: The proposed model for the collaboration network analysis together with the integrated machine learning techniques have been shown in this dissertation to outperform benchmark models and further improve predictive accuracy. Relationships among 23 validated corporate and economic predictors were captured, and all defined variables were identified as important, underscoring the advantages of employing a comprehensive dataset. The proposed model has also revealed that the most influential variables for collaboration formation pertain to previous successful collaborations within the same framework programme. Outlier collaboration communities, restricted to the European Unions core countries, were identified.

RT3.1: In regards of link prediction in European Union's Framework Programmes collaboration networks, the non-generic methods perform better than the generic ones, indicating nonlinear relationships in the model. The best performing methods among the applied non-generic ones are the Random Forest based ones.

Summary and Conclusion

This dissertation has advanced the understanding of European economic and research networks by integrating diverse methodological approaches within explanatory frameworks.

For the analysis of corporate ownership networks, a generalized yearly gravity-based economic null model (GEN) was proposed. This model was shown to provide superior estimates of network properties and link predictions compared to established topology-based and spatial models. By incorporating economic, financial, and technological indicators, the GEN model successfully explained the flow of investment from the most developed to the least developed regions within the EU. Furthermore, the integration of this model with community detection algorithms allowed for the delineation of economically coherent communities, revealing that national borders remain a primary structuring force in the European ownership landscape.

For the analysis of research collaborations, a highly accurate link prediction model was developed for the H2020 network by integrating multiple comprehensive databases. This approach enabled the identification of the main factors that influence collaboration, with prior project involvement and earned contributions emerging as the dominant determinants. The analysis also specified outlier collaboration communities, predominantly comprising organizations from EU core countries, which highlights the presence of strong, self-concentrating patterns of partnership.

5.1 Implications

The findings of the study hold significant relevance for decision-makers and policy formulators within the investigated domains. The following implications are derived from the results and are intended to inform strategic planning and policy development.

The analysis of the ownership network revealed that the predominant direction of investment flows is from economically advanced regions toward less developed areas. This insight provides a basis for governmental authorities to prioritize national infrastructure development initiatives in underdeveloped regions, thereby enhancing their attractiveness for future subsidiary establishment. Such targeted interventions may contribute to reducing regional disparities and fostering balanced economic growth.

The temporal stability observed in the ownership network between 2010 and 2018 indicates that the principal economic-investment communities have remained largely unchanged over this period. This persistence implies that investment flows predominantly circulate within the core EU countries in the long term. However, this equilibrium may be altered through deliberate policy interventions, such as the implementation of tax incentives or regulatory adjustments, which could redirect investment towards targeted regions.

The investigation of the Horizon H2020 collaboration network also yields several policy-relevant implications. The observed scale-free nature of link formation suggests that entities with established collaborative histories possess a disproportionately higher likelihood of securing additional partnerships compared to newcomers. In response, the Framework Programme (FP) policymakers might consider instituting upper limits on the number of projects awarded to individual entities, potentially differentiated by organizational size, to promote equitable participation.

Additionally, specific provisions could be introduced to facilitate the engagement of entities with no prior participation in subsidized (FP) projects. By easing eligibility criteria or providing targeted support, these measures could incentivize broader involvement and diversification within funding programs.

5.2 Research Summary Table

The below table contains the summarized Research Questions, Assumptions, and Theses as for a better overview combined together.

TABLE 5.1: Summary table for Research Questions, Assumptions and Theses

Item	Statement
RQ1:	Can the proposed gravity-based economic null model improve link prediction and network coefficient estimation, identify stable Emergent Innovation Communities, and provide insights into their spatial and temporal dynamics?
RA1:	Gravity-driven economic principles dominate ownership network formation, with gravity-based economic null model predictions reflecting real-world investment flows more accurately than topology-only models.
RT1:	In this dissertation, it has been demonstrated that the gravity-based economic null model reduces link prediction error in comparison to the Newman-Girvan and Expert models, while also enabling the identification of economic-investment communities and providing superior estimation of derived network parameters relative to the aforementioned models. The model has indicated that company establishments within the European Union are influenced by technological and economic disparities, with investment flows directed from more developed regions toward less developed ones.
RQ2:	To what extent do administrative borders influence investment flows, and how do these effects change when controlling for geographical distance?
RA2:	Administrative borders create structural breaks in ownership networks independent of geographic proximity, persisting across temporal layers.
RT2:	The gravity-based economic null model proposed in this work has revealed that primary investment flows are strongly shaped by administrative boundaries (country borders), as investments are predominantly established within national borders, resulting in capital largely remaining domestic. Although the European Union seeks to enhance integration and promote economic equality across all member states, administrative boundaries continue to exert a significant effect on the formation of the European ownership network.
RT2.1:	The proposed annual model introduced in this study, has the capability to identify temporal changes in economic-investment communities.

Item	Statement
RQ3:	Can the proposed model, applied to a comprehensive dataset, enhance our understanding and predictive accuracy of organizational collaboration and community structures in Framework Programmes beyond current benchmarks?
RA3:	Machine learning techniques including generic and non-generic approaches can be beneficial for improving the prediction of the connections in the collaboration network of the Horizon 2020 Programme and with the proper model, the influential factors can also be identified.
RT3:	The proposed model for the collaboration network analysis together with the integrated machine learning techniques have been shown in this dissertation to outperform benchmark models and further improve predictive accuracy. Relationships among 23 validated corporate and economic predictors were captured, and all defined variables were identified as important, underscoring the advantages of employing a comprehensive dataset. The proposed model has also revealed that the most influential variables for collaboration formation pertain to previous successful collaborations within the same framework programme. Outlier collaboration communities, restricted to the European Unions core countries, were identified.
RT3.1:	In regards of link prediction in European Union's Framework Programmes collaboration networks, the non-generic methods perform better than the generic ones, indicating nonlinear relationships in the model. The best performing methods among the applied non-generic ones are the Random Forest based ones.

5.3 Contribution to the Literature

The contributions of this work to the literature are threefold.

First, the proposed GEN model (published in Kosztyán et al., 2022) offers a novel and more accurate method for link prediction in spatial economic networks. It revealed that the subsidiary structure within the European Union is shaped by economic disparities, a finding that has significant implications for the European Union's goal of economic cohesion. The identification of stable, national-level Economic-Investment Communities EICs is a novel contribution that sheds light on areas for further policy development.

Second, as a result of the collaboration investigation (published in Kosztyán et al., 2024), an accurate and interpretable model was developed for link prediction in R&D&I networks. This was made possible by creating a unique research database that connects corporate, economic, patent, and collaboration data, enabling more complex and nuanced research than previously possible.

Third, key economic, technological, and, most importantly, collaboration history factors that influence partnership formation were identified and ranked. The proposed model is also capable of specifying outlier communities where collaboration is denser than predicted, providing a powerful tool for analyzing the underlying dynamics of research networks and informing policy interventions aimed at fostering broader and more inclusive collaboration.

Publications

In this chapter, the author's publications are mentioned that are related to the topic together with the MTMT profile. The publications are collected by different categories.

6.1 The author's publications related to the topic

Author's MTMT profile web-link[1], which also shows the following publications.

International Journal Articles

Zsolt T. Kosztyán and **Ferenc Király** and Attila I. Katona and Tibor Csizmadia and Beáta Fehérvölgyi (2024). Analysis and prediction of the Horizon 2020 R&D&I collaboration network. In: *Expert Systems with Applications*
DOI: doi.org/10.1016/j.eswa.2024.124417

Zsolt T. Kosztyán and **Ferenc Király** and Marcell T. Kurbucz, (2022) Analysis of ownership network of European companies using gravity models. In: *Applied Network Science*. DOI: doi.org/10.1007/s41109-022-00501-y

Hungarian Journal Articles

Zsolt T. Kosztyán and **Ferenc Király** and Marcell T. Kurbucz, (2024). Európai cégek tulajdonosi szerkezetének dinamikus hálózatelemzése. In: *Közgazdasági Szemle*
DOI: dx.doi.org-/10.18414/KSZ.2024.1.57

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Zsolt T. Kosztyán and **Ferenc Király**. Analysis of the ownership network of European companies using panel data gravity models. XXV. Tavaszi Szél Konferencia 2022. Pécs, Hungary

[1] https://m2.mtmt.hu/gui2/?type=authors&mode=browse&sel=10043340

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