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**Inventors' Mobility and the Geographies of Innovation:  
The Case of mRNA COVID-19 Vaccines**

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# Abstract

Recent evidence shows that inventors' mobility is a primary channel for, on the one hand, facilitating the spatial diffusion of knowledge—often tacit and sticky—and, on the other, diversifying regional innovation assets by escaping cognitive lock-ins and enabling technological change. This distinctive role has drawn greater attention to the phenomenon, particularly from a geographical perspective, as it exemplifies the nexus between spatiality and innovation: inventors' mobility not only contributes to the recombination and reuse of knowledge vital to the innovation process, but also shapes the geography of innovation and is therefore among the main drivers of pronounced spatial inequality in the allocation of resources, increasingly concentrated in a few hubs. Understanding this phenomenon is thus crucial for its impact on regional innovative capacities and, consequently, for equitable and effective regional development.

The aim of this thesis is to advance understanding of the spatiality of inventors' mobility by identifying the spatial structures that emerge from it, what these structures imply, how they change and co-evolve with the innovation process over time, which factors influence mobility, and how mobility is perceived by inventors themselves.

The principal case study reconstructs the innovation process that led to the implementation of mRNA vaccines—an innovation that has transformed modes of producing preventive medicines and enabled a rapid response to the COVID-19 pandemic. This process is particularly suited to the thesis because it spans a relatively long period during which research was initially driven by basic science—primarily involving public institutions, universities, and start-ups, in contrast to the skepticism of large firms—before a reversal in industry attitudes following breakthroughs that made the vaccine economically viable and scalable. Tracing inventors' mobility along this process sheds light on the spatial dynamics it produces.

Methodologically, the thesis adopts a multi-method and multi-level design. A relational-quantitative analysis using network methods explores complex and emergent spatial structures, alongside a qualitative analysis oriented to inventors' subjective perspectives through their life histories.

The discussion begins by retracing the main phases of the innovation process that led to mRNA vaccines, highlighting that for a long period it was driven by basic research—highly uncertain and at times marginalized. Together with the vaccine's distinctive features, this meant that for the first decades research proceeded across multiple disciplines and places, until the recent acceleration brought about by the concrete possibility of developing the product.

Subsequently, the economic-geography literature on inventors' mobility is examined with a critical lens, bringing to light three main areas of concern: (i) divergences over mobility's role as a source of knowledge diffusion and regional diversification versus evidence of concentration and specialization; (ii) ambiguities regarding the territorial effects of mobility, especially for origin regions; and (iii) a limited understanding of the drivers of mobility, which is predominantly framed within a microeconomic approach.

To advance understanding of these issues, three empirical studies are presented.

The first study identifies the spatial structures emerging from inventors' mobility and their implications for stability, efficiency, and equity. I map the career trajectories of the principal vaccine inventors to reconstruct a directed city-to-city mobility network. The analysis shows a scale-free network, i.e., a complex network with specific properties. Community detection reveals a core-periphery structure in which technology hubs form much denser inter-city connections that facilitate knowledge exchange and diversification. A distinctive feature of hubs thus emerges: rather than merely accumulating human capital, they promote its transit and circulation. Exponential Random Graph Models (ERGMs) estimates corroborate these findings, highlighting also the predominance of

intra-national mobility and the importance of maintaining a balanced mix of education-oriented and employment-oriented institutions to avoid losing human capital. In terms of implications, these geographical configurations prove highly resilient to random shocks that stress the ecosystem, yet strongly vulnerable when shocks strike the hubs, rendering the entire innovation system dependent on them. Moreover, network topology is not neutral with respect to inventors' mobility; it can itself amplify centralization, thereby posing risks to the equity and efficiency of the innovation process.

The second study complements the first by moving beyond a static view of the geography of innovation. Incorporating time, it examines how mobility-generated spatial structures change and co-evolve with stages of the innovation process. I reconstruct the mobility of all inventors involved and build a temporal network linking cities via inventors' moves. The process is divided into two periods: an initial phase characterized by low technological opportunities and even lower innovative opportunities—dominated by basic, exploratory research—and a subsequent phase in which innovative opportunities surpass technological ones, marking readiness for production and market introduction. The analysis indicates that in the first period the mobility-generated structures are quasi-random, non-hierarchical, and the network is sparse and fragmented. In the second period, the network becomes centralized around a few cities that connect a large share of the system. Temporal ERGMs (TERGMs) estimates show that in the first period inventors tend to move toward cities that have produced knowledge—especially incremental knowledge—whereas in the second period knowledge plays a smaller role, and inventors gravitate toward hubs holding complementary assets necessary for scaling and commercialization.

The third study adopts a biographical approach to gain a deeper understanding of inventors' motivations and viewpoints. It examines which factors researchers deem most important in their career and location choices, and how they perceive the spatial dynamics produced. Analysis of eleven life stories reveals an interplay between subjective drives and objective contexts shaping inventors' decision-making. The primary engine is an intrinsic, indeterminate “blind” motivation—often described as curiosity, the desire to learn and discover, and, given the field, to care. This initial impulse meets the socio-spatial context, which filters and channels it into concrete choices. Among the objective factors that inventors consider crucial are access to funding—mainly to sustain uncertain research rather than to maximize earnings—and the need to establish and preserve social ties. This dyadic dynamic between the subjective and the objective is perceived as co-evolutionary: researchers' choices and work influence socio-spatial contexts, which in turn reshape decision-making process. A perceived geographical division of the innovation process emerges; whereby certain places are more oriented toward particular phases due to this co-evolution reinforcing territorial specialization. At the same time, inventors express concerns that market tendencies to favor some phases over others risk marginalizing the latter.

This thesis highlights the interdependent relationship between the complex geographies generated by inventors' mobility and the innovation process. In particular, it shows how these geographies make the innovation system highly dependent on a small set of hub cities which, while crucial for the circulation of inventors and knowledge, simultaneously render the system vulnerable to shocks that may strike them, given their capacity to connect the entire spatial system. The thesis also shows that hubs do not play the same role throughout the innovation process: their influence is pivotal mainly in its final stage, whereas in the early stages inventors' mobility is primarily driven by the search for knowledge, producing an evolution of spatial patterns from quasi-random to centralized. Finally, the thesis underscores the dialectical, co-evolutionary relationship between inventors' subjective motivations and the socio-spatial contexts they help create, and it reports their concerns regarding the problems this process poses for the production of novel knowledge. The analysis points to the need for policies that mitigate the process's distortive and unequal effects by fostering the circulation—

rather than the retention—of human capital, and by directing efforts toward research that remains capable of taking the risks required to sustain it.

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# Chapter 1

## 1 Introduction

The inventors' mobility is recognized as the main channel through which knowledge—often tacit and sticky (Jaffe et al., 1993)—manages to diffuse across space (Breschi & Lissoni, 2009). This kind of knowledge, embodied in the inventors who possess it, follows their spatial trajectories, moving with them and reaching locations different from where it was originally generated, so it can be recombined or reused (Choudhury & Kim, 2019). This phenomenon can, on the one hand, ensure a more equitable distribution of innovative activity—which is already strongly concentrated due to its cumulative, localized, and path-dependent nature (Asheim & Gertler, 2006; Dosi, 1982)—and, on the other hand, foster unrelated diversification in both destination and origin regions (Diodato et al., 2023; Miguelez & Morrison, 2023) by combining external sources of knowledge, thereby avoiding cognitive lock-in and paving the way for technological change. These major opportunities that inventors' mobility seems to provide, however, face several limitations. Inventors—and highly skilled workers more generally—tend to move towards regions with an already high concentration of human capital, thereby reinforcing concentration rather than diffusion, or towards places recognized as world leaders in their field, which increases specialization rather than diversification (Caviggioli et al., 2020; Kerr et al., 2016). Moreover, the actual magnitude of these effects is not always clear when looking at origin and destination regions, especially regarding how much migrant inventors effectively contribute to the productivity of the first one and to what extent the latter can compensate for the initial loss of human capital through so-called “knowledge remittances” (Borjas & Doran, 2015; Fackler et al., 2020).

This thesis aims to provide greater clarity on this phenomenon and on the resulting geographies of innovation produced by it. It assumes that these geographies—the spatial configurations of the innovation process—are emergent phenomena generated by the interaction of places through inventors' mobility, in which the two processes are co-produced and co-evolve along the innovation trajectory. Demonstrating this assumption is the main objective of the thesis. To do so, it draws on the analysis of the innovation process that led to the implementation of the mRNA COVID-19 vaccine. This process offers a multi-decadal perspective, beginning with basic, curiosity-driven research, followed by early laboratory breakthroughs that made medical applications possible, and culminating in the final acceleration, which first involved biotech start-ups and subsequently large firms and policy-makers, ultimately resulting—60 years after the discovery of mRNA—in the development of a technology that enabled the first rapid vaccination on a global scale.

In analyzing how inventors' mobility and the resulting spatial formations co-evolve along this process, this thesis adopts a multi-method and multi-level approach. It combines a historical-quantitative analysis, centered on network analysis to reveal and interpret the emergent spatial structures, their meaning, and their implications, with a subjective-qualitative analysis, which focuses on the perspectives and life histories of the inventors involved in order to understand the factors driving their choices and how they experience mobility. This approach allows for the integration of large-scale, objective spatial structures with the subjective experiences of those who contributed to shaping them, thereby providing insights into the mechanisms linking these two dimensions.

## **1.1 Aims of the thesis and research questions**

The overall objective of this thesis is to understand how inventors' mobility contributes to shaping the geographies of innovation throughout the innovation process, and what are the implications for the places and actors involved. In other words, by analyzing the inventors' mobility throughout a specific innovation process, this study aims to contribute to a better understanding of the relationship between space and innovation.

This overarching aim is pursued through the reconstruction of the innovation process that led to the development of mRNA vaccines, a critical analysis of the literature on inventors' mobility, and three complementary empirical studies, each addressing different aspects of the phenomenon, with distinct research objectives and questions.

A descriptive reconstruction of the functioning and stages of the long history underlying this innovation process aims to introduce the case study, outline its main features, and facilitate the understanding of the subsequent empirical findings.

The primary aim of the critical literature review is to identify the main areas of interest within the field of inventors' mobility, discussing the most significant contributions and bringing together different disciplines and approaches. It seeks to highlight contrasting perspectives, identify gaps and limitations in the existing body of research, and propose possible new directions of inquiry.

The first study addresses the questions: "Which spatial patterns emerge from inventors' mobility, and what factors contribute to their formation? What are the implications of these patterns for the resilience and stability of the overall spatial structure?" The goal here is twofold: first, to provide an initial mapping of the relationships established through inventors' mobility across different cities and, consequently, to identify the type of spatial structures that emerge by following inventors along their career paths; and second, to assess the significance of these structures in terms of efficiency and equity.

The second study seeks to answer the questions: "How do the spatial structures generated by inventors' mobility evolve as technological and innovative opportunities change throughout the innovation process? How can different sources of knowledge influence these geographies?" This study investigates whether, and in what way, mobility changes across different phases of the innovation process, and how spatial structures co-evolve accordingly. In addition, it explores whether the production of different types of knowledge—incremental versus radical—has distinct effects on mobility, both in relation to the whole innovation process and to its specific stages.

The third study responds to the questions: "Which factors do inventors consider decisive in their location choices across their career path, and how do these factors influence the spatial configuration of the innovation process?" The aim here is also twofold: on the one hand, to explore inventors' decision-making processes in their location choices, examining how these evolve, how they are shaped by external factors, and how they contribute to the formation not only of the actual geography but also of the perceived geography of innovation. On the other hand, by shedding light on the factors that inventors consider as most important in their decisions, the study seeks to contribute to the design of policies capable of attracting and retaining highly skilled workers, which are essential for regional development.

## **1.2 Data collection**

To achieve the objectives of this thesis, it was necessary to reconstruct the mobility of the inventors who participated in this specific innovation process. Since no suitable dataset was available, a data collection process was designed starting from a few but reliable pieces of information, and then

proceeding step by step toward the construction of a comprehensive database. This paragraph summarizes the data collection process, highlighting its strengths and weaknesses.

The starting point consisted of the patents identified by Gaviria & Kilic (2021) as those essential for the production of the mRNA anti-COVID vaccine. First, the inventors listed in these patents were identified. To trace their mobility as accurately as possible, publicly available information about the places where they studied and worked throughout their lives was collected.

Subsequently, the focus expanded beyond the inventors directly involved in the final stage of the innovation process to include all those who contributed indirectly. To achieve this, all patents cited by the main ones were collected through web scraping, in order to reconstruct the broader knowledge base required for the innovation. Once again, all inventors named in these patents were identified, and for each of them, all additional patents registered under their name were gathered—provided they referred to technological classes consistent with the biopharmaceutical sector.

These patents were used to geolocate the inventors at specific points in time, based on the city of the applicant, thereby reconstructing their mobility by following the sequence of patents they filed. Geolocation was carried out through the USPTO for U.S. patents, while the remaining patents required manual work. Finally, to conduct interviews and collect inventors' life histories, email contacts were searched for—mostly through institutional webpages—and inventors were directly contacted with an interview request.

The uniqueness and specificity of this dataset represent its main strengths, as it allows the exploration and analysis of a particular innovation process that would otherwise be difficult to observe. The dataset is also rich in detailed information, enabling a faithful representation of reality. Moreover, selecting interviewees from this specific group of inventors made it possible to collect life histories that are inevitably intertwined with the innovation process under study.

However, several limitations must be acknowledged. First, the use of patent data is known to be problematic: on the one hand, it cannot capture the entire innovation process; on the other hand, it only allows tracing inventors' mobility when they file patents. Furthermore, issues of inventor disambiguation—although minimized—can never be completely resolved. Finally, the fact that only inventors with publicly available contact information could be approached restricts the ability to include all voices and life stories of researchers involved in this innovation process.

### **1.3 Structure of the thesis**

The thesis will follow a structure that is as linear as possible, although points of connection between the different studies strengthen the arguments presented through complementary methodologies. It begins with an overview of the functioning of the mRNA vaccine and the history of its innovation process, in order to contextualize and clarify the relevance of the chosen case study. This is followed by a critical review of the literature on inventors' mobility, aimed at identifying key gaps, understanding dominant approaches, and highlighting the innovative contributions of this thesis as well as their potential usefulness. The subsequent chapters present the three empirical studies. Finally, the concluding chapter integrates the findings of the individual studies, drawing together their results to assess their overall significance.

A brief outline of the chapters structuring the thesis is provided below.

#### **1.3.1 Chapter 2—Exploring the development of the mRNA vaccine**

The first chapter aims to illustrate the functioning and innovation history of the mRNA vaccine, the case study at the core of this thesis. Understanding its mechanism of action is crucial for grasping the complexity of this innovation, particularly the way in which multiple scientific disciplines had to converge and build upon each other to produce what ultimately revolutionized mass prevention

medicine. Equally important is the fact that the different components of this technology originated in distinct fields of research and, above all, in different places, which only came together toward the final stages of the process.

For this reason, the chapter reconstructs the history of the innovation process, beginning with an early stage strongly rooted in basic research which, for over twenty years, offered no apparent pharmaceutical applications but was instead driven by motivations that went beyond industry. It was only with the first in vitro synthesis of mRNA that the possibility of medical use could be theorized. Yet, for a long time, this line of research remained marginal, surrounded by skepticism regarding its fragility and actual effectiveness.

Only in the 2000s, thanks to a series of revolutionary discoveries that made the pharmaceutical application of mRNA genuinely feasible, the innovation process gain the necessary momentum, leading in a relatively short period to the development of vaccines. During this phase, industry interest grew, new start-ups—later widely known during the pandemic—were founded, government agencies allocated substantial investments, and large firms made their infrastructures available. Once the specificities of this innovation process are understood, it becomes easier to navigate the empirical studies that follow.

### **1.3.2 Chapter 3—Critical review of the literature**

The second chapter presents a review of the literature on inventors' mobility, drawing primarily on economic geography while also integrating contributions from related fields such as economic history and migration studies. The review is organized into three thematic sections, a division adopted solely for the sake of clarity, as these themes often overlap.

The first section examines the role of inventors' mobility in innovation, with particular reference to studies highlighting its ability to diffuse knowledge across space and to generate diversity within regions, thereby preventing lock-in and fostering technological change. These perspectives are contrasted with works reporting opposing results, highlighting the key gaps in the literature.

The second section focuses on the regional effects of inventors' mobility. Following the dominant approach in the literature, which distinguishes clearly between origin and destination regions, the effects on these two types of regions are treated separately. Once again, the most significant findings are presented alongside results that challenge them, providing a comprehensive overview and clarifying the main points of disagreement as well as how these might be addressed.

The third section reviews studies on factors influencing inventors' mobility, with a particular focus on its drivers. This body of work is shown to be strongly rooted in a microeconomic perspective, in which inventors are assumed to make mobility decisions through an ex-ante calculation comparing costs and benefits.

Taken together, the literature review serves to provide an overview of the current state of research on inventors' mobility, its achievements, its limitations, and its blind spots, thereby laying the groundwork for how this thesis contributes through its empirical studies.

### **1.3.3 Chapter 4—Network structure and resilience**

The first study of this thesis aims to outline the spatial and relational structures that emerge among cities through inventors' mobility. The objective is to demonstrate that the spatiality of this phenomenon is not limited to the mere transfer of resources such as human capital and knowledge, but rather that mobility generates complex interconnections between places, giving rise to unique spatial patterns with properties that go beyond the simple aggregation of flows.

The mobility of the key inventors who contributed to the innovation of the COVID-19 mRNA vaccine is mapped by tracing their career paths—from higher education to their most recent professional positions—using publicly available information (including curricula vitae, interviews, and social networks). These data are then used to construct a mobility network in which cities are represented as nodes and inventor movements create directed ties between them.

This network is first analyzed through degree distribution in order to assess whether the empirical network can be assimilated to well-known theoretical models. Building on this, the study investigates the emergent spatial patterns and the factors driving their formation. To do so, three different community detection methods are applied: the Stochastic Block Model, the Leiden algorithm, and Infomap. Each of these highlights distinct aspects of the network: respectively, the role of cities, the frequency of mobility-induced ties among them, and the capability of knowledge transfer.

The findings from these methods are subsequently tested and validated—or contested—through Exponential Random Graph Models (ERGMs), which help identify the factors underpinning the formation of specific spatial structures. Once the emergent geographies of inventors' mobility have been identified, the study examines their implications for the overall stability and efficiency of the network. In particular, sequential node and/or edge removal simulations are carried out, based on different characteristics, in order to observe the resulting effects on the network and to identify which cities make the structure most vulnerable. This, in turn, provides insights into the policy implications of such spatial formations.

In a second step, the analysis focuses exclusively on the topological properties of the network to train machine learning models capable of predicting link formation between cities with reasonable accuracy. This allows an exploration of how spatial patterns themselves may, to some extent, influence subsequent mobility trajectories.

In sum, this first study seeks to shed light, as comprehensively as possible, on the complex spatial dynamics that take shape through inventors' mobility. It also provides a compass for the second study, in which the temporal dimension will be added to the analysis.

### **1.3.4 Chapter 5—Network in motion**

Once the geographies that emerge from inventors' mobility have been identified, the next step is to understand how and, above all, when they emerge. This requires moving from an aggregated and static perspective of mobility to a more dynamic and temporal analysis, observing how mobility changes year by year across the entire innovation process. Doing so not only provides a more accurate and fine-grained understanding of the phenomenon by tracing its evolution over time but also offers the opportunity to examine how the innovation process unfolds in spatial terms.

While the factors that drive the innovation process over time are relatively well understood, much less is known about how these dynamics translate geographically. It is well established that in the early stages of the innovation process, technological opportunities outweigh innovative ones, since commercial perspectives and the prospect of profit are not yet clearly defined. Over time, both opportunities increase, until innovative opportunities surpass technological ones, culminating in a final product ready for the market.

To test how this theoretical process translates spatially, this study reconstructs the mobility of inventors involved in the development of the mRNA vaccine throughout the entire innovation process. In particular, the process is divided into two distinct periods: the first runs from the first in vitro realization of mRNA in 1984 to the discovery of pseudo-uridine in 2005; the second spans from 2005 until the final development of the vaccine in 2020. The first period is characterized by greater technological opportunities than profit opportunities, as although the vaccine was theoretically

possible, several essential components were still missing. The second period, by contrast, witnessed a series of breakthroughs that dramatically increased profit opportunities while technological opportunities gradually decreased.

By examining how the inventors' mobility network evolves and differs over time—and, crucially, between these two periods—this study seeks to clarify how the innovation process co-evolves with its spatial structures. The analysis begins with a descriptive exploration, comparing key network statistics from the empirical data with generative models such as Erdős–Rényi and Barabási–Albert (the former a random model where the probability of a tie between two nodes is fixed and equal, the latter a preferential-attachment model in which the probability depends on the number of existing ties a node already has). This comparison allows us to assess whether, and to what extent, the empirical network aligns with one of these well-known theoretical models over time.

In a second step, Temporal Exponential Random Graph Models (TERGMs)—an extension to longitudinal data of the model used in the first study—are applied to identify the evolving characteristics of the networks, the factors shaping them, and, above all, the differences between the two periods. In particular, the analysis investigates the extent to which the production of patents and knowledge—whether incremental or radical—contributes to the formation of spatial structures, and how the relative importance of these factors varies over time.

The results of this analysis reveal how the geography of the innovation process evolves and clarify where and when the greatest concentration of resources occurs, as well as how innovation hubs connect to the broader ecosystem.

### **1.3.5 Chapter 6—Inventors' journeys**

Once the macro-level spatial and temporal structures generated by inventors' mobility along the innovation process have been clarified, the third study turns to the underlying drivers of inventors' location choices, their motivations and decision-making processes. To this end, a qualitative approach is adopted, centered on the subjective perspectives and lived experiences of the inventors involved.

Specifically, the study analyzes the life stories of eleven inventors who contributed to the implementation of mRNA vaccines against COVID-19 at different stages of the innovation process. Life histories provide a rich and comprehensive perspective on inventors' careers and the motivations that shaped their decisions. By integrating this methodology with an evolutionary perspective, the study aims to build a bridge between the subjective, internal dynamics of inventors and the objective socio-spatial context, an aspect more extensively examined in economic geography than the former. The interviews, transcribed and coded, are analyzed across four logically connected thematic sections. The first section explores the intrinsic, subjective motivations driving inventors' career and location choices, internal drivers characterized by indeterminacy.

The second section incorporates the socio-spatial context as perceived by the inventors, focusing on which external factors they consider most influential or decisive in their decision-making processes. In this perspective, inventors' internal motivations provide the push, while the objective context acts as a filter, shaping the set of viable choices.

The third section examines the interaction between subjective and objective factors, showing how these co-evolve. The socio-spatial context evolves over time based on inventors' achievements, while, in turn, the context may reshape or constrain inventors' future choices.

The fourth and final section investigates the geographical division of the innovation process as perceived by the inventors themselves, and how this perceived geography tends to be reinforced over time by the very co-evolutionary process just described.

This study thus provides an in-depth understanding of the factors that inventors regard as most significant in shaping their location decisions. In doing so, it not only enriches the analysis of the innovation process but also offers valuable insights for the design of policies aimed at attracting and retaining highly skilled workers, which are increasingly crucial for regional development.



# Chapter 2

## 2 Case study: mRNA Vaccine

This chapter aims to illustrate in detail the history of the innovation process behind the mRNA vaccine and its functioning, which constitutes the central case study of this thesis. The choice of this technology as the object of analysis rests on several fundamental factors. First, the innovation process in question spans a very long period—approximately sixty years—during which multiple actors located in different parts of the world have contributed, in a dynamic that evolves from initial collaboration to eventual market competition. Second, this technology is deeply rooted in basic research, which not only enabled its initial theoretical conception but also provided essential tools for the effective realization of the product. Finally, despite its long history and the many indispensable contributions that led to the development of the vaccine, the greatest economic returns have geographically concentrated in those areas where technologically advanced bio-pharmaceutical hubs were already established. To better understand these dynamics, the following sections will first outline the mechanism of action of the vaccine—in order to account for the various components required for its functioning—and then present the main stages of its innovation process. Reconstructing in a detailed and comprehensive way the individual stages of the innovation process that ultimately led to mRNA vaccines is essential for understanding—geographically—the roles of actors, institutions, and places that shaped the production of knowledge and complementary assets, thereby shaping the spatial ecosystem within which inventors move.

### 2.1 mRNA vaccine mechanism of action

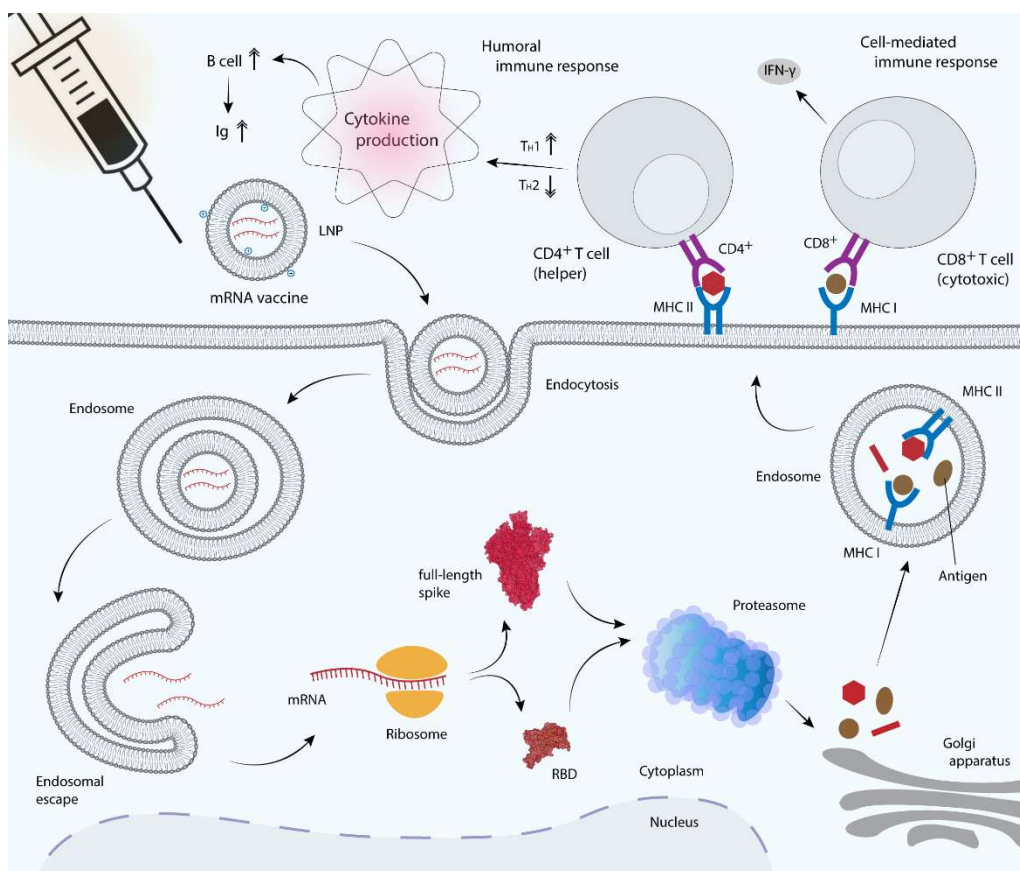
The purpose of mRNA vaccines is identical to that of traditional vaccines: to stimulate an immune response in the body in which they are administered, thereby generating antibodies capable of countering a specific pathogen if it appears. While in traditional vaccines the antigen (i.e., the marker identified as foreign and targeted by antibodies) is produced externally through cell cultures or recombinant proteins and then injected into the body, in the case of mRNA vaccines, the production of antigens occurs directly inside the body (Pardi et al., 2018). This is the innovative feature that distinguishes mRNA vaccines from traditional ones.

mRNA, or messenger ribonucleic acid, is an RNA molecule whose function is to carry the genetic sequence of a protein to a ribosome—located in the cytoplasm of the cell—which then produces the protein. In mRNA vaccines, the genetic sequence delivered to the ribosome is that of a protein from a virus or other pathogen, known as the spike protein, which has been previously identified and encoded. In this way, mRNA enables the internal production of antigens, offering several advantages for manufacturers. On the one hand, it allows for greater scalability and production speed, as well as the exploitation of economies of scale. On the other hand, it makes laboratory production safer, as it involves working with genetic sequences rather than live viruses—thus virtually eliminating the risk of outbreaks in production facilities (Leong et al., 2025; Pardi et al., 2018; Verbeke et al., 2022; Zhang et al., 2023).

Additionally, the body naturally degrades the mRNA within a few days of its administration, making it safe for patients (Pardi et al., 2018; Polack et al., 2020).

Although the rapid degradation of mRNA is beneficial for the patient, this fragility also presents one of the main challenges for researchers, as the mRNA could degrade before completing its function. Furthermore, in order to transmit the genetic sequence of the spike protein, the mRNA must reach the ribosome located inside the cytoplasm of a dendritic cell (an immune cell responsible for producing antigens). This cell is surrounded by a negatively charged protective membrane—just like the mRNA—which creates an electrostatic repulsion that hinders the mRNA from entering the cell. Both challenges have been addressed through the use of lipid nanoparticles (LNP). These nanoparticles serve two purposes: they protect the mRNA during transit, preventing its degradation, and they provide a positive electrostatic charge that facilitates penetration through the cell membrane (Hald Albertsen et al., 2022). These LNP are composed of four types of lipids, one of which is ionizable, meaning it loses its positive charge due to the alkalinity of the bloodstream, thereby reducing its toxicity.

*Figure 2.1 mRNA vaccine mechanism of action*



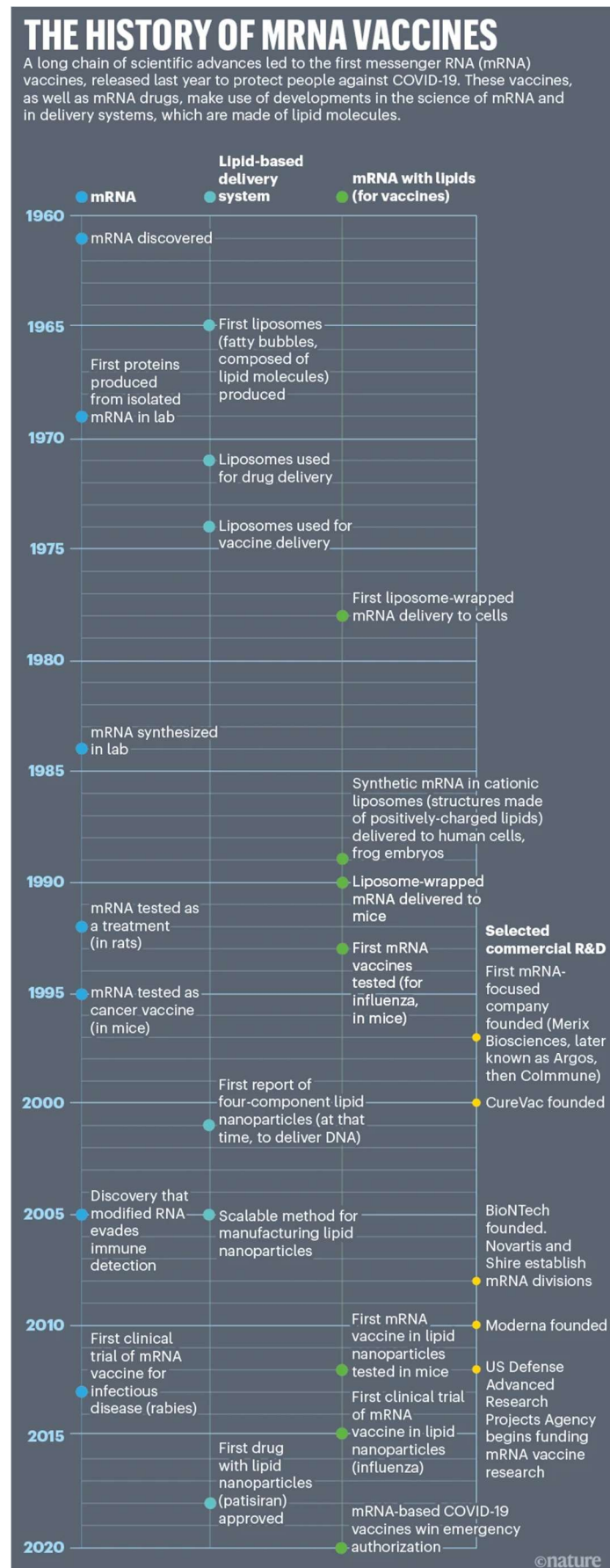
Source: Salleh, M. Z.; Norazmi, M. N.; Deris, Z. Z. (2022) Immunogenicity mechanism of mRNA vaccines and their limitations in promoting adaptive protection against SARS-CoV-2. *10.7717/peerj.13083/fig-4*

To complete the picture, it should also be noted that normally mRNA triggered inflammatory responses in the host organism. For this reason, the mRNA vaccines used to combat the COVID-19 pandemic contain so-called modified mRNA: one of the mRNA's natural molecules, uridine—which was responsible for inflammatory reactions—was replaced with the harmless pseudo-uridine (Karikó et al., 2005; Morais et al., 2021)

This overview makes clear that this new technology is, in fact, the result of multiple contributions, parallel lines of research, and scientific challenges, whose full potential was realized through their convergence and interaction.

The following sections will outline the key stages of this complex innovation process, which unfolded over approximately sixty years and is summarized in Figure 2.2.

Figure 2.2 mRNA vaccines history



## 2.2 The discovery of mRNA and the liposome

The foundations of mRNA vaccine innovation lie in basic research and can be traced back to two key discoveries made in 1961: messenger RNA (mRNA) and the liposome.

To understand their impact, it is essential to recall that, by the late 1950s, genetic biology was still a relatively young science, with many unresolved questions occupying researchers. One of the major puzzles concerned how DNA transmitted information that ultimately led to protein production.

One of the pioneers in this area was Francis Crick who, in 1957, during a lecture held at University College London, formulated the so-called central dogma of molecular biology. In simple terms, this theory held that DNA produces RNA, and RNA produces proteins, with no reverse flow possible. Crick had already hypothesized that a type of RNA played a role in transporting information to ribosomes, but this was still far from understanding the specific function of what would later be known as mRNA (Cobb, 2017).

Around the same time, at the Pasteur Institute in Paris, Arthur Pardee, Jacques Monod, and François Jacob were conducting research on inducible gene expression. During their experiments, they hypothesized the existence of a chemical signal that acted as an immediate intermediary between the gene and the host cell, enabling protein synthesis (Jacob & Monod, 1961). So, they start to focus on the nature of this mysterious "messenger molecule", initially referred to as "X".

These two research trajectories, although different in approach, were addressing the same fundamental problem. Their paths converged on April 15, 1960, during a conference in London attended by both Crick and Jacob. In an informal meeting at King's College, Cambridge, Crick, Jacob, and future Nobel laureate Sydney Brenner discussed the ongoing experiments in Paris. Crick quickly grasped that the mysterious molecule "X" could be the same RNA molecule responsible for transferring genetic information to the ribosome. This was the first time messenger RNA was theorized, and the term "mRNA" would be adopted later that autumn (Losick, 2025).

However, the hypothesis still required experimental validation. Brenner and Jacob sought the help of Matt Meselson at Caltech in Pasadena, where the necessary ultracentrifuges were available. In the summer of 1960, their experiment succeeded, providing the first evidence for the existence of mRNA. Meanwhile, molecular biologist and geneticist James Watson, together with a team from Harvard and the Pasteur Institute, was also conducting experiments aimed to detect what would soon be called mRNA. Given the significant investment of time and resources in the project, Watson was outraged upon learning that Brenner, Jacob, and Meselson had submitted their discovery for publication in *Nature*. He sent them a telegram asking for a short delay in publication, so that his own work would not be rendered obsolete. The scientists agreed, and both their article and Watson's team's paper were published in *Nature* in May 1961. In the same month, Jacob and Monod published their theoretical model of the mRNA structure in the *Journal of Molecular Biology* (Cobb, 2015).

From a mobility perspective, this main discovery already highlight how scientific progress can depend on temporary moves, meetings, and the capability of access to place-specific infrastructures. That same year also had another discovery crucial to the development of modern mRNA vaccines: liposomes.

A liposome is a spherical vesicle surrounded by a lipid bilayer. It is used as a vector to transport drugs and nutrients, and it laid the groundwork for the later development of lipid nanoparticles, which deliver mRNA into cells during vaccination.

Unlike the discovery of mRNA, the identification of liposomes is clearly attributed to Alec Douglas Bangham, a haematologist at the Babraham Institute in Cambridge, UK. In 1961, Bangham and his colleague Horne were testing a newly acquired electron microscope when they observed that dehydrated lipids, upon contact with sufficient water, spontaneously reorganized into spherical bilayer structures. The resemblance to the cell membrane was immediately apparent, and in this way they deduced the molecular composition of biological membranes.

The following year, Bangham demonstrated that lipid vesicles could be used to encapsulate and release substances under certain conditions. The term "liposome," derived from the Greek lipo (fat) and soma (body), was suggested by his friend Gerald Weissmann, professor emeritus at the New York University School of Medicine, during one of their frequent discussions at a local pub.

This was a pivotal discovery that significantly influenced the pharmaceutical industry, and interest in liposomes continues to grow today (Trucillo et al., 2020).

As for mRNA, initial interest was purely scientific. At the time, no one envisioned its use as a therapeutic agent, largely because the tools to synthesize genetic material in the lab were still lacking. For this reason, early mRNA experiments were intended to better understand molecular processes. However, two notable experiments conducted in 1978 demonstrated that mRNA transported via liposomes could be used to induce protein production in target cells.

The first, by Giorgos Dimitriadis, involved injecting mRNA extracted from rabbit blood into mouse cells (Dimitriadis, 1978). The second, conducted by Marc Ostro, Dario Giacomoni, Don Lavelle, William Paxton, and Sheldon Dray, used rabbit mRNA to target human cells (Ostro et al., 1978).

Even so, the idea of a pharmaceutical application remained distant. Serious industrial interest in the therapeutic potential of mRNA would not emerge until 1984.

### **2.3 In vitro mRNA production**

The main reason why mRNA had not yet been considered a useful tool for medicine lies in the fact that the necessary skills to produce mRNA in the laboratory were not yet available, thus, it could not be used and manipulated by scientists.

This limitation was overcome in 1984, when Paul Krieg and Douglas Melton, at Harvard University, succeeded for the first time in synthesizing biologically active mRNA in the laboratory. To do this, they used an RNA polymerase enzyme derived from a virus and a methodology which, although updated over time, is still in use today.

Moreover, after synthesizing the mRNA, the two scientists were able to introduce it into frog eggs and demonstrated that the lab-produced mRNA functioned exactly as natural messenger RNA would. Melton, in a sense, foresaw the potential of mRNA in the medical and pharmaceutical fields, recognizing that it could both promote and inhibit protein production. In 1987, he helped found a company called Oligogen, which has become Gilead Sciences, based in Foster City, California.

At that time, however, the idea of using mRNA for vaccines had not even been imagined. Nonetheless, their work would go on to inspire one of the most important contributions to mRNA vaccine development, the one of Katalin Karikó. Karikó herself has expressed her gratitude to Melton and Krieg, referring that the latter supported her by sending the plasmid necessary for mRNA synthesis. Although this might now be seen as a major breakthrough, at the time RNA was considered highly unstable, and anything related to it was approached with caution and skepticism. This attitude likely explains why Harvard University decided not to patent the invention, instead transferring it to Promega Corporation, a molecular biology company based in Madison, Wisconsin. In exchange, the university received modest royalties and a case of Veuve Clicquot Champagne.

Despite the general skepticism toward mRNA during those years, the work of Melton and Krieg opened the door to further research along this new trajectory. It was in this context that Robert Malone—a controversial figure who later self-identified as the father of mRNA vaccines—began his research. In 1987, while he was a researcher at the Salk Institute for Biological Studies in California, Malone used the techniques recently developed by Melton and Krieg at Harvard to synthesize mRNA. Then he used a new type of positively charged liposome to facilitate the delivery of mRNA into human and frog cells. Realizing the potential of his experiments, he noted in his personal files the possibility of using mRNA as a therapeutic agent.

Despite these early academic successes, Malone did not complete his PhD due to conflicts with his supervisor, Inder Verma. As a result, in 1989 he left academia and began working for Philip Felgner—the inventor of the liposome used in Malone experiments—at the start-up Vical, based in San Diego, California.

During this period, Malone and fellow researchers at Vical, in collaboration with the University of Wisconsin–Madison, demonstrated that lipid-encapsulated mRNA could induce protein production in mice. They also explored the possibility of using mRNA as a vaccine, particularly against HIV, and observed partial protection against infection. However, they did not directly investigate whether a specific immune response was triggered.

As noted, Malone later described himself as the father of the mRNA vaccine, a claim that remains controversial. Not only these early results were still far from a fully developed vaccine (as would later become clear), but Malone was also just one among several researchers at Vical who contributed to that patent.

## **2.4 Early attempts to create a vaccine**

The work conducted by Vical on protein production in mice through mRNA attracted the attention of Merck & Co., one of the world's largest pharmaceutical companies and a major vaccine producer. In 1991, the two companies signed a multimillion-dollar collaboration agreement aimed at developing an influenza vaccine. However, the still prohibitively high costs and the intrinsic instability of mRNA led both companies to abandon the project.

In 1992, researchers at the Scripps Research Institute in La Jolla, California, achieved another exciting scientific result: they used mRNA to replace a missing protein, in an attempt to treat diabetes insipidus in rats. Unfortunately, similar results would not be replicated by other laboratories until more than two decades later.

The following year, in Strasbourg, France, researchers at the company Transgène, led by Pierre Meulien, went beyond the results obtained by their American counterparts: they demonstrated that mRNA delivered via liposomes triggered a specific antiviral immune response in mice.

Transgène patented the invention, but once again, continuing the research was too costly for such a high-risk project. Over time, Transgène also lost its intellectual property rights when its parent company chose not to renew the patent.

At this point, both Merck and Transgène shifted their focus toward DNA-based vaccines. Although indirect, this shift also benefited the development of mRNA vaccines: many of the procedures and techniques developed for DNA vaccine production turned out to be fully transferable to mRNA vaccine manufacturing.

The idea of an mRNA vaccine, however, was not entirely abandoned. In fact, it began to stimulate the interest of researchers working in oncology. Naturally, in this field, the focus was less on prevention and more on therapy.

The basic premise was that, if mRNA could code for proteins produced by cancer cells, then delivering this mRNA into the body could induce the production of tumor-associated proteins and train the immune system to recognize and attack those cells.

Motivated by this idea, several cancer researchers began exploring the potential of mRNA vaccines. In 1995, Robert Conry and his team developed what could be considered an early version of an mRNA vaccine, designed to produce cancer antigens.

However, when Conry, encouraged by his results, approached Ambion—a Texas-based company specializing in RNA laboratory supplies—about the possibility of commercializing the invention, the company responded that there was no realistic prospect of financial return.

A different approach was adopted by immunologist Eli Gilboa and his colleagues at the Duke University Medical Center in Durham, North Carolina. The researchers first extracted immune cells from blood, then introduced mRNA encoding a tumor-specific protein to encourage uptake, and finally reinjected the modified cells into the body, where they could attack the tumor.

This approach initially proved effective in mice, prompting the researchers to begin human trials. The promising results also led Gilboa and his team to found Merix Bioscience—now known as CoImmune—in 1997, widely recognized as the first biotechnology company focused on mRNA.

Gilboa's work appeared promising until a few years ago, when one of the company's most advanced vaccines failed in a large-scale clinical trial.

Nonetheless, Gilboa's contribution went beyond his scientific research and the spin-off company Merix Bioscience: his work also influenced and inspired Ingmar Hoerr and Uğur Şahin, the respective founders of CureVac and BioNTech.

These early attempts in vaccine development already offer clues about the geography that emerges during this phase. While large companies—typically located in major technological hubs—step back, research nevertheless continues at the margins, inevitably shaping the mobility of the inventors involved.

## **2.5 The new Millennium and the turning point for mRNA technology**

The new millennium marked a turning point for mRNA technology. In 2000, Ingmar Hoerr defended his doctoral dissertation at the University of Tübingen in Germany. The focus of his dissertation was the *in vivo* application of mRNA vaccines as a means of stimulating a specific immune response. In his work, Hoerr not only demonstrated the efficacy of this approach in mice, but also showed that, under specific conditions, the degradation of mRNA could be avoided.

Encouraged by these results, Hoerr founded the now well-known company CureVac later that same year in Tübingen, alongside Steve Pascolo and Florian von der Mülbe, with the collaboration of University of Tübingen professors Hans-Georg Rammensee and Günther Jung.

Hoerr later acknowledged that securing funding for the venture was extremely difficult, largely due to the prevailing skepticism surrounding mRNA. CureVac's success was undoubtedly facilitated by its close collaboration with the University of Tübingen, as Hoerr himself recalled in his speech upon being awarded the title of Honorary Senator by the university:

“The University of Tübingen had a very strong influence on me during and after my doctoral studies. Not only did I complete my foundational work on the therapeutic potential of mRNA vaccines, but I was also given the opportunity to grow CureVac from a start-up into the company it is today.”

CureVac's activities began immediately with human trials. Even before formal clinical testing, the company's scientific director and co-founder, Steve Pascolo, self-administered the mRNA vaccine to test its effects, and still bears the scars from the biopsies conducted for analysis. Hoerr and his collaborators have the distinction of being the first in the world to administer an mRNA vaccine, which in 2003 was used for the treatment of skin cancer.



At the same time, two other pairs of scientists were also working on mRNA technology: Katalin Karikó and Drew Weissman in the United States, and Uğur Şahin and Özlem Türeci in Germany. Karikó's name is now closely associated with the mRNA COVID-19 vaccine, as she received the Nobel Prize in Medicine together with her colleague Weissman for their groundbreaking work in the field. However, this recognition came only after decades of persistent effort. The Hungarian-born biochemist moved to the United States to pursue her research on the pharmaceutical use of mRNA, but she was also met with skepticism. She faced numerous grant rejections and, in 1995, was given an ultimatum: leave the University of Pennsylvania or accept a demotion. Karikó chose the latter and continued working undeterred. In 1997, at the same university, she met immunologist Drew Weissman, and they began a fruitful collaboration.

Initially, their goal was to develop an mRNA vaccine against HIV, but in early experiments, they observed that mRNA triggered strong inflammatory reactions in mice. After years of investigation, they identified the reason of these reactions: a nucleotide in the mRNA called uridine. The breakthrough came in 2005 when Karikó and Weissman demonstrated that by chemically modifying the uridine bonds—effectively replacing it with a similar molecule, pseudo-uridine—the body no longer recognized the mRNA as a threat, and the inflammatory response was eliminated.

Although we now understand the revolutionary nature of this discovery, at the time very few appreciated its potential.

Karikó and Weissman also founded a start-up called RNRx, which received approximately \$900,000 in U.S. government funding through grants aimed at small and medium-sized enterprises. Nevertheless, RNRx had a relatively short lifespan and ceased operations in 2013, coinciding with Karikó's promotion as Vice President at BioNTech.

BioNTech RNA Pharmaceuticals was founded in 2008 in Mainz, Germany, by husband-and-wife team Uğur Şahin and Özlem Türeci, after years of research into the pharmaceutical applications of mRNA. The company initially received funding from the German Federal Ministry of Research through the GO-Bio biotechnology development program and soon attracted €150,000 in strategic investment capital. Among its notable co-founders are Andreas and Thomas Strüngmann, who had previously founded the pharmaceutical company Hexal in 1986 and sold it in 2005 for €6.7 billion. From the outset, the company's goal, once again, was the development of mRNA-based cancer therapies.

## **2.6 Another piece of the puzzle: lipid nanoparticles**

As previously discussed, mRNA requires a delivery vehicle, a platform that can both protect it and ensure its successful entry into the cell membrane and subsequently into the cytoplasm.

Until relatively recent years, the standard solution was the use of liposomes—an invention dating back to the 1960s—employed with various modifications over time.

What ultimately made mRNA vaccines a scalable product for pharmaceutical companies was the result of the insight and work of Pieter Cullis, a biochemist at the University of British Columbia in Vancouver, Canada, along with his collaborators.

As early as the 1990s, Cullis had been working on the development of lipid nanoparticles capable of delivering strands of nucleic acids as part of gene-silencing therapies.

During the 2000s, he founded several companies—including Arbutus Biopharma and Acuitas Therapeutics, both based in Vancouver—redirecting his research focus toward the use of lipid nanoparticles for delivering mRNA-based drugs.

In 2012, Acuitas began collaborating with several mRNA-focused companies, including Drew Weissman's team at the University of Pennsylvania, to test various combinations of lipid

nanoparticles and mRNA. One of these combinations is the same formulation now used in the CureVac and Pfizer–BioNTech vaccines.

These nanoparticles are composed of four different lipids, one of which is ionizable, meaning it loses its positive charge and becomes neutral. This feature helps prevent toxic effects in the body that were sometimes observed when using positively charged liposomes.

In addition to this critical advantage, the lipid nanoparticles developed by the Canadian laboratories offer greater protection for the mRNA, thus addressing one of the most common criticisms of this technology: the perceived instability and rapid degradation of nucleic acid strands.

## **2.7 Industrial acceleration process**

The discovery of lipid nanoparticles by Pieter Cullis and his collaborators, together with the modified mRNA developed by Karikó and Weissman, transformed the once hypothetical concept of an mRNA vaccine into a truly available technology. In fact, around the same time, several pharmaceutical companies established dedicated research units focused on this emerging field.

Among them, the Swiss pharmaceutical giant Novartis launched an mRNA vaccine research hub in 2008, led by Andy Geall. By 2012, Geall's team had successfully vaccinated rats against a respiratory virus. In March 2013, following the identification of three human cases of avian influenza in China, Geall was asked whether it was possible to rapidly develop a vaccine to prevent a potential outbreak. He answered affirmatively, stating that all he needed was just the genetic sequence.

This presented the perfect opportunity to demonstrate one of the key advantages of mRNA technology: speed. Remarkably, Geall's team progressed from zero to mouse trials in less than a month, whereas traditional approaches would have required over a year (Dolgin, 2021).

However, the timing was not yet mature. The capacity to produce mRNA at clinical scale was still limited, and in 2015 Novartis sold off this vaccine division.

Nonetheless, attention toward mRNA vaccines had clearly intensified following the introduction of lipid nanoparticle delivery systems. In fact, starting in 2012, the U.S. Defense Advanced Research Projects Agency (DARPA) began funding multiple companies engaged in mRNA research, including major pharmaceutical firms such as Novartis, AstraZeneca, Sanofi Pasteur, and Pfizer. Most of these large corporations eventually abandoned their efforts to develop mRNA vaccines.

Among the DARPA-funded recipients that remained committed to mRNA technology were the already-established CureVac (Tübingen) and the newly founded start-up Moderna (Cambridge, Massachusetts).

Moderna was born from an idea by Derrick Rossi, a biologist at Stanford University who, since 2005, had been fascinated by the work of Karikó and Weissman, though for different reasons. Rossi envisioned using modified mRNA to generate embryonic stem cells, which have the ability to transform into any cell type. Given the ethical controversies surrounding the use of embryos for stem cell research, Rossi aimed to sidestep this issue by using mRNA to reprogram somatic cells into pluripotent stem cells, thereby achieving the benefits without the ethical concerns.

In 2009, while serving as a professor at Harvard University, Rossi met immunologist Timothy Springer, also a professor at Harvard, who was impressed by the potential of Rossi's work. Springer introduced Rossi to Robert Langer, a prominent professor of biomedical engineering at the Massachusetts Institute of Technology and a prolific inventor. During their meeting, Langer was astonished by the implications of Rossi's findings and suggested that modified mRNA could be used for far more than stem cells like, for example, for producing drugs and vaccines.

Langer decided to invest in the venture that Rossi and Springer were planning, and in 2010, they founded Moderna, a name derived from the phrase "modified RNA." In addition to financial backing

from Langer and Springer, the company secured early support from the venture capital firm Flagship Ventures, led by Noubar Afeyan, who would become the company's majority shareholder. In 2011, Afeyan appointed Stéphane Bancel as CEO, trusting in his proven managerial experience in the pharmaceutical sector.

Combining Rossi's innovative ideas with a professionally managed business strategy, the fledgling company quickly attracted significant capital. In addition to receiving \$25 million in DARPA funding, by 2015 Moderna had raised over \$1 billion, built on the promise of using mRNA as a pharmacological platform to treat rare diseases caused by protein production deficiencies.

However, the project proved overly ambitious. As the company's early vision began to falter, Bancel redirected Moderna's focus toward vaccine development. This strategic pivot disappointed several investors, who did not see vaccine platforms as financially attractive, and for years Moderna failed to achieve notable success. In fact, at the start of the COVID-19 pandemic, only one of the company's nine proposed vaccines had reached large-scale trials, and by 2019 Moderna had accumulated losses totaling \$1.5 billion since its founding.

On the other side of the Atlantic, between 2014 and 2019, BioNTech focused heavily on research, building a solid portfolio of patents and forming numerous partnerships, including with Pfizer and Genentech, as well as public scientific institutions such as the University of Warsaw and the University of Mainz, with which it maintains close collaboration.

Meanwhile, still in Germany, CureVac also demonstrated strong engagement beyond laboratory research. In 2013, the company organized the first international conference on mRNA health in collaboration with the University of Tübingen. In 2019, CureVac received a \$34 million grant from the Coalition for Epidemic Preparedness Innovations (CEPI)—a global public-private partnership—aimed at supporting the development of mRNA vaccine platforms.

This acceleration process—set in motion by the breakthrough discoveries that enabled the concrete development of the vaccine—reveals a strong reallocation of economic and human resources toward biotechnology hubs that had initially played a secondary and uncertain role, but which in this final phase became the primary centers of attraction for inventors seeking to continue their research in this field.

## **2.8 The race for a vaccine against COVID-19 pandemic**

As is well known, it was the COVID-19 pandemic that provided this technology the opportunity to demonstrate its full potential.

In January 2020, when the SARS-CoV-2 virus was still largely confined to the region of Wuhan, China, scientists had already begun working on vaccine development. In particular, three companies previously mentioned—Moderna, BioNTech, and CureVac—initiated efforts to develop potential vaccine candidates.

Of the three, only the vaccines developed by Moderna and BioNTech would ultimately be approved and brought to market. CureVac, on the other hand, withdrew its candidate—CVnCoV—in October 2021, as it demonstrated only 47% efficacy against the virus, a rate considered too low, especially when compared to the Moderna and BioNTech candidates.

As previously noted, an mRNA vaccine requires the genetic sequence of a specific viral protein against which protection is sought. On January 10, 2020, the complete genome of the virus—soon to become globally infamous—was published online. This prompted scientists to begin identifying its proteins. Among them were biologist Jason McLellan at the University of Texas at Austin, Texas, working in collaboration with Andrew Ward at the Scripps Research Institute in La Jolla, California, and virologist Barney Graham at the National Institute of Allergy and Infectious Diseases' (NIAID) Vaccine Research Center in Bethesda, Maryland.

On January 13, 2020, the researchers realized that they could genetically modify the virus's spike protein to make it harmless. That same day, Graham contacted Moderna—the company already collaborating with NIAID—and the Cambridge-based start-up began developing a SARS-CoV-2 vaccine even before receiving the spike protein (Scudellari, 2020).

Once the spike protein sequence was obtained, Moderna quickly moved into production. On February 7, 2020, the company had already manufactured its first batch of the vaccine, named mRNA-1273. The project was supported by the U.S. Biomedical Advanced Research and Development Authority (BARDA), which invested \$955 million.

On March 16, 2020, following FDA approval of clinical trials for Moderna's candidate, human testing began with funding from the U.S. National Institutes of Health. These trials concluded on November 30, 2020, with highly positive results: the vaccine showed a 94.1% efficacy against SARS-CoV-2 and 100% efficacy in preventing severe infections.

On December 18, 2020, the vaccine—marketed under the name Spikevax—was approved for use in the United States, and on January 6, 2021, in the European Union.

BioNTech's progress was equally swift, showcasing one of the main advantages of mRNA technology: speed. The company was already collaborating with Pfizer and took the opportunity to strengthen this partnership. In addition, it established an alliance with Fosun Pharma in Shanghai to commercialize the vaccine in the Chinese market.

In June 2020, BioNTech received €100 million in funding from the European Investment Bank, followed in September by an additional €375 million from the German Federal Ministry of Education and Research.

In November 2020, BioNTech announced that clinical trials of its vaccine candidate showed 95% efficacy against SARS-CoV-2. The following month, the Pfizer–BioNTech vaccine—designated BNT162b2—was granted emergency use authorization and entered commercial distribution. mRNA vaccines had thus become a global reality, fulfilling the efforts of all the researchers who had been working toward their development for decades.

# Chapter 3

## 3 Mobility and innovation: A critical review

### 3.1 Introduction

The positive relationship between human mobility and innovation is well-established, through its recognized role in driving human progress and the diffusion of knowledge since the Neolithic era (Manning & Trimmer, 2020; Skoglund et al., 2012). Recently, thanks to greater data availability, migratory waves—such as the Huguenots in Prussia or Jews and Soviets in the United States—have underscored the significance of mobility in the diffusion and production of innovation (De Rassenfosse & Pellegrino, 2024; Hornung, 2014; Moser et al., 2014).

It is quite intuitive that the topic of inventors' mobility is inherently interdisciplinary, intersecting fields such as economic geography, migration economics, economics of science, labor economics, as well as classical and modern historiography (Lissoni, 2018). This is because this form of mobility simultaneously implicates labour markets, migration, individual biographies, and scientific and technological advancement.

Although there is consensus on the importance of mobility for innovation, the diversity of approaches has led to contrasting positions regarding the theoretical motivations behind mobility's impact on innovation, as well as the effects on various geographic entities. Moreover, the discussion on mobility has often been confined to the phenomenon of migration alone. While migration certainly constitutes a significant aspect of mobility, it isn't exhaustive, representing only a specific case of mobility that often involves the spatial movement of entire communities, and so different effects compared to individual mobility (Lissoni, 2018).

In this thesis, mobility refers to the process through which inventors change affiliations—and thus locations—over the course of their careers, rather than to a single migratory event. Empirically and methodologically, mobility will be captured both through changes in affiliation observed across an inventor's consecutive patents (while acknowledging the limitations of this approach) and through more targeted sources, including evidence on inventors' careers and life histories.

The objective of this review is not to provide a comprehensive reconstruction of the literature on inventors' mobility but rather to offer a critical approach to the topic. It illustrates the most significant findings, highlights the contrasting viewpoints, identifies gaps and shortcomings in the existing narrative, and suggests ways these might be addressed.

The approach to gathering literature sources began with keyword searches in two major databases (Scopus and Google Scholar). The keywords used were “Inventors' mobility” and “Migration and innovation”. The identified articles were then analyzed to determine the major thematic areas, with additional sources collected through citations.

It is important to emphasize that this thesis seeks to show that the relationship between mobility and innovation is not fixed; rather, the role of mobility evolves across the innovation process, contributing—together with it—to a co-evolutionary dynamic that shapes the spatiality of innovation. Across disciplines, research on inventors' mobility and innovation has converged around three recurring debates. First, what mobility does for innovation: it may diffuse tacit knowledge and foster recombination, but it may also entail displacement or simply reflect the relocation of already productive inventors. Second, where benefits and costs accrue: findings range from regional

upgrading and diversification to the reinforcement of spatial hierarchies and core–periphery patterns. Third, why mobility occurs: explanations combine individual incentives and constraints, organisational strategies, networks, and place-based attributes. This chapter follows this logic to build a coherent thread through a fragmented literature and to prepare the process-based interpretation developed in the empirical chapters.

The general topic will therefore be broken down into these major thematic areas, allowing for a focused analysis of the most important findings. This breakdown is reflected in the structure of the review. Specifically, the first section will explore the reasons why inventors' mobility is particularly important for innovation, distinguishing between the diffusion of knowledge across space and the generation of diversity. The second section will examine the spatial effects of this mobility, considering both origin and destination regions. The third section will focus on the drivers that influence mobility itself. The last section summarizes all the findings exposed previously and suggests new research directions and approaches used in this thesis in order to clarify the most controversial aspects of this phenomenon and contribute to its understanding.

### **3.2 Mechanisms of Impact: How Mobility Drives Innovation**

One of the cornerstones of the geography of innovation, around which the entire literature revolves, is that innovative activity is not uniformly distributed across space but tends to concentrate in specific regions (Asheim & Gertler, 2006). This is largely due to the tacit and “sticky” nature of knowledge, which limits its spatial diffusion (Boschma & Lambooy, 1999; Jaffe et al., 1993). Therefore, it is crucial to investigate the primary channels of knowledge diffusion. In this context, the inventors' mobility becomes a central theme in economic geography literature, whereas previously, it was largely confined to historiography (Migueluez & Noumedem Temgoua, 2020). Particularly, the pioneering work of Breschi & Lissoni (2009) identifies human capital mobility as the main channel for knowledge diffusion and low mobility as the reason for the high spatial concentration of innovative activity. Following this work, the literature increasingly focused on the role of mobility in knowledge diffusion. When discussing flows, there is inevitably at least one source and one destination. The origin-destination topic will be comprehensively revisited in the next paragraph; now, it is essential to define the theoretical mechanisms linking mobility and knowledge diffusion. Thus, let's ask: Does mobility actually facilitate knowledge diffusion? If so, what kind of knowledge is diffused, and how does this process occur?

The first question might seem leading, but it is legitimate when trying to detect knowledge transfer by the effects of migration on local scientific production, where results are conflicting: while incoming human capital flows disproportionately increase patent production (Hunt & Gauthier-Loiselle, 2010), a more careful analysis shows that this is actually the result of a “displacement effect” (Borjas & Doran, 2015) where native inventors, rather than benefiting from the knowledge brought in by migrant inventors, tend to shift towards different areas of expertise. Furthermore, skilled workers tend to relocate to areas with already high concentrations of human capital (Kerr et al., 2016), raising the question of reverse causality—whether migrants are exploiting existing knowledge rather than contributing their own (Hilaire-Perez & Verna, 2006). While the extent of knowledge diffusion through migration remains ambiguous when measured solely by patent output, the results become more conclusive when patent citations are considered as a proxy for knowledge transfer, offering a clearer indication of the impact. Ganguli (2015) uses a difference-in-differences approach to estimate the causal impact of the migration of Russian scientists to the United States after the collapse of the Soviet Union on knowledge flows. The results show a disproportionate increase in citations of Soviet-

era articles following the scientists' relocation to the United States, demonstrating how geographic mobility serves as a crucial channel for the transfer of ideas.

Regarding what is actually being diffused, knowledge is the main focus, as it is considered the primary fuel for innovation. However, it is well-known that innovation itself is a complex process that requires the coexistence of various factors. In this context, the classic distinction between technical/scientific knowledge and commercial/entrepreneurial information (Cowan, 2000) is useful. Regarding the latter, there is great evidence of the role played by migrant inventors in providing relevant information to firms in destination countries for mergers and acquisitions operations undertaken in their origin countries (Useche et al., 2020), their ability to foster collaborative networks between companies (Tóth & Lengyel, 2021), their impact on local entrepreneurship (Balsmeier et al., 2020), and in promoting FDIs (Foley & Kerr, 2013). Despite this, many questions remain regarding the transfers made by migrant inventors, particularly about what type of knowledge they are able to diffuse and how it differs from native knowledge. But most importantly, does the specific type of knowledge possessed by inventors influence their propensity or patterns of mobility? So far, there is no answer to this question.

About how migrant inventors contribute to the diffusion of knowledge and/or information, two approaches can be distinguished: the transfer-based approach and the community-centered approach (Lissoni, 2018). The first considers the migrant as the unit of analysis, possessing specific knowledge and skills that can be transferred to the destination country if there are the right conditions, such as a favourable and tolerant climate towards foreigners (Scoville, 1952). The second approach, in contrast to the first, focuses on the role of the community and ethnic ties in diffusion, emphasizing the importance of minority communities in facing social discrimination or legal restrictions that may arise in the destination region. In this context, the migrant community tends to specialize in sectors left open by natives, facilitating the dissemination of information primarily among the migrants themselves (Lissoni, 2018). The importance of these ethnic ties is demonstrated not only by the tendency of co-ethnic inventors to cite each other, especially if they belong to a minority (Breschi et al., 2017), but also to collaborate more frequently among themselves (Freeman & Huang, 2015), even though this tendency towards homophily—where migrant inventors prefer to collaborate with other migrant inventors—seems to have a negative impact on the quality of innovation (Almeida et al., 2015). This brings to another relevant theme related to the inventors' mobility, which has recently gained prominence: diversity.

The emergence of this new strand can be traced back to the literature on unrelated diversification. Without delving too deeply into detail, the idea originates from the observation that innovative activity is highly path-dependent (Dosi, 1982), meaning that regions tend to diversify more in activities related to their specialization (Hidalgo et al., 2018; Pinheiro et al., 2018). This path dependence can lead to technological lock-in, and the only hope of avoiding this is by diversifying into unrelated activities (Saviotti & Frenken, 2008). However, the factors that enable this unrelated diversification are still under investigation (Boschma, 2017). What is certain is that regions need different and non-redundant knowledge, which can be obtained through various gatekeepers—actors who serve as intermediaries in the innovation network, facilitate novelty generation by external resource transfers—(Breschi & Lenzi, 2015; Morrison et al., 2013), and inventors' mobility can be one of them. Hence, the hypothesis is that migrant inventors not only diffuse their knowledge through their mobility but that this knowledge is also inherently different from native knowledge, thereby enabling a technological shift. This hypothesis is supported by studies on mass migration to the United States between 1870 and 1940, where the inventive activity of migrants not only brought regional benefits but also shaped the technological evolution of the United States through the introduction of new technologies (Diodato et al., 2022). But what mechanisms make this possible? These can be

summarized into two main mechanisms: knowledge recombination and knowledge reuse (Choudhury & Kim, 2019).

Knowledge recombination occurs as a result of collaboration between inventors of different ethnicities or backgrounds. These "non-ethnic" teams (as the members do not belong to a single ethnicity) can combine their different knowledge to create something that otherwise would not have been possible, thereby increasing the value of their patents (Ferrucci & Lissoni, 2019). However, this phenomenon contrasts with the homophily tendency previously observed; thus, knowledge recombination cannot be taken for granted. Homophily is closely linked to the second mechanism, knowledge reuse, which involves continuing to work with the knowledge that migrants themselves have imported. This occurs in ethnic teams (whose members belong to the same ethnicity or region) formed in regions different from their origin. While both mechanisms can contribute to unrelated diversification, knowledge reuse has a more significant impact on it (Migueluez & Morrison, 2023). This is theoretically understandable, as the knowledge obtained through recombination is also derived from native knowledge, which is likely correlated with regional specialization, whereas reuse is more likely to result in non-correlated knowledge. This view is consistent with the historical work of Koch et al. (2023), which shows that the immigration of individuals specialized in a particular area leads to the emergence of that specialization in the region, while emigration reduces the likelihood of maintaining that specialization.

However, the literature is not unanimous on the role of inventors' mobility in unrelated diversification and thus in technological change. Caviggioli et al., (2020) have even demonstrated that migration and technological diversification are negatively correlated. This can be explained by the tendency of companies to attract workers already specialized in their activities, leaving little room for diversity. To resolve this incompatibility, the same reflection seen previously applies: identifying the different types of knowledge and how they affect the mobility of inventors. Indeed, none of these studies consider the innovation process within which all this takes place, and that this process actually requires both diversity and specialization. Also, the apparent tension between diversity and specialization in regional innovation can be explained by considering the different factors that drive inventors' mobility. When inventors move to regions that are leaders in specific fields to enhance their human capital, the result could be greater specialization. Conversely, if mobility is driven by other factors, such as seeking a less discriminatory environment, this could foster greater diversity. Therefore, understanding the underlying drivers of mobility is crucial to understanding the relationship with regional innovation.

### **3.3 Regional effects of inventors' mobility**

As mentioned in the previous section, inventors' mobility involves a flow that inherently requires both a source and a destination, geographically identified as origin and destination region. This section aims to examine the distinct effects of mobility on these regions, addressing the impacts on the destination region and the origin region separately due to their differing characteristics.

#### **3.3.1 Destination Regions**

The effects of inventors' mobility at the regional level have predominantly been examined with a focus on destination regions, where these effects are more pronounced. Initially, the literature concentrated on the impact of inventors' inflows on destination regions. Bahar et al., (2020) find that regions can gain a patenting advantage ranging from 25% to 60% in specific technologies when the number of foreign inventors specializing in these technologies doubles, thereby confirming the role of migrant inventors in the importation of knowledge. Additionally, Capello & Lenzi (2019) highlight



that the inflow of inventors can lead to structural changes in innovation models, facilitating the shift towards more complex models.

However, the impact of inventors' mobility is not uniform and appears to depend on the pre-existing innovation model in the destination region, particularly favoring models that can either strengthen existing knowledge networks or create new ones.

The ongoing debate on the potential displacement effect on native patenting remains unresolved. Borjas & Doran (2015) suggest that this displacement effect may vary based on different immigration regulations. In this regard, Kerr & Lincoln (2010) examine the impact of migration driven by H-1B visas (temporary U.S. visas for highly specialized personnel), finding that an increase in these visas results in a higher number of patents assigned to Indian and Chinese inventors, with limited displacement effects on native inventors. This finding indicates that regulated migration can lead to a direct contribution from migrant inventors.

Interestingly, inventors do not need to travel long distances to benefit regions with their positive effects. Even intraregional mobility is associated with improved innovative activity (Miguélez & Moreno, 2013). This improvement may stem from both an enhancement in human capital and a better match between skills and opportunities, which can increase inventors' productivity by 30% (Pellegrino et al., 2023). It is also important to note that geographic mobility may, but not always, coincide with job mobility, and that could influence the impact. For instance, corporate mobile inventors tend to be more productive than those who do not change jobs, while higher initial productivity reduces the likelihood of changing employers (Hoisl, 2007).

This relationship is also geographically evident: Cappelli et al. (2019) analyze the impact of inventors' inflows and outflows on total factor productivity growth in Italian regions. Their results indicate that inflows have a positive impact on the destination region, although the positive effects may take longer to materialize when the inventor also changes employers. Conversely, the negative effect of outflows is even more pronounced when the inventor changes employers, underscoring the potential negative impact of brain drain. In contrast, Prato (2022) proposes a model in which migrants not only become more productive after relocating (due to a better spatial allocation of talent) but also maintain relationships with inventors in their origin countries, generating knowledge spillovers that benefit both the destination and origin countries—a win-win scenario.

### **3.3.2 Origin Regions**

The aforementioned observations exemplify the ambiguity within the literature regarding the effects of inventors' mobility on origin countries. Initially, the phenomenon was predominantly seen with concern, especially as a loss of human capital with potentially disastrous effects for developing countries (Bhagwati & Hamada, 1974). However, recent studies have identified various channels and mechanisms through which origin countries may also benefit from mobility, possibly offsetting the initial loss of human capital. Although the primary concern remains the loss of human capital in already fragile contexts, the brain drain phenomenon is not limited to developing countries but affects various regions to differing degrees. An illustrative case is Poland, where between 2004 and 2012, emigrant inventors produced a greater number of patents abroad than those filed in Poland during the same period (Wachowska, 2018), highlighting how brain drain can pose a significant challenge to growth. Therefore, identifying the mechanisms through which this loss can be mitigated has great importance for innovation policy.

One mechanism can be defined as the "incentive effect", which arises from the prospect of achieving higher economic returns by first investing in one's education and then emigrating to countries that can better compensate for one's talent. When migration opportunities are not perfect, the origin

country can still experience an increase in human capital (Faini, 2003). Empirically, Beine et al. (2011), using a dataset of 147 countries from 1975 to 2000, found evidence that the prospect of emigration can indeed incentivize investment in education, though under specific conditions: the wage differential between the destination and origin countries must be substantial, and the emigration rate must not become excessively high; otherwise, the effect reverses.

The most studied compensation mechanism, however, is the so-called "knowledge remittances," the technical-scientific equivalent of the monetary remittances that migrants send to their origin countries. These remittances can take various forms that are not mutually exclusive and can be broadly categorized into two main types: knowledge transfer through social contacts and return or circular migration.

The first type intuitively involves the transfer of foreign knowledge by migrants to their origin countries by maintaining contact with inventors there. Agrawal et al. (2011) call this phenomenon the "brain bank" effect, in contrast to the "brain drain," and they attempt to analyze it by focusing on the case study of India. They find that, on average, the brain drain effect prevails, although the brain bank effect is significant for more substantial innovations. Using a citation-based approach to trace knowledge flows, Breschi et al. (2017) explore the "brain gain" effect, which occurs when foreign-born inventors operating in the United States are disproportionately cited by inventors in their origin countries. Their findings indicate that this effect is significant only in specific countries (China, Russia, South Korea), underscoring the critical role of origin countries' characteristics, particularly their absorptive capacity. Moreover, the same study emphasizes the importance of multinational corporations in facilitating these knowledge transfers. Similar results are obtained by Miguelez & Noumedem Temgoua (2020) who find a positive impact only in developing countries, with multinational corporations playing a key role in promoting these transfers. It appears that such knowledge transfers occur spatially but within the same multinational companies, where migrant inventors act as bridges between the headquarters and subsidiaries in their origin countries, so the transferred knowledge can be limited to that within the multinational itself (Marino et al., 2020).

The second category of knowledge remittances considers the possibility that migrants may not permanently settle in the destination country but might return to their origin countries. Saxenian (2005) argues that the increasing mobility of inventors, particularly engineers and entrepreneurs born in China and India but operating in Silicon Valley, has transformed brain drain into "brain circulation". These migrants, through their mobility, act as bridges to their origin countries, facilitating the transfer not only of technical knowledge but also of organizational and entrepreneurial models, thereby transforming the innovation ecosystem in their countries. However, this study focuses on China and India; entirely different results are obtained when considering countries like Mexico, where return migration has ambiguous effects and then dissipate within five years (Diodato et al., 2023). To achieve positive results, it is necessary to reintroduce a player previously identified as crucial: the multinational corporation. When considering managers of multinational corporations who are return migrants, it is observed that their team's members not only file a disproportionately high number of patents but also tend to cite the patents of the headquarters much more than others (Choudhury, 2016). The mechanism of knowledge remittances fundamentally relies on the migrants' ability to diffuse knowledge, but as previously discussed, they can also diffuse other information useful for business decisions. Here, too, the role of multinational corporations is crucial, as they can obtain information from migrant inventors that can reduce costs and encourage investments in the inventors' origin countries (Foley & Kerr, 2013).

The emerging research on the role of migrant inventors in generating diversity has also contributed to the study of mechanisms that could compensate the brain drain, asserting that migration leads to unrelated diversification even in the origin countries (Di Iasio & Miguelez, 2022), potentially serving

as a channel for developing countries to catch up with advanced economies. Despite all these efforts, it cannot be definitively stated that inventors' mobility leads to a win-win situation for both origin and destination regions, especially considering that the highest levels of brain drain are observed in Africa and the Caribbean (Miguélez & Fink, 2023), which do not seem to possess the necessary characteristics to benefit from the brain gain effect. The most significant finding is certainly the understanding of the role of multinational corporations in facilitating this effect. It raises the question of how institutions such as multinational corporations (but not exclusively) contribute to shaping this geography. Furthermore, the literature has predominantly adopted a perspective where countries are the geographic unit of analysis, with little consideration of other forms of mobility and their significance within the innovation process.

### **3.4 Factors influencing inventors' mobility**

Having established the importance and effects of inventors' mobility on the innovative capacity of the regions involved, the question arises as to what factors determine and drive mobility. Understanding the drivers of mobility is crucial from a regional perspective, as it would enable the implementation of precise policies aimed at attracting talent and increasing productivity and, as mentioned previously, it could also shed light on the diversification-specialization debates. So, what factors motivate inventors to relocate? First, it has been observed that mobility enhances the productivity of inventors themselves (Van Der Wouden & Rigby, 2021), which could already serve as an incentive, especially when higher productivity translates into higher wages. This increase in productivity is evidently also reflected in the locational choices inventors make, as they tend to be more strongly attracted to places that already exhibit a high concentration of human capital, thereby enabling them to benefit from agglomeration economies, economic externalities, and knowledge spillovers (Kerr et al., 2016)

From a microeconomic point of view, the decision to move will be made when the benefits outweigh the costs incurred for the relocation. It is therefore not surprising that key factors in mobility include significant wage differentials between countries, greater employment opportunities, or the chance to broaden one's skills (Kerr et al., 2016). All these have the aim of maximizing benefits. On the other hand, it is also necessary to minimize costs, and that influences the choice of destination, with a preference for regions that have a geographical, cultural, technological, and institutional proximity (Gorin, 2016). The opportunities seeking in a different region can lead to higher costs, especially in the presence of information asymmetries, and this is where another crucial factor comes into play: the social network. Dorner et al. (2016), leveraging the natural experiment of German reunification after the collapse of the Soviet Union, find that stronger social ties between regions in West and East Germany lead to greater migration of inventors, due to the reduction of information asymmetries and associated costs. Although these social networks are often co-ethnic and provide support to the migrant inventor, the ethnic diversity of the network can also play a crucial role in attracting migrants to a region (Campo et al., 2022), likely due to the inventors' desire to benefits of the externalities generated by diversity.

The discussion thus far has focused exclusively on the factors influencing inventors' choices, but there are also demand-side factors that are fundamentally responsible for creating the opportunities inventors seek. First, companies tend to hire based on a learning-by-hiring logic, meaning they are inclined to recruit inventors with strong skills, particularly those skills that are complementary to the competencies of other inventors and/or regarding areas where the company is not dominant (Palomeras & Melero, 2010). It is therefore no coincidence that the likelihood of an inventor moving, including geographically, is linked to the diversification of their skills and their productivity (Haller,

2022). This trend is also observable in the transfer of inventors between universities and the private sector, with such mobility strongly connected to the patenting productivity of inventors, while being indifferent to their scientific output (Crespi et al., 2007), indicating that opportunities for inventors arise when they possess tacit knowledge that can be transferred.

Conventional economic accounts often understate the role of “soft” or intangible considerations—difficult to observe and measure, yet potentially decisive in the location decisions of highly skilled workers such as inventors. This perspective became especially salient after Richard Florida’s (2002) formulation of the “creative class,” which argued that immaterial attributes can operate as major magnets for creative workers, summarized in his 3T framework (Technology, Talent, and Tolerance). Building on this approach, a substantial body of research has relied on different empirical proxies to document that intangible dimensions—most notably quality of life and social tolerance—are also strongly associated with the attraction of high-skilled workers (Acs & Megyesi, 2009; Florida, 2014; Rao & Dai, 2017). At the same time, this literature is subject to important caveats, including competing interpretations that emphasize reverse causality (Albouy & Stuart, 2020).

The factors discussed so far primarily focus on objective, economic or non-economic influences on inventors’ mobility. While this is an excellent starting point, continuing solely along this path eventually leads to a dead end, as the decision-making process is undoubtedly a subjective matter. Behavioural studies are often confined to inter-firm mobility and typically reference the productivity of inventors and their subsequent risk propensity (Di Lorenzo & Almeida, 2012). Adopting a qualitative approach could shed light on hidden dynamics within inventors’ decision-making processes, thereby contributing new insights that could generate novel research paths.

### **3.5 Discussion and research directions**

Inventors’ mobility has emerged as a central topic in academic discourse, especially in relation to its impact on innovation and regional economies. This review has sought to highlight various aspects of this phenomenon, emphasizing both its potential benefits and the challenges it presents, thus revealing a complex landscape filled with opportunities and obstacles.

While it is undeniable that inventors’ mobility plays a crucial role in facilitating the spatial diffusion of knowledge and enhancing innovative output, the literature remains ambiguous in explaining the mechanisms that enable these outcomes. A primary point of contention concerns the actual contribution of migrants’ inventors to the innovative production in destination regions. While an increase in patenting activity is often observed, some argue that this may result from the displacement of native innovation by migrants, who primarily choose their destination to exploit existing knowledge. These conflicting positions become even more evident when considering the kind of impact on destination regions, where mobility seems to simultaneously drive both diversification and specialization. This duality is shaped by the interplay between diversity and homophily, presenting a paradox in the dynamics of innovation. One way to account for these apparently conflicting dynamics arise from the same phenomenon would be to analyze mobility within the broader innovation process—a complex phenomenon requiring both variety and specialization—and to examine its relationship with mobility.

It has also been demonstrated that the narrative of inventors’ mobility, and highly skilled migration more broadly, being universally beneficial to both destination and origin regions is, in fact, quite fragile. The so-called “brain gain” occurs predominantly under stringent conditions and is closely linked to intra-firm mobility within multinational corporations. This finding underscores the necessity of exploring the “dark side” of innovation, a topic frequently overlooked (Morrison, 2023), wherein

inventors' mobility and the consequent concentration of human capital may indeed be key factors in understanding the growing spatial inequalities (Storper, 2018).

To achieve this understanding, it may be necessary to partially depart from the approach predominantly used so far, which has focused mainly on countries as the primary geographic unit. This approach has largely ignored, with few exceptions, intra-regional mobility and, consequently, intra-regional disparities. The country-level approach overlooks critical dynamics at multiple scales, including intra-regional and urban levels, as well as interactions between innovative and less innovative regions. Neglecting these dimensions risks missing key mechanisms that drive spatial inequalities. Additionally, there is a need to move beyond the origin/destination dichotomy, as these two dimensions can coexist within the spatial trajectories of inventors, shaping a complex geography that deserves to be analyzed to better understand the role of regions in the innovation process.

Finally, this review has highlighted the multiplicity of factors driving inventors' mobility, including both economic and non-economic factors. However, the literature has predominantly concentrated on the attractiveness of regions, using a microeconomic approach to explain inventors' choices and the technical characteristics that make an inventor more mobile. What has been almost entirely overlooked is the subjective decision-making process of inventors, who may be motivated by a much broader range of factors. Therefore, a qualitative analysis of the factors that inventors themselves perceive as most influential in their spatial location choices is necessary. Such an analysis could reveal previously unconsidered factors, potentially opening new research directions.

In addition, much of the literature reviewed here—as well as part of this thesis—relies primarily on patents as a data source. While patents are highly valuable informational tools, as they provide longitudinal evidence on inventive activity, they are not able to capture all forms of mobility (for instance temporary, informal, or occasional movements) and they overlook innovative activity that does not result in patents. These limitations motivate the mixed-method approach adopted in this thesis, which integrates patent data with biographical data on inventors.

To sum up, the approach adopted in this thesis builds precisely on the limitations highlighted in the review and seeks to overcome them through a relational, dynamic, and process-based understanding of mobility—and its spatiality—embedded within an innovation process that co-evolves with it. The analysis of the spatial relations established by inventors throughout their career trajectories will shed light on the broader geographies of innovation and their implications, as well as provide insights into their evolution over time and the drivers of specific configurations. In addition, the qualitative approach centered on inventors' life stories will allow for a deeper exploration of the factors generating mobility and will highlight the ways in which inventors experience and interpret the phenomenon.

To clarify how this thesis intends to contribute to the debate surrounding the many themes around which the literature on inventors' mobility revolves, Table 3.1 summarizes the key concepts and refers readers to the specific chapters in which they will be taken up again.

*Table 3.1 Key concepts and mechanisms linking inventors' mobility and innovation*

| Concept             | Explanation                                                                                               | Key references                                                       | Thesis location                                         |
|---------------------|-----------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------|---------------------------------------------------------|
| Knowledge diffusion | Mobility carries tacit, place-embedded knowledge across space, enabling learning beyond local boundaries. | Jaffe et al., 1993; Boschma & Lambooy, 1999; Breschi & Lissoni, 2009 | Ch.3 interprets inter-city links as knowledge channels. |

|                                                      |                                                                                                                                                                                                |                                                                                 |                                                                                                                                                      |
|------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                      |                                                                                                                                                                                                |                                                                                 | Ch.4 examines how diffusion vs concentration patterns evolve over time.                                                                              |
| Mobility as a gatekeeper                             | Mobile inventors can bridge otherwise disconnected places/communities, acting as brokers that enable novel recombination.                                                                      | Breschi & Lissoni, 2009; Filippetti & Zinilli, 2023; Verginer & Riccaboni, 2021 | Ch.3 communities/centralities (hubs vs connectors); interpretation of bridging roles in the mobility network.                                        |
| Recombination vs reuse in diversification            | Incoming knowledge can be recombined with local knowledge (recombination) or reused in a new place (reuse), potentially fostering diversification.                                             | Choudhury & Kim, 2019; Miguelez & Morrison, 2023                                | Ch.4 process-based interpretation of when diversification effects are more likely.<br>Ch.5. informs qualitative prompts in.                          |
| Specialisation / homophily mechanisms                | Mobility may reinforce specialisation when inventors sort into places already leading in their field (skills/technology matching).                                                             | Caviggioli et al., 2020; Kerr et al., 2016                                      | Ch.3–4 interpretation of hub dominance and community structure; reading of national/international clustering.                                        |
| Brain drain / brain gain and uneven regional effects | Mobility can deplete origin regions' human capital while benefiting destinations; impacts are often asymmetric and can reinforce spatial hierarchies.                                          | Bhagwati & Hamada, 1974; Borjas & Doran, 2015                                   | Ch.3 discusses implications of network structure for inequality and resilience.                                                                      |
| Brain circulation                                    | Beyond drain/gain, mobility can create trans-local linkages through return migration, diaspora networks, and knowledge remittances—often conditional on institutions and complementary assets. | Saxenian, 2005; Kerr et al., 2016                                               | Ch.3-4 relational view (multi-node pathways) complements origin/destination binaries. Ch.5 captures lived meanings of return and transnational ties. |
| Microeconomic drivers of mobility                    | Inventors move when expected benefits (wages, opportunities, productivity) outweigh costs; mobility can also                                                                                   | Kerr et al., 2016                                                               | Ch.5 life histories nuance incentives/constraints.                                                                                                   |

|                                                                |                                                                                                                                         |                                                                                         |                                                                                                                        |
|----------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|
|                                                                | raise<br>productivity.                                                                                                                  | inventor                                                                                |                                                                                                                        |
| Networks and social ties                                       | Ties reduce information frictions and facilitate mobility; social connectedness can shape where inventors go and how knowledge travels. | Dorner et al., 2016; Campo et al., 2022                                                 | Ch.5 narratives on family/professional ties.                                                                           |
| Proximity (geographic, cultural, technological, institutional) | Mobility is patterned by multiple proximities that lower costs and increase match quality (not just physical distance).                 | Gorin, 2016; Kerr et al., 2016                                                          | Ch.4 interpretation of national/international flow.<br>Ch.5 framing of trajectories and constraints.                   |
| Agglomeration economies & regional innovation systems          | Inventors are pulled toward places with dense knowledge externalities, specialised institutions, and stronger innovation systems.       | Asheim & Gertler, 2006; Feldman, 1999; Jaffe et al., 1993; Döring & Schnellenbach, 2006 | Ch.3 node attributes and hub interpretation; Ch.4 covariate interpretation for why certain cities emerge as key nodes. |
| Amenities / ‘soft’ locational factors                          | Quality of life and ‘soft’ place attributes can attract/retain high-skilled workers, though causality is debated.                       | Florida, 2002; Florida, 2014; Acs & Megyesi, 2009; Albouy & Stuart, 2020                | Ch.5 narratives on place attraction/retention.                                                                         |

# Chapter 4

## 4 Communities, Centralities and Resilience to Shocks: A Network Analysis on mRNA COVID-19 Vaccines' Inventors' Mobility

### 4.1 Introduction

From a geographical perspective, it is well established that innovative activity tends to concentrate in specific places (Asheim & Gertler, 2006) due to the tacit and "sticky" nature of the knowledge required (Boschma & Lambooy, 1999; Jaffe et al., 1993) and the cumulative, path-dependent nature of the innovation process (Dosi, 1982). While inventors' mobility contributes to the spatial diffusion of knowledge (Breschi & Lissoni, 2009), at the same time, it tends to gravitate toward places that already exhibit a high concentration of human capital, leveraging the locally available knowledge (Hilaire-Perez & Verna, 2006; Kerr et al., 2016). This implicit contradiction in the spatial mechanisms governing mobility—where it simultaneously diffuses and concentrates knowledge—is compounded by a limited understanding of the geographic effects of this phenomenon.

Studying inventors' mobility offers a useful lens for understanding the spatial dynamics unfolding among the places linked by such movement, delineating a complex geography that underscores the interdependence among sites of innovation. A network perspective can complement prior research on inventors' mobility, which has largely adopted a place-based approach and emphasized the origin–destination dichotomy. This study leverages the complexity of the spatial relations generated by inventors over their career trajectories to contribute to a more dynamic understanding of an inherently geographic process.

This study aims to contribute to research on inventors' mobility by placing greater emphasis on the spatial relationships that emerge through mobility among cities engaged in the innovation process. Specifically, I answer the following questions: Which spatial patterns emerge from inventors' mobility, and what factors contribute to their formation? What are the implications of these patterns for the resilience and stability of the overall spatial structure?

To address these questions, the study focuses on the mobility of key inventors involved in the development of mRNA COVID-19 vaccines. This choice is particularly relevant because the pandemic has highlighted the critical importance of biotechnological innovation from both an economic and social perspective. Moreover, the biopharmaceutical sector is known for its involvement of multiple actors, including universities, pharmaceutical companies, start-ups, and both public and private research centers.

To analyze the complex spatial relationships generated by inventors' mobility, I will reconstruct a mobility network. This network will connect cities through the unidirectional movements of inventors between them. This study focuses not on individual moves but on the trajectories inventors trace over their entire careers, beginning with higher education.

Using three different community detection methods—Stochastic Block Model, Leiden algorithm, and Infomap—the study will identify the various structures that can represent the network. Through these three detection methods, cities are grouped based on their roles in the network, the density of mobility flows between them, and their capacity to facilitate knowledge diffusion through inventors. This will



make it possible to determine which cities form the most cohesive ties, which corridors facilitate or constrain knowledge circulation, to identify bottlenecks, and to characterize overall network structures ranging from uniform configurations to core-periphery patterns.

Additionally, I will implement Exponential Random Graph Models (ERGMs) to identify the structural factors—network characteristics such as mutual relations or preferential attachment—and city attributes—e.g. the presence of public or private institutions—that drive inventors' mobility between locations. The goal is to understand—based on the characteristics of the network and of individual cities—which factors facilitate inventor inflows and outflows.

To further investigate the resilience of the network, city-level shock simulations—through nodal removal—will be conducted. These simulations will assess the network's ability to self-organize in response to random disruptions while also identifying its vulnerability to shocks targeting specific cities. These shocks are intended to simulate endogenous or exogenous events that could affect cities or entire countries, such as economic-financial crises or the implementation of policies that restrict inbound or outbound mobility, a concern sharpened by recent geopolitical developments and revived policy debates in the United States and beyond.

Finally, I will implement and train link-prediction algorithms based solely on the network's topological properties, in order to infer the most likely mobility trajectories given the network structure. This will help isolate the effects that the network's own structure may have on mobility and clarify how it may steer mobility in a co-evolutionary perspective.

The study is structured as follows: the following section presents the theoretical background and the research gaps this study aims to address; section three details the data collection process and methodological framework; section four discusses the results; and the last section provides conclusions, discusses implications, and suggests ways to overcome the study's limitations.

## **4.2 Inventors' mobility, knowledge and space**

Knowledge undeniably plays a fundamental role in the innovation process. Due to its often tacit and "sticky" nature (Boschma & Lambooy, 1999; Jaffe et al., 1993), which makes it difficult to transfer across space, it is considered a key factor in the spatial concentration of innovative activity (Asheim & Gertler, 2006). However, mobility has been identified as a channel through which knowledge diffusion may become more equitable and widespread. In their seminal study, Breschi & Lissoni (2009) demonstrate that human capital mobility facilitates the spatial diffusion of knowledge, suggesting that the spatial concentration of innovative activity may be attributed to low mobility rates. Nevertheless, increased mobility does not necessarily lead to a more even distribution of innovation across space, as highly skilled workers tend to relocate themselves to regions already rich in human capital (Kerr et al., 2016). This occurs because such places offer inventors the opportunities to leverage existing, concentrated knowledge (Hilaire-Perez & Verna, 2006).

This raises important questions about the actual effects of mobility on the regions involved. While it is evident that mobile inventors contribute to knowledge transfer in the destination regions (Ganguli, 2015), leading to significant increases in patenting activity (Bahar et al., 2020), and benefiting themselves from higher productivity compared to their less mobile counterparts (Pellegrino et al., 2023), these positive effects may stem from the replacement of native human capital with migrant talent, reducing the local capability (Borjas & Doran, 2015). Indeed, mobile inventors influence destination regions not only by facilitating knowledge diffusion but also by introducing new technologies, thereby enabling unrelated diversification (Diodato et al., 2022). This can occur in two ways: through knowledge recombination or knowledge reuse (Choudhury & Kim, 2019). In the first case, migrant inventors collaborate with native counterparts, combining their knowledge and

generating high-quality innovation (Ferrucci & Lissoni, 2019), which remains partially related to local knowledge. In the second case, migrant inventors do not collaborate with natives but instead produce their knowledge in a location other than their origin one, and the destination region benefits from unrelated diversification (Migueluez & Morrison, 2023). In contrast to this perspective, Caviggioli et al. (2020) argue that migration and technological diversification are negatively correlated, as inventors tend to move in locations specializing in their skills.

While the effects on destination regions appear ambiguous yet generally positive in terms of productivity, the discussion becomes even more complex when considering the effects on origin regions. Traditionally, mobility has been perceived negatively due to the undeniable loss of human capital suffered by these regions (Bhagwati & Hamada, 1974), particularly given the substantial—often public—investment required to develop this capital. This highlights the less examined side of the innovation process: its potential to exacerbate spatial inequalities. However, recent studies have explored mechanisms through which origin regions may also benefit from mobility, challenging the conventional "brain drain" narrative with the concept of "brain gain." One proposed mechanism is the tendency for populations in origin regions to invest more in human capital in anticipation of migration opportunities, which could lead to a more skilled workforce in the region if migration opportunities are limited (Faini, 2003). Empirical analyses indicate that this is true only under specific conditions, such as significant wage gap between regions and low emigration rates; otherwise, the effects may be even negative (Beine et al., 2011).

The most compelling channel is the transfer of "knowledge remittances" (Fackler et al., 2020), wherein migrants transfer knowledge back to their origin countries through social networks and/or return migration. In the first case, migrants diffuse knowledge to their countries of origin through sustained social ties. However, research suggests that this alone is insufficient to compensate for the initial loss of human capital (Agrawal et al., 2011) and that multinational firms play a crucial role in facilitating this transfer (Breschi et al., 2017; Migueluez & Noumedem Temgoua, 2020), and so mostly able to transfer intra-firm knowledge (Marino et al., 2020). Nevertheless, some argue that this process could still lead to unrelated diversification in origin countries (Di Iasio & Migueluez, 2022). A similar argument applies to return or circular migration, where returning inventors act also as agents of transformation, introducing new innovation models acquired abroad (Saxenian, 2005). Yet again, these benefits are not available to all origin regions (Diodato et al., 2023) and are primarily driven by intra-firm mobility within multinationals (Choudhury, 2016).

Despite the extensive literature on the subject, the debate on the effects of inventors' mobility remains ambiguous in several aspects. While mobility undoubtedly serves as a key mechanism for knowledge diffusion and technological change, its impact on origin and destination regions remains ambivalent and context-dependent. This ambiguity may stem from an insufficient consideration of the complex dimension of the phenomenon: the simplistic dichotomy between origin and destination regions fails to capture the spatial complexity of mobility and its consequences. Beyond the simple transfer and spatial redistribution of knowledge and human capital, inventors' mobility is an inherently relational phenomenon: it creates links between entities across space and, in doing so, reshapes the very geography of innovation. Adopting a relational perspective makes clear that the topology produced by inventors' career trajectories is not neutral. Rather, it can generate cumulative advantage through preferential-attachment mechanisms, leading to a core-periphery spatial configuration (Vaccario et al., 2020; Zheng et al., 2025). The geography-shaping capacity of this process becomes even more apparent when considering that inventors' mobility networks tend to organize into communities—clusters of nodes that are more densely connected internally than externally—thereby creating privileged channels that narrow feasible pathways toward a limited set of destinations (Kiss & Buzás, 2016). From this standpoint, space is no longer a mere container in which events occur; instead,

relational dynamics contribute to the emergence of geographical units that may or may not coincide with administrative boundaries (Nelson, 2021). Consequently, a relational approach also enables a deeper understanding of the role of geographical distance and national borders in inventors' mobility: while mobility is undoubtedly influenced by geographic and institutional proximity, inventors appear more able to cross national borders than other factors that are fundamental to the innovation process (Morescalchi et al., 2015). Furthermore, the role of institutions—public or private, research or business-oriented—in shaping mobility patterns and mediating the effects of knowledge circulation remains less explored (Qiao et al., 2024). This role has been addressed in the literature largely in an aspatial way, focusing on inventors' mobility between organizations and its implications for knowledge diffusion and, in turn, innovative productivity. Early research concentrated on inter-firm mobility and on the benefits accruing to firms through a “learning-by-hiring” logic (Palomeras & Melero, 2010; Song et al., 2003). Subsequently, attention shifted to academic inventors, and especially to their mobility into industry—a movement that is crucial for linking scientific and applied research—with younger inventors and those at the beginning of their careers being more likely to move into the private sector (Crespi et al., 2007).

Even if our understanding of the extent to which the nature of institutions facilitates mobility remains limited, yet some evidence has emerged. First, as noted above, institutional proximity clearly acts as a facilitator of mobility, as sharing the same rules, norms, and organizational routines reduces the costs of moving (Boschma, 2005). It follows that inventors' spatial mobility is likely to be facilitated when it occurs within the same organization, particularly in the case of multinational corporations, where intra-firm transfers can enable inventors to cross national borders as part of knowledge-integration strategies (Castellani et al., 2022). Moreover, universities also play a key role in facilitating mobility: a substantial share of “migrant inventors” relocates before the start of their inventive careers, or even before completing education, suggesting that education-related mobility often represents a decisive first step shaping subsequent trajectories (Lissoni & Miguelez, 2024).

Given these gaps, this study seeks to examine the geographical dynamics and configurations emerging from inventors' mobility throughout their careers, the factors shaping these configurations, and their broader implications.

## **4.3 Data and Methods**

### **4.3.1 Data**

To reconstruct the mobility flows of key inventors involved in the development of mRNA COVID-19 vaccines, this study first identified 89 patents deemed fundamental by Gaviria & Kilic (2021) for the production of this technology. The content of these patents was retrieved using Google Patents, and the inventors listed on each patent were identified, totalling 145 individuals. Additionally, the assignee that filed these patents and their geographical locations were mapped to determine the primary actors of innovation in this field.

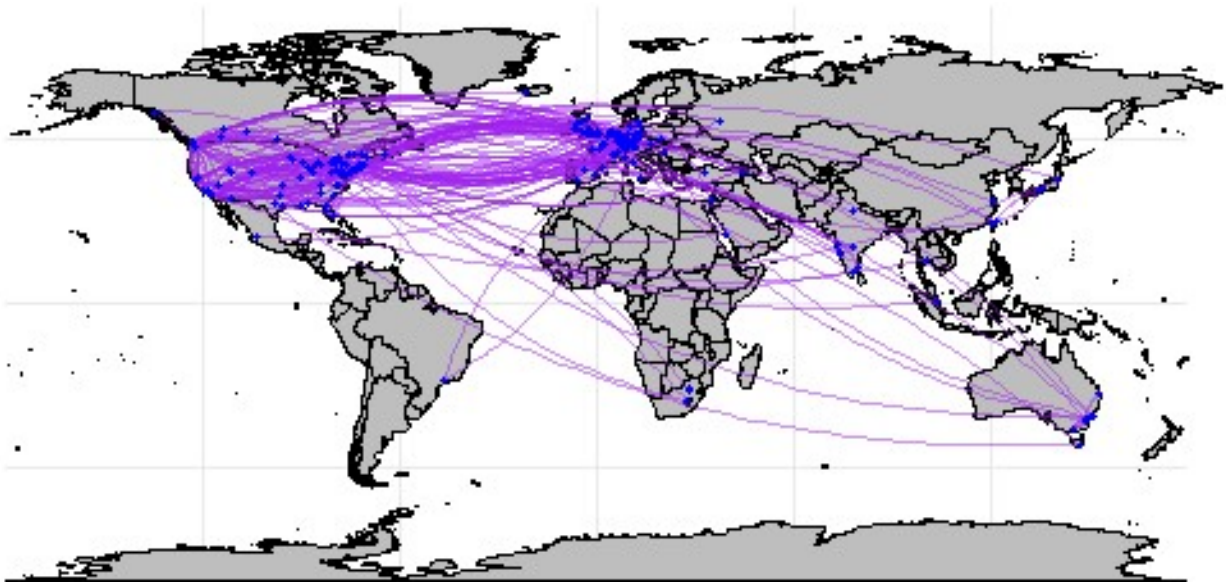
For each inventor, career trajectory information was collected using publicly available open-source resources, primarily—but not limited to—LinkedIn, Wikipedia pages, interviews, and CVs. These data include the institutions where inventors studied—beginning with tertiary education—and worked. Based on this information, the geographical locations of these institutions (city, state, country) were determined, as well as distinctions between educational and employment institutions and whether they were public or private. Although exact timeframes for each location were not always available, the sequential order of locations for each inventor was established, enabling the reconstruction of their mobility trajectories. The novelty of this approach lies in integrating a network-

based mapping of career trajectories with information that goes beyond what is contained in patents or publications, enabling a much more accurate capture of mobility (Ge et al., 2016).

### 4.3.2 Network creation

Using the collected data, a directed network was constructed to represent the mobility patterns of key inventors throughout their careers. In this network, cities serve as nodes, connected by unidirectional links representing inventor movements (Figure 4.1). Each city-node is characterized by attributes such as the country it belongs to, the percentage of public institutions involved, and the percentage of institutions providing education.<sup>1</sup>

*Figure 4.1 Mobility Network Map*



*The map shows the Spatial representation of the network generated by inventors' mobility.*

The resulting network exhibits a strongly heavy-tailed degree distribution (Figure 4.2), indicating pronounced heterogeneity in cities' connectivity. Using standard procedures for discrete heavy-tailed data, a power-law fit provides an adequate description of the upper tail of the distribution with an estimated exponent  $\gamma$  of 2.31 above  $x_{min} = 4$  (Figure 4.3-4.4). Following (Zinilli, 2016), I compare the power-law distribution with exponential, lognormal and Poisson distribution to test which better fit the degree distribution (Table 4.1). Goodness-of-fit tests do not reject the power-law model for the tail, and likelihood-ratio comparisons show that it fits the data significantly better than exponential and Poisson alternatives, while comparisons with the lognormal distribution are inconclusive. Accordingly, I interpret the network as hub-dominated and consistent with power-law-like behavior in the upper tail. This is substantively important because a hub-dominated topology—regardless of whether the best-fitting tail model is a pure power law or another heavy-tailed form—tends to generate distinctive structural properties commonly discussed in the complex-network literature (Barabási & Albert, 1999). In particular, strong connectivity concentration can support the emergence of meso-scale structures (e.g., communities and core-periphery patterns), self-reinforcing dynamics

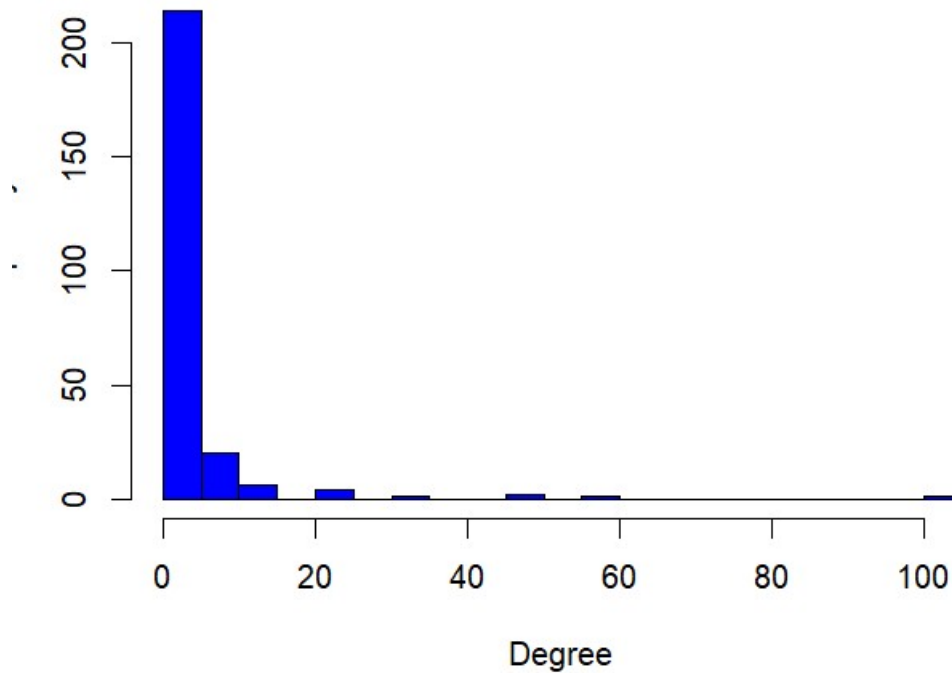
<sup>1</sup> The percentage of public institutions involved is calculated by dividing the number of public institutions at which the inventors worked or studied in a given city by the total number of institutions at which the inventors worked or studied in that city. Similarly, the percentage of institutions that provided education is calculated as the ratio between the number of institutions that provided education to the inventors in a city and the total number of institutions in that city with which the inventors were involved. These two measures are not intended to estimate the total stock of assets present in the cities, but only those that the inventors actually made use of and that, consequently, influenced their choices

in tie formation (e.g., cumulative advantage), and robustness to random shocks alongside vulnerability to targeted disruptions of highly connected hubs. Building on this, this study aims to, on the one hand, identify emerging communities within the network and analyze the factors influencing geographic roles in the network and, on the other hand, assess the network's robustness and vulnerability, also examine the implications of this specific topology for mobility dynamics.

*Table 4.1 Degree distribution comparison*

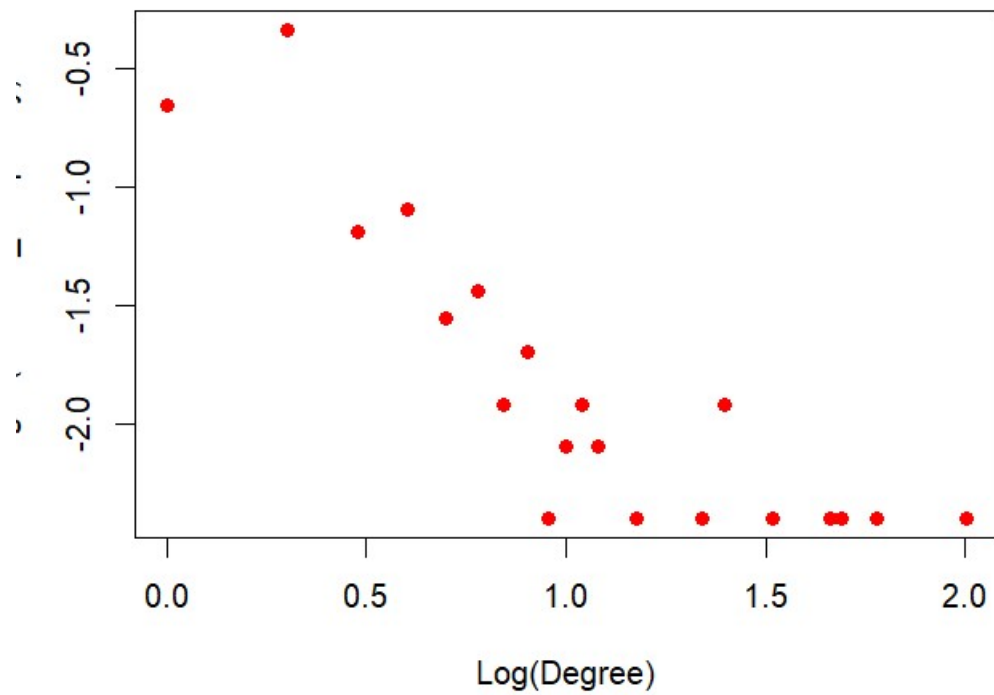
| Degree type  | X(min) | $\gamma$ | GOF p-value | Lognormal |       | Exponential |        | Poisson |       |
|--------------|--------|----------|-------------|-----------|-------|-------------|--------|---------|-------|
|              |        |          |             | LLR       | p     | LLR         | p      | LLR     | p     |
| Degree (all) | 4      | 2,31     | 0,626       | -0,733    | 0,463 | 2,841       | 0,004  | 2,465   | 0,013 |
| In-degree    | 1      | 2,2      | 0,89        | 0,086     | 0,931 | 3,599       | 0,0003 | 2,78    | 0,005 |
| Out-degree   | 1      | 2,21     | 0,543       | -0,6      | 0,548 | 2,683       | 0,007  | 2,476   | 0,013 |

*Figure 4.2 Degree Distribution*



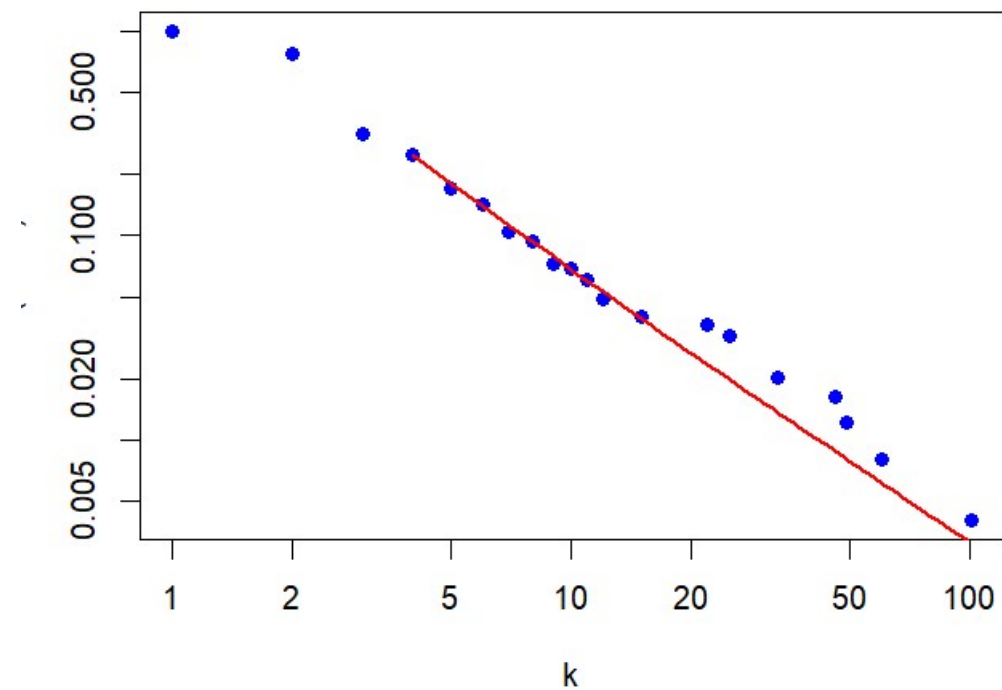
*The histogram illustrates the degree distribution of the network, showing the number of cities per degree.*

Figure 4.3 Degree Distribution Log-Log



The log-log scatter plot of the degree distribution visualizes whether the network follows a power-law behaviour. A linear trend in this space would suggest scale-free characteristics.

Figure 4.4 Cumulative Degree Distribution



This plot shows the cumulative degree distribution of a network (blue points) on a logarithmic scale, compared to a fitted power-law function (red line). The alignment between the empirical data and the theoretical power law suggests a scale-free structure.

### 4.3.3 Community Detection

The concept of community in network analysis remains a topic of debate: a community is, ultimately, a construct, a category created to identify individuals similar to one another by virtue of a given characteristic; as those characteristics change, the same individuals may find themselves in different communities, or still in the same one. For this reason, and to capture the emerging communities within the network from different perspectives, this study applies three distinct community detection methods, each representing a different conceptualization of community, specifically:

*Poisson-Adjusted Stochastic Block Model (SBM)*: This method identifies communities of nodes playing similar roles within the network structure and, by extension, within inventors' mobility network. The stochastic block model is a generative and probabilistic model that assumes the network is generated through a process where nodes belong to blocks, and the probability of connections depends solely on the block to which nodes belong. This study employs a Poisson-distributed variant, which is particularly suited for weighted networks like the one under analysis (Lee & Wilkinson, 2019). The optimal number of blocks (and, consequently, communities) is determined by maximizing the Integrated Complete Likelihood (ICL), which balances goodness-of-fit and model complexity based on number of blocks (Biernacki et al., 2000).

*Leiden Algorithm*: This approach detects city-based communities where inventors' mobility creates dense and intense intra-community relationships compared to their external connections.

Designed as an improvement over the Louvain algorithm, which identifies communities based on modularity optimization, the Leiden algorithm overcomes issues such as the formation of poorly connected or even disconnected communities (Traag et al., 2019). The model's resolution parameter sets a threshold requiring communities to have a density greater than this value while inter-community density remain below it. In this study, the resolution parameter is set to 0.01.

*Infomap*: Based on information theory, this method is particularly effective for identifying communities in directed networks like the one under study. Infomap operates by modelling random walks within the network, aiming to minimize the map equation (Rosvall & Bergstrom, 2008). Communities are thus detected as groups of nodes where a random walker is more likely to remain, representing clusters of cities where mobility channels are more effective in knowledge diffusion. Indeed, the subset of cities in which the random walker is most likely to become 'trapped' corresponds to those cities that, through inventors' mobility, have created pathways that make knowledge transfer among them more likely, while excluding or limiting the diffusion of this knowledge outside the community.

These three methods provide complementary insights into the community structures within the mobility network, enabling a more comprehensive understanding of the spatial patterns emerging from inventors' mobility and their broader implications.

### 4.3.4 Exponential random graph models (ERGMs)

To analyze the structural properties of the mobility network—i.e. the endogenous network patterns that arise from the topology itself—and identify the key factors shaping its complex geography, this study employs moreover an Exponential Random Graph Models (ERGMs). ERGMs constitute a family of statistical models that estimate the probability of network formation based on structural characteristics or nodal attributes (Robins et al., 2007). In other words, they allow us to determine the

likelihood of a link forming between two nodes as a function of specific features. This study considers the following structural and nodal characteristics:

### **Structural Features:**

#### *Mutuality*

*Mutual* captures the tendency to form bidirectional ties in the network. In a mobility network like this, it is particularly relevant for understanding the extent to which inventors, as they move, create reciprocal ties between cities.

#### *Geometrically Weighted Out-Degree and In-Degree*

*Gwodeg* and *Gwidedeg* Measure the impact of degree distribution on link formation probability. This, in turn, allows us to isolate effects attributable solely to the network's topology and to understand the formation and role of hubs in inventors' mobility.

### **Nodal Attributes:**

#### *Education Percentage and Public Percentage*

Assess and evaluate the effect of educational institutions and public institutions on link formation. Them therefore helps assess the extent to which the presence of such institutions explains inventor inflows to—or outflows from—cities.

#### *Nation*

Examines the propensity for mobility ties between cities within the same country. It is useful for capturing intra-national mobility and gauging its weight within overall mobility.

#### *SBM Communities*

Assesses the probability of link formation for core or peripheral cities. The aim here is to understand how membership in a given community may influence the probability of observing inventor inflows to, or outflows from, a city.

### **4.3.5 Resilience and vulnerability to shocks**

A defining characteristic of complex networks is their ability to self-organize (Barabási & Albert, 1999), resulting in greater robustness to random node removal than random networks while simultaneously exhibiting heightened vulnerability to targeted attacks on key nodes. To test this hypothesis and explore the effects of exogenous or endogenous shocks on network resilience, this study implements a series of simulations involving the sequential removal of nodes based on different criteria. These simulations aim, on the one hand, to identify which characteristics of cities make them so central that the entire network becomes highly dependent on them, and, on the other hand, to understand how shocks—economic, financial, or political—can affect the network's structure. The latter is particularly relevant in the current geopolitical context, which is already constraining mobility. The goal is to assess the impact of node removal on the size of the giant component and network global efficiency, measured as the inverse of average path length.

Simulations are conducted using six node removal strategies:



*Random Node Removal:* Nodes (i.e. cities) are removed randomly to establish a baseline for robustness assessment and to compare with subsequent targeted removal strategies.

*Degree-Based Removal:* Nodes are removed in decreasing order of degree to evaluate network vulnerability to shocks affecting the most central cities.

*Institution-Based Removal:* Nodes are removed based on the prevalence of public or private institutions, first targeting cities with a high concentration of public institutions and then those with a stronger private sector presence.

*Education and Employment-Based Removal:* Nodes are sequentially removed based on their involvement in education or employment provision, first removing cities with the highest education-related activity and then those primarily offering employment.

*Mobility Role-Based Removal:* Cities are categorized as major importers or exporters of inventors based on a polarization index, defined as the ratio between the difference in in-degree and out-degree to total degree. Nodes are removed in decreasing order to assess the impact of targeting cities that mostly attract human capital and in increasing order to examine the effects on cities that primarily export talent.

*Country-Based Removal:* Simulations are conducted for each country involved in the mobility process to simulate the effects of entry or exit restrictions imposed by national policies.

These simulations serve not only to verify whether the network behaves as a complex system capable of withstanding shocks but also to reveal its critical vulnerabilities. The findings will offer insights into the key nodes/cities shaping the network's stability and highlight the conditions under which the network is most susceptible to disruption.

#### **4.3.6 Link prediction**

To understand the effects of the geography shaped by inventors' mobility on future mobility patterns, link prediction is applied using only the topological features of the network. In the literature on collaboration and knowledge networks, link prediction is increasingly framed as a way to uncover and interpret endogenous mechanisms of network evolution. In particular, link-prediction frameworks are used to evaluate how much of link formation can be explained by network structure alone and, by extension, which structural tendencies are most consistent with the observed system dynamics (Resce et al., 2022; Zinilli & Cerulli, 2023). Here I follow the same approach and extend it to the case of inventors' mobility. The aim is to understand how the geography produced by this mobility can co-evolve with it and, potentially, reproduce the characteristics observed in the previous analysis. Specifically, four features are computed to assess the likelihood of a connection between two nodes:

*Common Neighbors:* Calculates the number of shared neighbors between two nodes. The assumption is that nodes with more shared neighbors are more likely to be connected. Given the directed nature of the network, the out-neighbors of node  $u$  and the in-neighbors of node  $v$  are considered to assess the probability of a directed connection from  $u$  to  $v$ . Put differently, the probability of a directed flow of inventors from city  $u$  to city  $v$  increases with the number (and strength) of existing indirect paths between the two cities.

*Preferential Attachment:* Based on the "rich-get-richer" hypothesis, this metric is calculated as the product of the out-degree of  $u$  and the in-degree of  $v$ . Higher values indicate a greater likelihood of  $u$  being connected to  $v$ . In this case, the probability of observing a flow of inventors from city  $u$  to city  $v$  rises with the number of inventors leaving  $u$  and the number entering  $v$ , regardless of their routes.

*Jaccard Index:* Similar to Common Neighbors but normalized by the total number of neighbors of the two nodes. This ensures that the value is lower when nodes share a smaller percentage of neighbors compared to the total number of their neighbors.

*Adamic-Adar Index:* Similar to Common Neighbors, but it assigns lower weights to shared neighbors with high degrees, emphasizing the influence of low-degree neighbors because more relevant.

In essence, I aim to test the extent to which these structural features of the network can predict inventors' mobility, isolating their effect and clarifying the direction in which the network's structure alone may evolve within a co-evolutionary dynamic between individual mobility and the system's broader spatial organization.

The dataset is constructed by selecting all existing edges in the network and randomly generating an equal number of non-existent edges. These edges are labelled accordingly, and the features described above are computed.

The dataset is then split into a training set (80%) for training machine learning models and a test set (20%) for performance evaluation. Four machine learning models are tested using five-fold cross-validation:

*Random Forest:* An ensemble learning method that constructs and combines multiple decision trees. Each tree is trained on a bootstrapped sample of the original data, and the splits are determined based on a randomly selected subset of features used as variables (Breiman, 2001).

*Neural Networks:* Inspired by the functioning of biological neural networks, these models consist of interconnected layers of nodes (neurons). A neural network typically has an input layer, an output layer, and one or more hidden layers. The connections between neurons have specific weights that are adjusted during the training process through backpropagation.

*Gradient Boosting:* Another ensemble method based on decision trees. Unlike Random Forest, Gradient Boosting trains models sequentially. Starting with a simple model (weak learner), each subsequent model learns by correcting the errors of the previous models (Friedman, 2001).

*K-Nearest Neighbors:* A simple yet effective method where the value of the target variable is determined based on the values of its  $k$  nearest neighbors, according to a distance metric—typically Euclidean distance (Cover & Hart, 1967).

To further improve performance, a grid search is performed to identify the optimal combination of hyperparameters for each model. Specifically:

*Random Forest:* Number of variables considered (2, 3, 4)

*Neural Networks:* Number of neurons in the hidden layer (1, 3, 5) and the regularization factor (0.1, 0.5, 1)

*Gradient Boosting*: Number of trees (50, 100, 150), interaction depth (1, 3, 5), learning rate (0.01, 0.1), and minimum number of observations per node (5, 10)

*K-Nearest Neighbors*: Number of neighbors considered (3, 5, 7, 9)

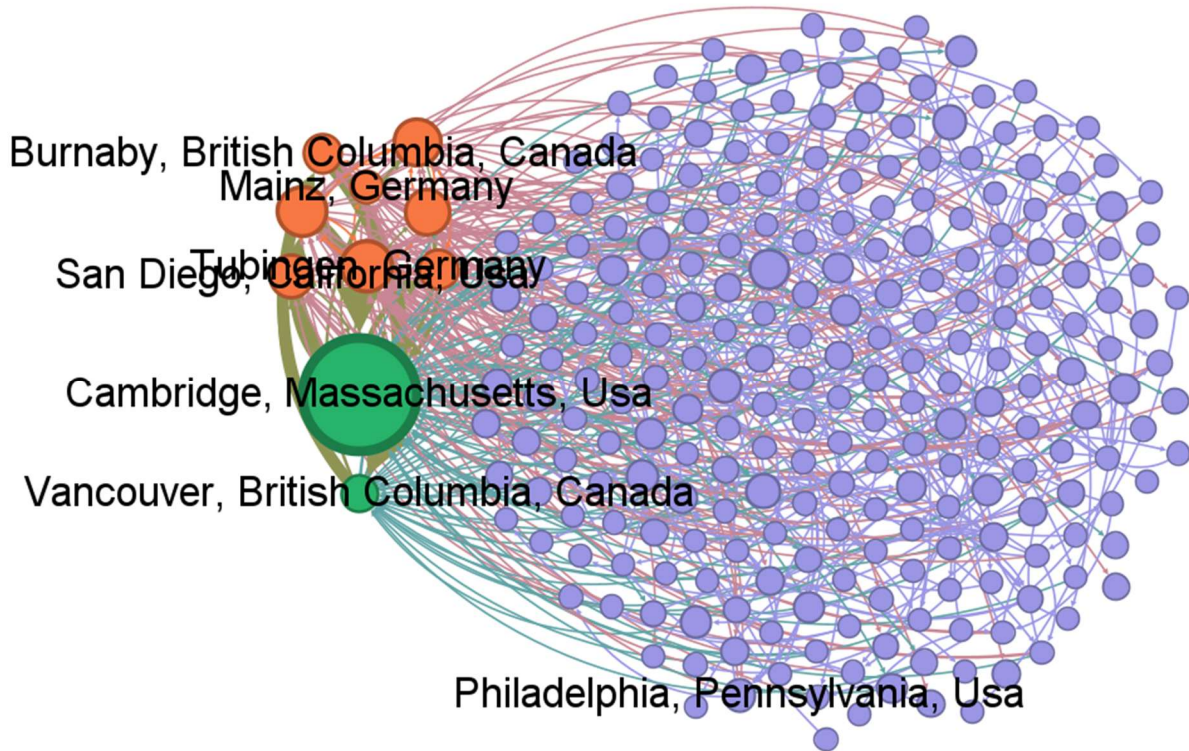
After evaluating the performance of the models, the links with a probability greater than 80% will be selected and incorporated into the original network to assess the effects of mobility generated by the network's topology.

## **4.4 Results**

### **4.4.1 Emerging communities**

The identification of communities through the three different methods previously discussed reveals three distinct and highly significant network structures. The SBM method highlights a typical core-periphery structure where the core is represented by 2 smaller but central blocks and the periphery by a big but less connected block (Figure 4.5). In particular, three communities emerge: one that includes the vast majority of cities involved, and two others—where the main innovation hubs are located—that are smaller in size but highly connected. Notably, there is strong mutuality among the few cities belonging to the two core blocks, with a connection density that, although lower than that with the periphery in absolute terms, remains highly significant considering the substantial size difference between the core and peripheral blocks (Table 4.4 in Appendix A).

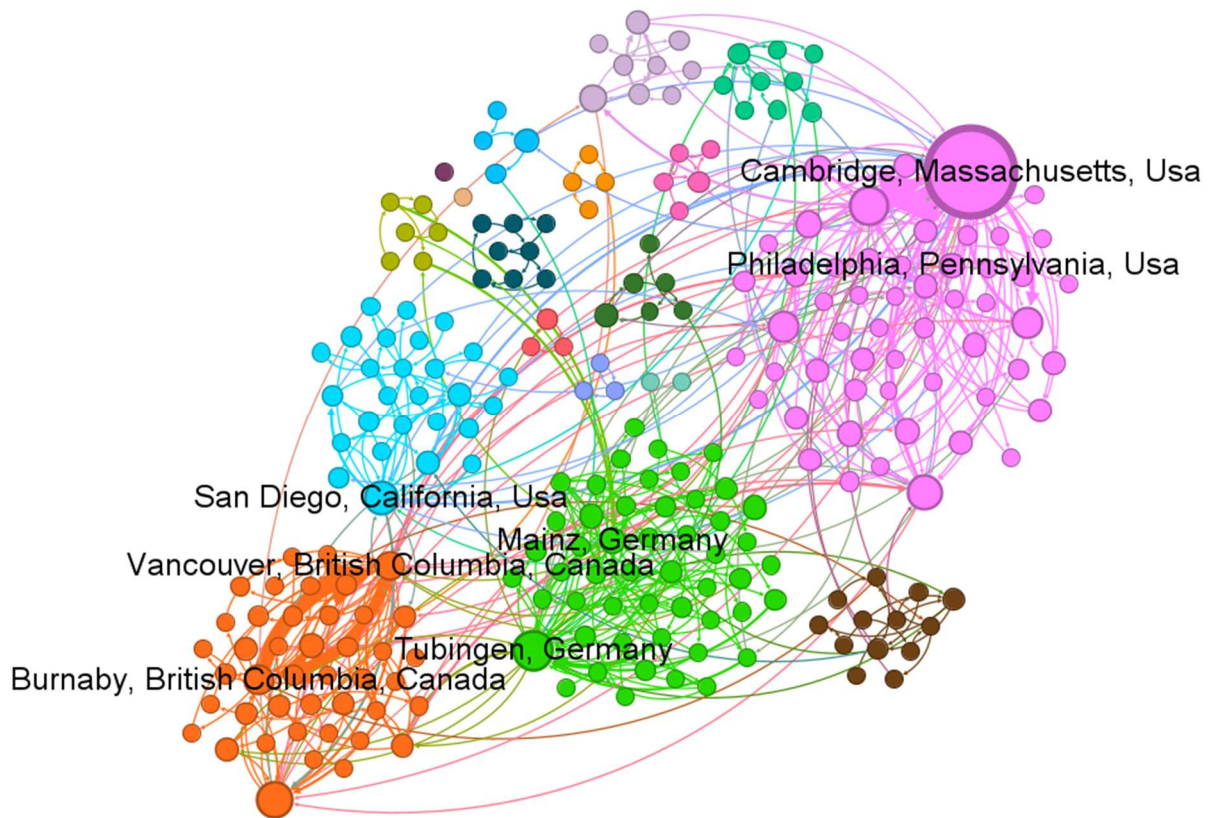
Figure 4.5 SBM Communities



*The visualization represents the network communities detected using the Stochastic Block Model. Each node corresponds to a city, and edges represent inventor mobility between them. Node sizes are proportional to their authority scores from the HITS algorithm, highlighting influential locations in terms of knowledge reception.*

Using the Leiden algorithm, a larger number of communities is identified (Figure 4.6). In this case, it becomes evident that the main innovation hubs belong to different communities, indicating that the densest connections generated by inventors' mobility do not involve all hubs equally. More specifically, hubs within different communities tend to belong to the same country or, at least, the same geographic area. Examining the distribution of the national attribute within communities (Table 4.5 in Appendix A), we observe that nodes belonging to the same country are highly likely to be grouped together.

Figure 4.6 Leiden Communities

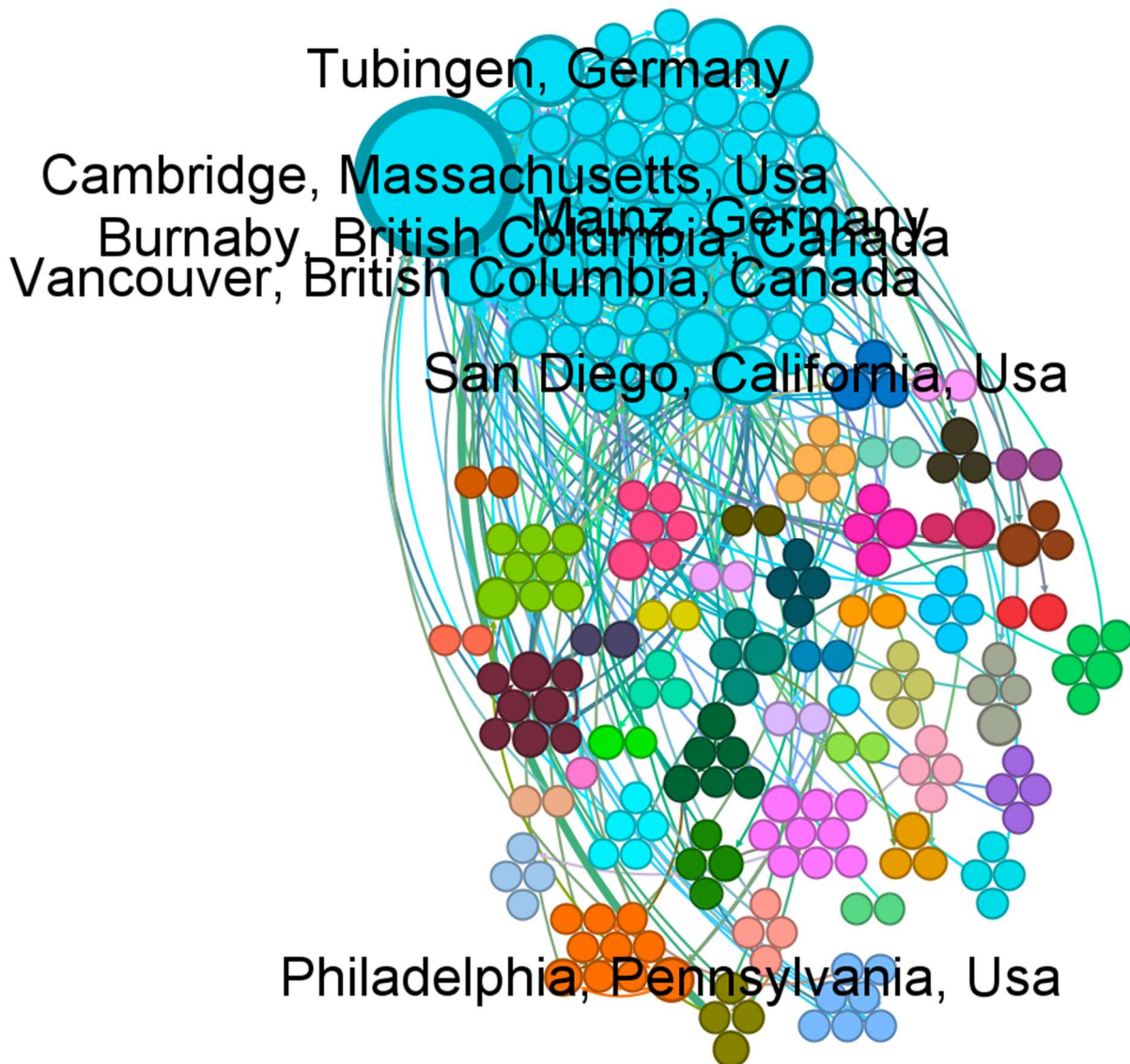


*The visualization represents the network communities detected using the Leiden algorithm. Each node corresponds to a city, and edges represent inventor mobility between them. Node sizes are proportional to their authority scores from the HITS algorithm, highlighting influential locations in terms of knowledge reception.*

The results obtained through community detection using the Infomap algorithm are even more striking (Figure 4.7). A large number of small-sized communities emerge, with the exception of one particularly large community that includes the main innovation hubs. On one hand, this structure reinforces the earlier intuition from the SBM approach, which highlighted the capacity of innovation centers to facilitate the circulation of inventors—and consequently of knowledge. On the other hand, it also suggests that this circulation remains largely confined within a closed circuit, excluding much of the network.



Figure 4.7 Infomap Communities



*The visualization represents the network communities detected using the Infomap algorithm. Each node corresponds to a city, and edges represent inventor mobility between them. Node sizes are proportional to their authority scores from the HITS algorithm, highlighting influential locations in terms of knowledge reception.*

Since the three algorithms identify communities according to different criteria, community membership carries a different meaning for each city. It is therefore equally useful to examine how the key cities behind this innovation are positioned simultaneously across all three levels.

First, in the dual core identified by the SBM, Vancouver, BC and Cambridge, MA stand apart from the rest of the core, which appears to function as a supporting structure for them. This is consistent with the roles these two cities played in the development of the mRNA vaccine (Cambridge) and in lipid nanoparticle production (Vancouver). Their strong interconnection with the remaining core seems to create a form of hierarchy, which helps to interpret why almost all major cities fall within the large community identified by Infomap, capturing how inventors' mobility can facilitate knowledge diffusion, evidently to the advantage of hub cities.

By contrast, the fragmentation of these cities into different communities under the Leiden algorithm suggests that this structure cannot be explained simply by the density of inventor flows between cities, but rather by the roles these flows play within the network. Finally, the case of Philadelphia, PA is illustrative: it appears peripheral both in SBM and in Infomap. This is because its contribution to vaccine development lies in the scientific discovery of pseudouridine, an essential invention that, rather than making Philadelphia central within the network, was effectively transferred to the vaccine hub-cities.

#### 4.4.2 Network structure and mobility pattern: ERGMs estimation

The analysis conducted using Exponential Random Graph Models (ERGMs) allowed for the identification of the key factors characterizing the network and those influencing its structure. Given the correlation between *edu\_percentage* and *pub\_percentage*, the two variables were included in separate models. Moreover, following best practices, the decay parameter of the geometrically weighted degree term was fixed first to 0.1 and then to 0.5, to ensure consistency (Wang et al., 2024). The estimates presented below refer to the model that showed the best goodness-of-fit (see Appendix C).

Table 4.2 ERGMs Results

|                                    | Estimate | Std, Error | MCMC % | z value | Pr(> z ) |     |
|------------------------------------|----------|------------|--------|---------|----------|-----|
| edges                              | -2,802   | 0,191      | 0      | -14,645 | < 1e-04  | *** |
| mutual                             | 2,356    | 0,224      | 0      | 10,487  | < 1e-04  | *** |
| Gwodeg (0.1)                       | 2,397    | 0,291      | 0      | 8,221   | < 1e-04  | *** |
| Gwideg (0.1)                       | 1,502    | 0,248      | 0      | 6,055   | < 1e-04  | *** |
| education_percentage<br>(nodeicov) | -1,030   | 0,207      | 0      | -4,981  | < 1e-04  | *** |
| education_percentage<br>(nodeocov) | 0,69     | 0,179      | 0      | 3,852   | 0,000117 | *** |
| Nation (nodematch)                 | 1,706    | 0,111      | 0      | 15,353  | < 1e-04  | *** |
| SBM.2 (nodeifactor)                | 0,841    | 0,198      | 0      | 4,23    | < 1e-04  | *** |
| SBM.3 (nodeifactor)                | -2,440   | 0,155      | 0      | -15,711 | < 1e-04  | *** |
| SBM.2 (nodeofactor)                | 1,028    | 0,241      | 0      | 4,264   | < 1e-04  | *** |
| SBM.3 (nodeofactor)                | -2,119   | 0,199      | 0      | -10,646 | < 1e-04  | *** |

The table shows ERGMs results for two models. Significance code based on p-value: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

Table 4.1 shows the estimations. *Edges* refers to the number of ties in the network; it can be viewed as the intercept, as it sets the baseline density on which the other terms operate. A negative coefficient indicates a sparse network, as one would expect in real-world networks. The model indicates a positive and significant effect of mutuality (*mutual*), highlighting a tendency toward reciprocity between cities. This finding reinforces the earlier hypothesis that inventors' mobility does not merely

result in the concentration of human capital in certain cities but rather facilitates its circulation across them.

However, as previously shown, this circulation of human capital is not uniformly distributed across all cities. It is plausible to assume that certain cities benefit more from this process than others. The *gwodegree* and *gwidegree* results obtained by the model estimation further confirm this hypothesis. Both coefficients are positive and significant, indicating that the network is characterized by cities with high out-degree and high in-degree, underscoring the fundamental role of mobility hubs within the network. At the same time, the *gwodegree* coefficient is relatively higher than the *gwidegree* coefficient, suggesting that the number of cities with a high out-degree (i.e., those exporting inventors) is greater than the number of cities with a high in-degree (i.e., those importing inventors). This finding points to a hierarchical network structure in which, despite the circulation of human capital, a process of human capital drainage toward certain cities emerges.

The model also reveals a positive and significant coefficient for national similarity (*Nation*), confirming a strong tendency toward mobility within national borders.

Additionally, the model reveal significant and distinct effects of the types of institutions involved in the mobility process.

Regarding the presence of educational institutions in a city, a higher percentage of these institutions give a negative effect on the city's ability to attract inventors (*edu\_percent nodeicov*), while there is a positive probability that inventors will emigrate from the city (*edu\_percent nodeocov*).

It is important to note that this analysis does not consider all institutions present in each city, but only those that have hosted the inventors for various reasons. This makes these results even more interesting, as they reflect choices made—whether freely or constrained—by the inventors themselves, shaping the characteristics of these cities.

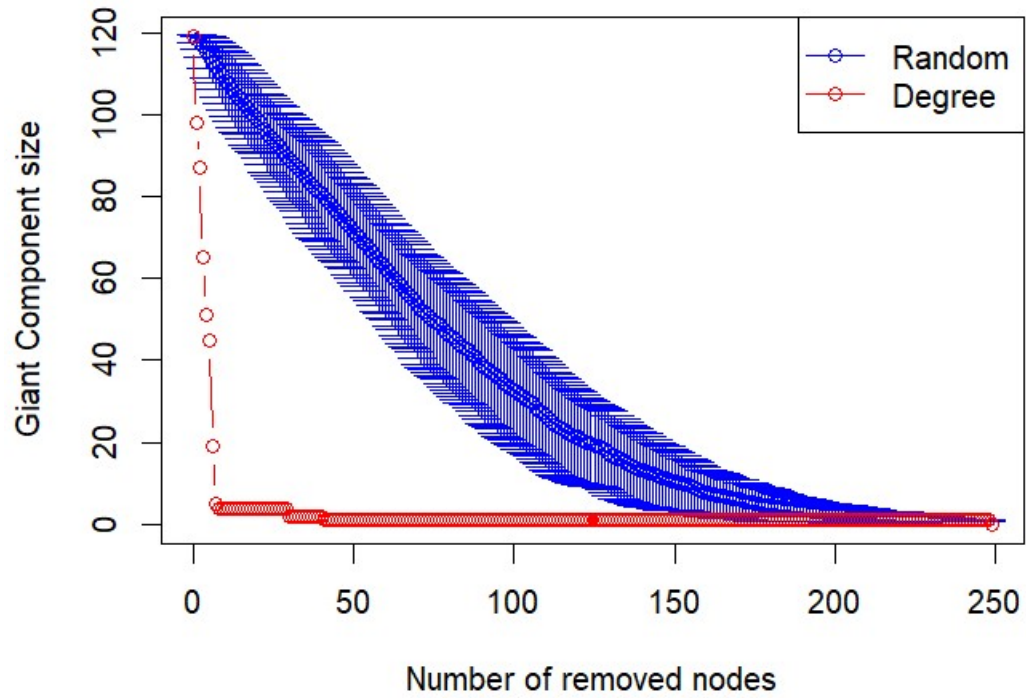
#### 4.4.3 Resilience and vulnerability to shocks

It is well known that scale-free networks, such as the one analyzed in this study, have the ability to self-organize and thus withstand the random removal of nodes while being highly vulnerable to targeted removal of specific nodes. This is particularly relevant in the context of the inventors' mobility network, as it allows us to understand how the network reacts to exogenous or endogenous shocks affecting the cities involved in the process and on which cities the network is most dependent. Here are showed the results of simulations representing such shocks, modelled according to the removal strategies previously described.

First, the hypothesis of network robustness to random node removal is confirmed. Both the giant component and global efficiency—particularly the latter—decrease gradually as nodes are sequentially and randomly removed. At the same time, the network proves to be highly vulnerable to targeted attacks, particularly on high-degree cities (hubs). The removal of these hubs causes a rapid collapse in both the size of the giant component and global efficiency (Figure 4.8-4.9).

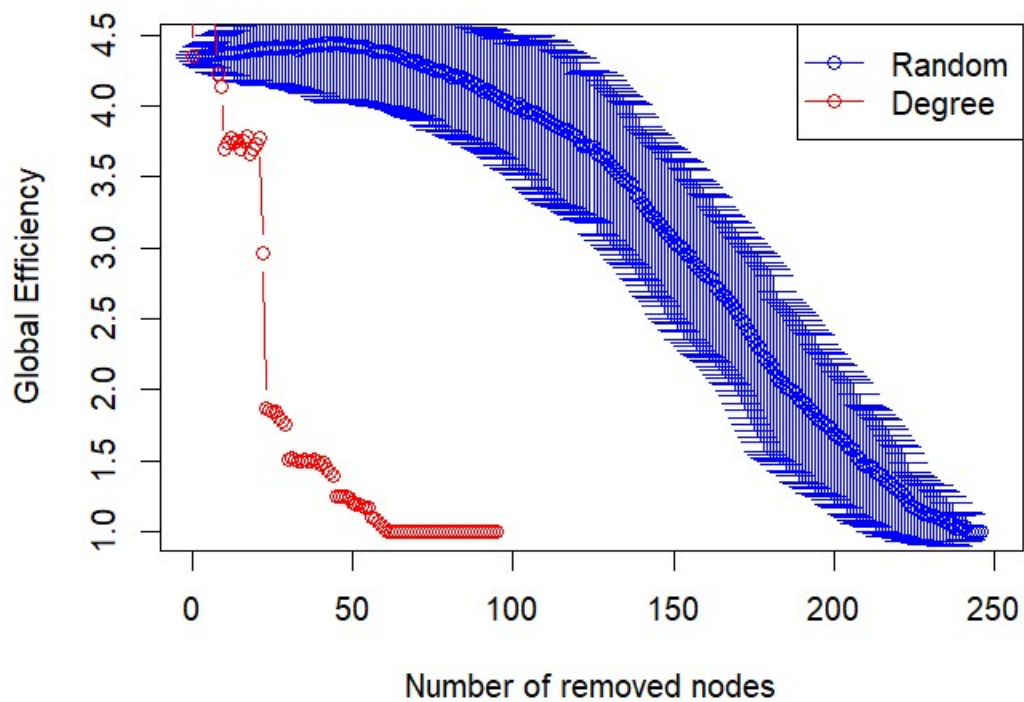


Figure 4.8 Robustness on Giant Component Size



This figure examines the effect of **random node removal** (blue) versus **degree-based removal** (red) on Giant Component Size.

Figure 4.9 Robustness on Global Efficiency



This figure examines the effect of **random node removal** (blue) versus **degree-based removal** (red) on Global Efficiency

This result becomes even more evident when nodes are removed based on their polarization index, which distinguishes between net importers and net exporters of human capital (Figure 4.13 in

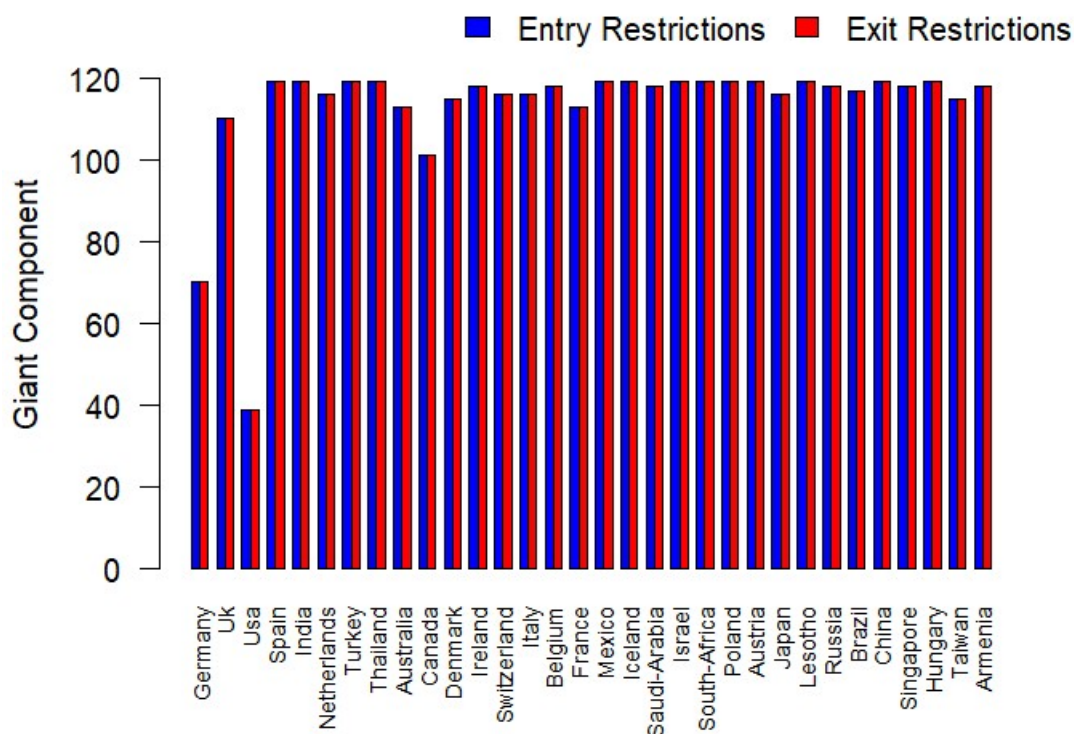
Appendix B). The network is found to be highly resilient to the removal of cities that primarily export human capital, whereas cities that import it most are far more relevant to the network's structure. This further confirms the previous findings and raises additional concerns about the unequal manner in which shocks may be addressed.

The role of institutions in cities has already been shown to be crucial for attracting or losing inventors. Here, the simulations aim to assess whether a higher presence of educational or work institutions, and further distinguishing between public and private institutions, affects a city vulnerability. In other words, the simulations investigate whether certain types of cities are more critical in the mobility network.

The results (Figure 4.14-4.15 in Appendix B) indicate that while the removal of nodes characterized by private and work institutions has a more pronounced effect, this effect cannot be considered significant. Instead, what stands out is the drastic decline that occurs when nodes with a balanced combination of different institutions are removed.

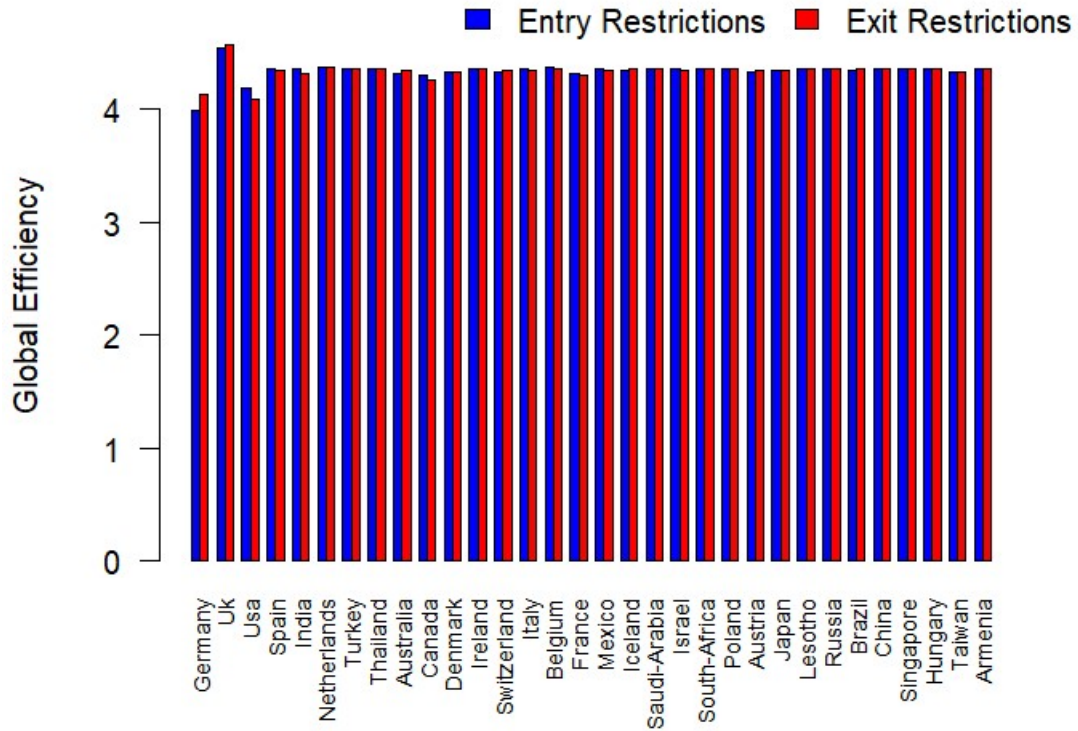
Finally, the analysis of the impact of national restrictions suggests that both inbound and outbound mobility limitations have similar effects on the inventor mobility network (Figure 4.10). Notably, most countries' restrictions do not significantly affect the size of the giant component, with the exception of the United States, Germany, and to some extent Canada, as these countries host the major innovation hubs. Regarding global efficiency (Figure 4.11), the impact of restrictions remains minimal, even when considering the aforementioned countries. This finding highlights a network structure in which, even if all cities in a certain country are removed, and even if those are currently highly central, the mobility network can self-organize into an alternative structure that maintains the same level of efficiency. This is possible because alternative pathways connecting cities through inventors already exist within the network.

Figure 4.10 Impact of National Restrictions on Giant Component



The bar chart compares the size of the giant component under entry restrictions (blue) and exit restrictions (red) for all countries involved.

Figure 4.11 Impact of National Restrictions on Global Efficiency



The bar chart compares the global efficiency under entry restrictions (blue) and exit restrictions (red) for all countries involved.

In summary, the inventor mobility network appears to be robust to random shocks while simultaneously exhibiting a strong dependence on a few key cities (hubs), raising concerns about the potential for this configuration to reinforce existing spatial inequalities. Nevertheless, the analysis also highlights the importance of an equilibrated institutional composition in cities, which enhances their relevance within the network.

#### 4.4.4 Link prediction

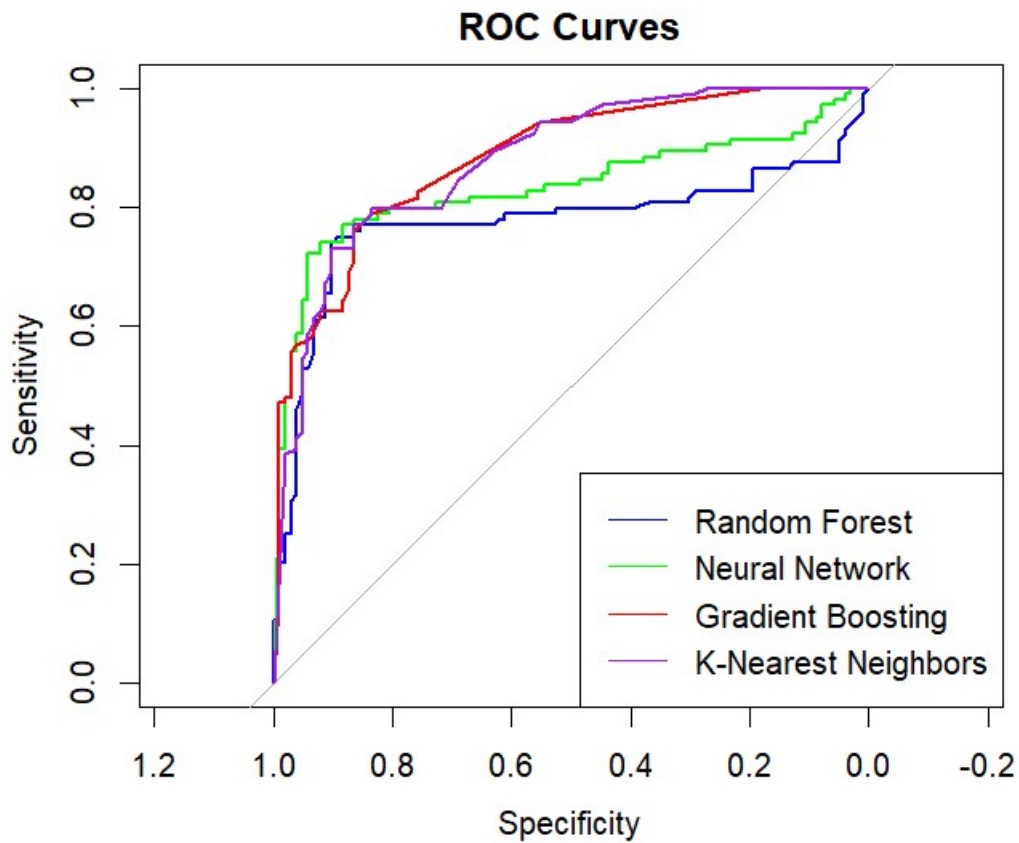
The training of machine learning models to understand the effect of network topology on mobility has yielded positive results (Table 4.2). All models exhibit an accuracy above 80%, meaning that more than 80% of predictions are correct across the dataset. The models also perform well in terms of precision, considering the possibility of random predictions; indeed, Cohen's kappa values are all above 0.6. The results further indicate a strong ability of the models to identify true positives and true negatives. The McNemar's Test P-Value suggests that only the random forest model shows a statistically significant difference compared to other models, which otherwise exhibit similar performance. Based on this, gradient boosting was selected as the preferred model, as it achieved the highest AUC (area under the curve) value, as highlighted by the Receiver Operating Characteristic (ROC) curves (Figure 4.12), indicating its superior ability to discriminate between positive and negative classes.

Table 4.3 Link Prediction Models' Performance

|                        | Random Forest | Neural Network | Gradient Boosting (GBM) | K-Nearest Neighbors |
|------------------------|---------------|----------------|-------------------------|---------------------|
| Accuracy (%)           | 81.640        | 81.640         | 80.680                  | 81.640              |
| Kappa                  | 0.633         | 0.633          | 0.614                   | 0.633               |
| Balanced Accuracy (%)  | 81.680        | 81.660         | 80.700                  | 81.670              |
| Sensitivity            | 0.893         | 0.854          | 0.864                   | 0.864               |
| Specificity            | 0.740         | 0.779          | 0.750                   | 0.769               |
| Pos Pred Value         | 0.773         | 0.793          | 0.774                   | 0.788               |
| Neg Pred Value         | 0.875         | 0.844          | 0.848                   | 0.851               |
| AUC                    | 0.774         | 0.834          | 0.884                   | 0.880               |
| Mcnemar's Test P-Value | 0.015         | 0.256          | 0.082                   | 0.144               |

The table compares the performance of different machine learning models (Random Forest, Neural Network, Gradient Boosting, and K-Nearest Neighbors) for link prediction.

Figure 4.12 ROC Curves



The Receiver Operating Characteristic (ROC) curves illustrate the trade-off between sensitivity and specificity for different models.

The model was subsequently used to predict links that would be added to the original network if they had a probability exceeding 80%.

The comparison between the original network and the network with the predicted links (Table 4.3) reveals noteworthy characteristics. Naturally, the differences are subtle due to the limited number of

accurately predicted links, but analyzing the variations in network metrics provides valuable insights into the direction the network is evolving compared to its original state.

*Table 4.4 Networks Comparison*

| <b>Metric</b>              | <b>Original Network</b> | <b>Network with Predictions</b> |
|----------------------------|-------------------------|---------------------------------|
| Density                    | 0.008                   | 0.010                           |
| Diameter                   | 11.000                  | 11.000                          |
| Transitivity               | 0.062                   | 0.064                           |
| Average Degree             | 4.209                   | 4.763                           |
| Assortativity              | -0.006                  | -0.051                          |
| Average Path Length        | 4.357                   | 4.304                           |
| Degree Centralization      | 0.196                   | 0.251                           |
| Betweenness Centralization | 0.245                   | 0.241                           |
| Eigen Centralization       | 0.983                   | 0.983                           |

*The table presents structural differences between the original network and the network with predicted links.*

First, an increase in network density is observed, indicating that the new connections—and therefore the new movements of inventors between cities—are not merely redundant but instead create novel pathways that were absent in the original network. Additional metrics provide further insights into the nature of these new connections. Specifically, there is a reduction in assortativity, meaning that the newly formed connections occur more frequently between nodes with differing degrees. In other words, inventor mobility increasingly links hubs to peripheral cities compared to the initial configuration. The directionality of these connections likely favors hubs, as shown by the increase in their indegree (Table 4.6 in Appendix B), indicating a higher inflow of inventors into these cities. As a result, the network becomes more centralized, as evidenced by the increase in degree centralization (from 0.196 to 0.251). This further reinforces the conclusions drawn in the previous section regarding the implications of a network highly vulnerable to shocks affecting central nodes, specifically, the hubs.

Another significant finding is the reduction in betweenness centralization, suggesting that intermediary nodes facilitating inventor mobility now play a less critical role. This aligns with the observation that inventors can now move directly to hubs without passing through intermediate cities, reducing overall spatial knowledge transfer. These results are further supported by the increase in transitivity and the decrease in average path length. While these changes make the network more efficient, they simultaneously exacerbate spatial disparities by limiting knowledge diffusion among cities and instead directing it straight to the hubs.

## 4.5 Discussion

The results of the community analysis highlighted the complexity of the geography shaped by inventors' mobility and revealed spatial patterns that deserve further investigation. First, the stochastic block model showed that hubs tend to play similar roles, contributing to the formation of a centralized network characterized by a strong exchange of intellectual resources among them. This finding already suggests that inventors' mobility throughout their careers cannot be reduced to the mere concentration of human capital in hubs, nor can these hubs be viewed simply as accumulators of resources aimed at fostering innovation. Instead, the role of hubs is not only to attract human capital but also to facilitate its circulation, both toward other hubs and toward peripheral cities. What likely distinguishes hubs from peripheral cities in terms of mobility is the number of inventors who "pass through" and/or "return" to them. This dynamic flow of inventors—and consequently of knowledge—could have a greater impact on innovative capacity than mere accumulation.

At the same time, the communities identified through the Leiden algorithm displayed a high density of connections within national borders, along with a relative balance in the types of institutions involved, whether public or private, educational or work-related. This is a particularly interesting result, as it highlights the importance of intranational mobility, which is often overlooked but plays a crucial role in forming geographically dense structures compared to external density. Indeed, these communities of cities—strongly interconnected, especially through intranational mobility—and exhibiting a balanced composition of public versus private and education-oriented versus work-oriented institutions, suggest a distinctive role for this type of mobility: connecting different kinds of institutions by bringing them into contact with one another.

Furthermore, Infomap identifies a large community that includes the main innovation hubs, which are thus able to generate an extensive subnetwork of knowledge transfer, whereas for peripheral cities, this remains limited. This results in a fundamental distinction between hubs and peripheral cities: hubs are not only more involved in knowledge circulation, but this circulation also affects a significantly larger number of cities, whereas knowledge exchanges in peripheral cities remain highly constrained.

The analysis conducted on communities' detection demonstrates that inventors' mobility generates geographies that go beyond the mere accumulation of human capital in hubs. Instead, the process appears to be more dynamic, involving multiple cities that facilitate human capital circulation and enable continuous knowledge transfer. However, a clear disparity between core and peripheral cities also emerges: peripheral cities experience a much more limited diversity of knowledge flows brought by mobile inventors. Finally, this analysis underscores the need to further investigate the role of intranational mobility, particularly in its ability to connect different institutions within the same national context.

The results were confirmed and further explored through the estimation of ERGMs. What emerged is a strong mutuality within the network generated by inventors, which facilitates the circulation of knowledge between cities. However, this circulation is not evenly distributed; instead, it tends to favor certain cities, creating key hubs for the movement of inventors and, consequently, for knowledge flows. This spatial disparity becomes even more apparent when considering the institutional factors that contribute to it. In particular, the analysis showed that cities primarily chosen by inventors for educational purposes are more likely to experience a loss of human capital rather than a gain, underscoring the need for a spatial balance between education and employment opportunities.

Moreover, the simulations on the network's robustness and vulnerability confirmed the typical hypothesis concerning complex networks and their capacity for self-organization. This finding highlights the strong dependence of the inventors' mobility network on its hubs. In contrast, when the shock affects the network randomly, no significant effects are observed. These results underscore the

fact that knowledge circulation remains highly centralized. Since the efficiency of this network depends on its hubs, we can expect that more resources will be allocated by policy-makers to prevent or mitigate shocks affecting these cities rather than others, thereby exacerbating regional inequality. The simulations also suggested that hubs are likely perceived by inventors as offering a greater institutional balance. This reinforces the idea that different institutions—far from being in competition or hierarchically superior to one another—prove to be complementary and indispensable. Previous analyses have demonstrated that this complementarity is sought at the national level through intranational mobility; now, it is evident that a balanced institutional composition characterizes the nodes that sustain the network's efficiency and connectivity.

This, combined with the fact that, as shown, imposing entry or exit restrictions on inventors does not undermine the efficiency of the network but at most may reduce its size, presents a policy opportunity: addressing inequality by fostering institutional balance in cities, rather than implementing mobility restrictions. As demonstrated, such restrictions would be counterproductive for those implementing them, but would not impact network efficiency, making them ineffective from a global perspective.

Finally, link prediction shown how inventors' mobility tends to co-evolve with the very geography it helps to produce. The analysis suggests that mobility, and the geography it generates, intensifies the centralization of the system and its dependence on hubs. While greater efficiency may enable a faster and more direct transfer of inventors and expertise to major innovation centers, it risks amplifying regional disparities, limiting opportunities for other cities to benefit from knowledge flows. Furthermore, as discussed in previous sections, innovation may depend more on the circulation of human capital rather than its mere concentration in hubs. If mobility between cities were to decline in favor of greater centralization in key innovation centers, the innovation process itself could be jeopardized. The dynamism and exchange of knowledge across territories are crucial elements for generating new ideas and disseminating skills. A mobility pattern increasingly focused on reaching hubs could hinder these processes, potentially leading to negative consequences for overall innovative capacity.

## 4.6 Conclusions

The analysis conducted has allowed to identify the complex geography emerging from the mobility of key inventors who contributed to the development of the mRNA-based COVID-19 vaccine. This geography follows a core-periphery pattern, where a few hubs concentrate the majority of inventors movements, while peripheral cities remain relatively less dynamic. This finding helps clarify the seemingly contrasting positions in the theoretical background, where mobility is seen both as a driver of knowledge diffusion across space (Breschi & Lissoni, 2009) and as a mechanism reinforcing the concentration of human capital (Kerr et al., 2016). Results of this study suggest that, given the complexity of the phenomenon, these two perspectives are not contradictory but rather complementary. Mobility does generate knowledge circulation, but this circulation gravitates around hubs, making human capital accumulation a more dynamic process. The hubs, in turn, facilitate knowledge exchange, which translates into higher innovative productivity (Pellegrino et al., 2023). This higher productivity is further reinforced when human capital circulates across different institutions (Cappelli et al., 2019). In particular, intranational mobility not only plays a crucial role in creating connections between cities, but it also fosters a balanced involvement of public and private institutions and improves the match between education and employment. This balance is essential at the aggregate level, but it is also a defining characteristic of innovative hubs. The absence of such equilibrium reduces a city relevance within the mobility network and leads to a loss of human capital when the institutional landscape is skewed toward either educational or public institutions.



The complex nature of the mobility network analyzed also highlights its self-organizing capacity, which results in resilience to random shocks but heightened vulnerability when shocks target the hubs. This poses a spatial inequality problem that goes beyond the mere unequal distribution of innovative activity. The network's strong dependence on hubs grants them significant power over peripheral cities, whose mobility policies become largely inconsequential. The increasing importance of hubs could also lead policymakers to grant them privileged treatment—as is already the case—thereby exacerbating spatial inequalities and further limiting efforts to address them.

Achieving greater spatial equality faces an additional challenge: the geography generated by inventors' mobility. The spatial topology of the network further reinforces the attractiveness of hubs, making them the primary destination for inventors while reducing the involvement of other cities. This trend not only exacerbates regional disparities but, as discussed earlier, could also hinder the dynamics of human capital circulation and exchange, ultimately reducing innovative productivity.

This study has several limitations that should be addressed for a more comprehensive and robust understanding of the phenomenon. First, due to the self-reported nature of the data, it was not possible to incorporate a temporal dimension, which is crucial for capturing the dynamics of mobility and could alter the weight assigned to different cities over time. Additionally, the study only focusses on the final-stage inventors involved in the vaccine development process, limiting the scope to the final phase of an otherwise complex innovation process. Finally, while the study highlights the role of intranational mobility, further research is needed to fully understand how this type of mobility contributes to innovation differently.

These limitations can and should be addressed through a more detailed integration of temporal data, a broader analysis encompassing the entire innovation process, and a deeper investigation of intraregional mobility. Overcoming these challenges would enhance our understanding of the phenomenon and provide policymakers with better tools to foster a more equitable innovation process.

In the next chapter, some of these limitations will already be overcome through the analysis of the entire innovation process that led to the development of the vaccines, a process that unfolded over roughly sixty years.



## 4.7 Appendix A

Table 4.5 SBM Communities Degree Attributes

| Community | Nodes | Edges | Weighted Indegree | Weighted Outdegree | In-Out Ratio | Normalized Ratio |
|-----------|-------|-------|-------------------|--------------------|--------------|------------------|
| 1         | 8     | 11    | 99                | 141                | 0,70         | 0,08             |
| 2         | 2     | 0     | 71                | 90                 | 0,78         | 0,39             |
| 3         | 239   | 204   | 354               | 293                | 1,20         | 0,005            |

The table summarizes the degree metrics of communities detected using the Stochastic Block Model. Weighted indegree and outdegree represent the number of inbound and outbound connections, In-Out Ratio is the ratio between them, Normalized Ratio is the previous ratio weighted by the number of nodes.

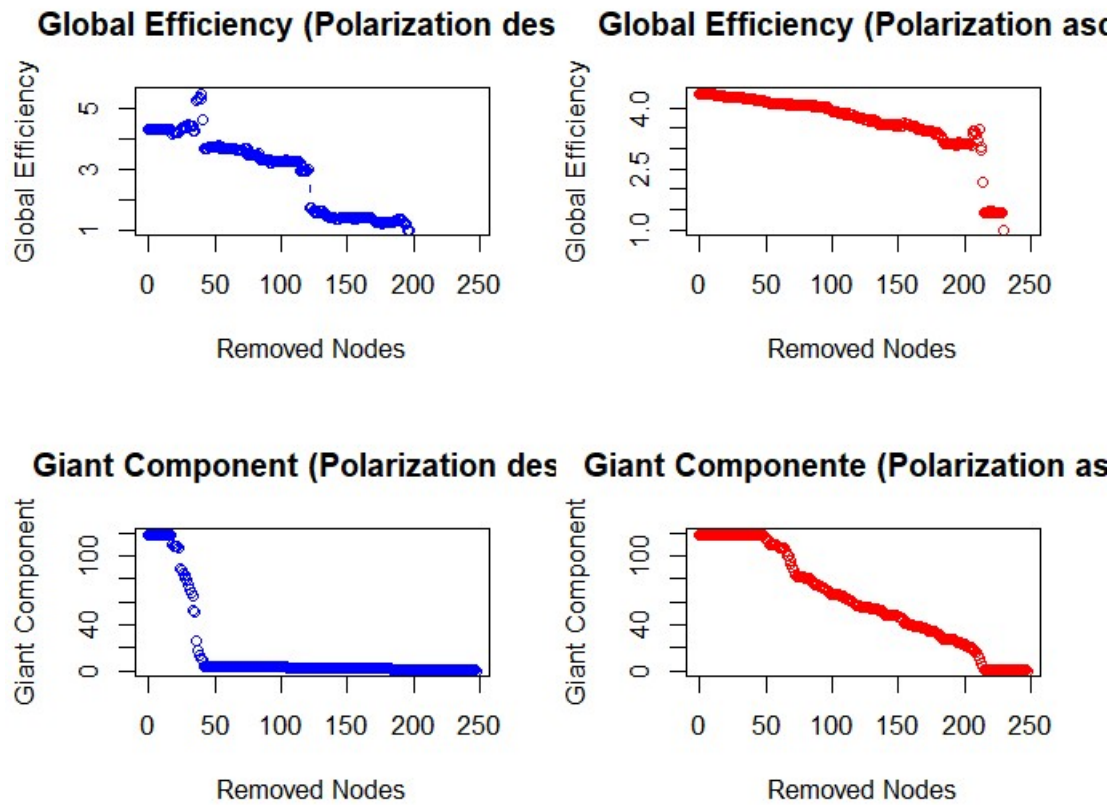
Table 4.6 Leiden Communities Attributes

| Community | Number of Countries | Biggest Country Frequency | Average Education Percentage | Average Public Percentage |
|-----------|---------------------|---------------------------|------------------------------|---------------------------|
| 1         | 15                  | 0,62                      | 0,39                         | 0,69                      |
| 2         | 13                  | 0,66                      | 0,32                         | 0,37                      |
| 3         | 1                   | 1                         | 0,37                         | 0,5                       |
| 4         | 3                   | 0,5                       | 0,39                         | 0,84                      |
| 5         | 6                   | 0,38                      | 0,64                         | 0,74                      |
| 6         | 10                  | 0,32                      | 0,37                         | 0,5                       |
| 7         | 2                   | 0,88                      | 0,39                         | 0,31                      |
| 8         | 3                   | 0,5                       | 0,5                          | 0,68                      |
| 9         | 5                   | 0,33                      | 0,42                         | 0,61                      |
| 10        | 1                   | 1                         | 0,5                          | 0,5                       |
| 11        | 1                   | 1                         | 0,5                          | 0,6                       |
| 12        | 5                   | 0,74                      | 0,38                         | 0,48                      |
| 13        | 2                   | 0,66                      | 0                            | 0                         |
| 14        | 3                   | 0,5                       | 0,44                         | 0,58                      |
| 15        | 2                   | 0,5                       | 0,5                          | 0                         |
| 16        | 2                   | 0,66                      | 0,66                         | 0,66                      |
| 17        | 1                   | 1                         | 0,5                          | 1                         |
| 18        | 1                   | 1                         | 0                            | 0                         |

The table summarizes attributes of communities detected using the Leiden algorithm. Biggest Country Frequency is the percentage of nodes belonging to the most prominent country of the community, Average Education and Public percentage is the average of the node's percentage of the community.

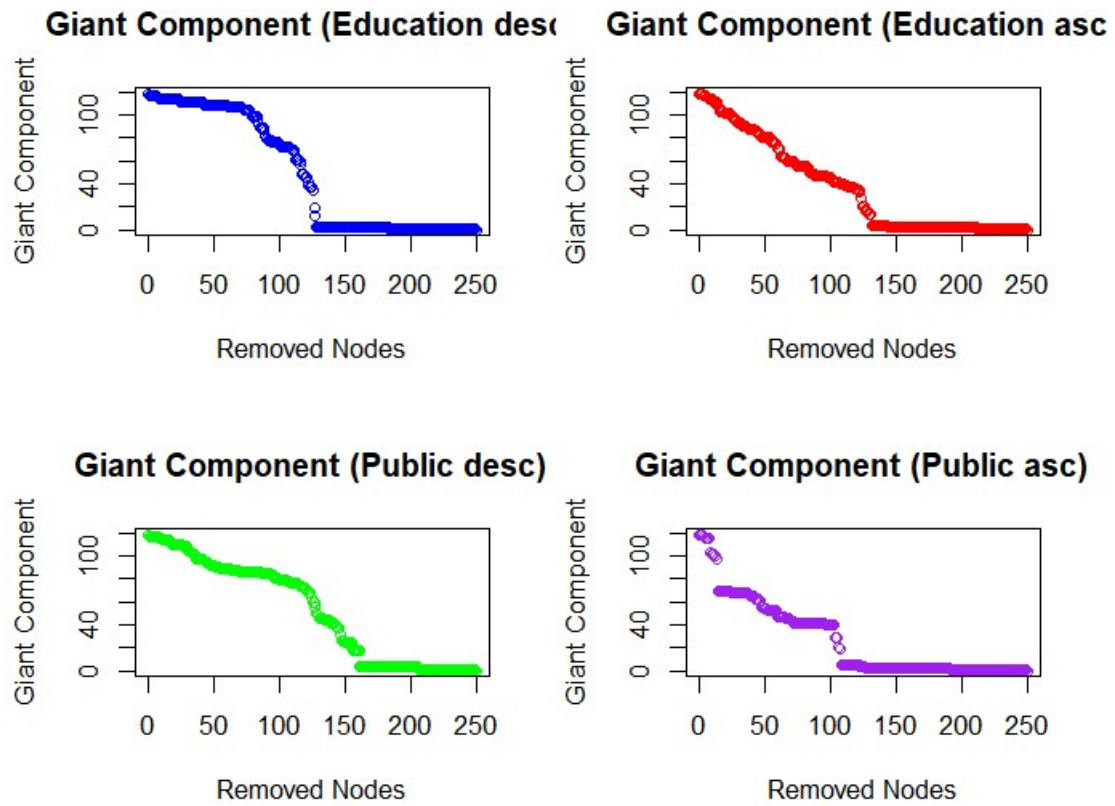
## 4.8 Appendix B

Figure 4.13 Robustness based on Polarization



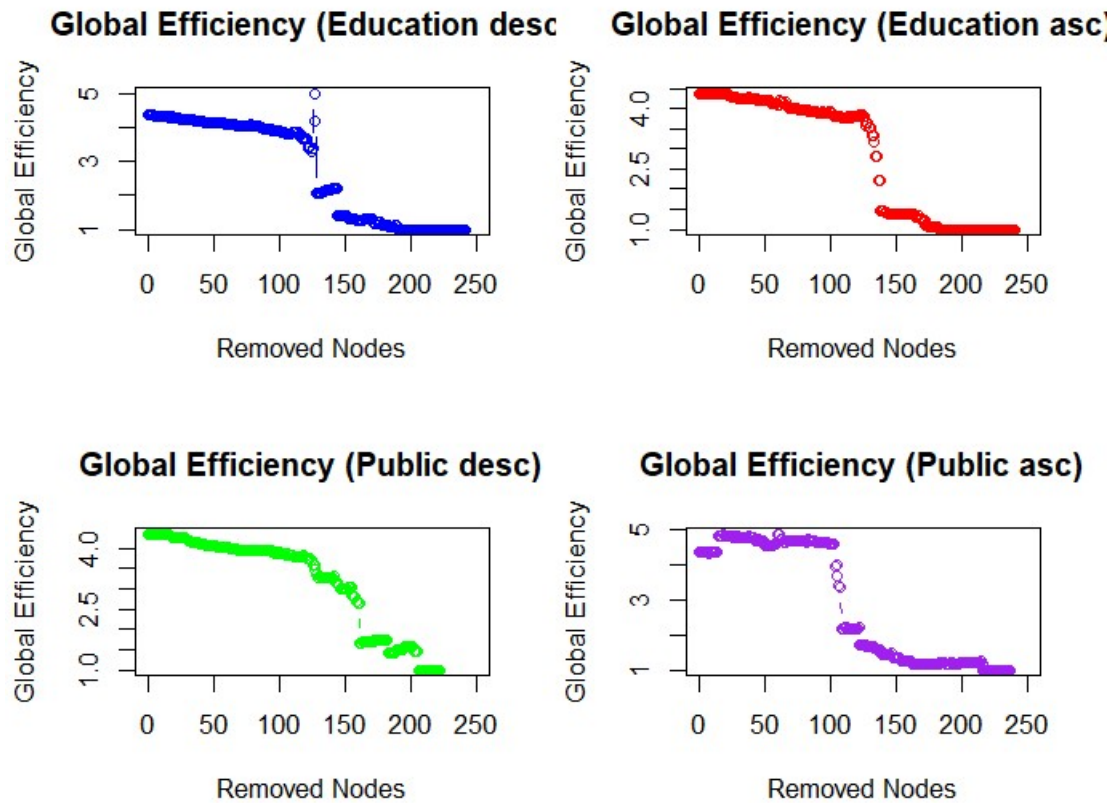
Plots explore how the giant component size (below) and global efficiency (above) change when nodes are removed based on the polarization index, either in descending (blue) or ascending (red) order.

Figure 4.14 Robustness of Giant Component based on Attributes



Plots track the decline of the giant component size as nodes associated with education (above) or public (below) institutions are removed in descending (left) or ascending (right) order.

Figure 4.15 Robustness of Global Efficiency based on Attributes



Plots track the decline in global efficiency as nodes associated with education (above) or public (below) institutions are removed in descending (left) or ascending (right) order.

Table 4.7 First Ten Cities per Indegree and Outdegree

| Node                                | Indegree Original | Node                                | Indegree with Predictions | Node                                | Outdegree Original | Node                                | Outdegree with Predictions |
|-------------------------------------|-------------------|-------------------------------------|---------------------------|-------------------------------------|--------------------|-------------------------------------|----------------------------|
| Cambridge, Massachusetts, USA       | 56                | Cambridge, Massachusetts, USA       | 75                        | Cambridge, Massachusetts, USA       | 45                 | Cambridge, Massachusetts, USA       | 54                         |
| Vancouver, British Columbia, Canada | 34                | Vancouver, British Columbia, Canada | 41                        | Vancouver, British Columbia, Canada | 26                 | Vancouver, British Columbia, Canada | 30                         |
| Tubingen, Germany                   | 30                | Tubingen, Germany                   | 40                        | Boston, Massachusetts, USA          | 22                 | Boston, Massachusetts, USA          | 28                         |
| Boston, Massachusetts, USA          | 27                | Boston, Massachusetts, USA          | 30                        | Tubingen, Germany                   | 16                 | Tubingen, Germany                   | 18                         |
| Mainz, Germany                      | 19                | Mainz, Germany                      | 21                        | Burnaby, British Columbia, Canada   | 15                 | Burnaby, British Columbia, Canada   | 16                         |

|                                            |    |                                            |    |                                     |    |                                     |    |
|--------------------------------------------|----|--------------------------------------------|----|-------------------------------------|----|-------------------------------------|----|
| Burnaby,<br>British<br>Columbia,<br>Canada | 18 | Burnaby,<br>British<br>Columbia,<br>Canada | 19 | San Francisco,<br>California, USA   | 12 | New York, New<br>York, USA          | 14 |
| San Diego,<br>California, USA              | 15 | San Francisco,<br>California, USA          | 17 | New York, New<br>York, USA          | 11 | San Francisco,<br>California, USA   | 13 |
| San Francisco,<br>California, USA          | 13 | San Diego,<br>California, USA              | 15 | San Diego,<br>California, USA       | 10 | San Diego,<br>California, USA       | 11 |
| New York, New<br>York, USA                 | 11 | New York, New<br>York, USA                 | 13 | London, UK                          | 8  | London, UK                          | 9  |
| Lexington,<br>Massachusetts,<br>USA        | 8  | Lexington,<br>Massachusetts,<br>USA        | 9  | Lexington,<br>Massachusetts,<br>USA | 7  | Lexington,<br>Massachusetts,<br>USA | 8  |

*The table presents the comparison between indegree (left) and outdegree (right) of the original network and the network with predicted links of the first ten cities.*

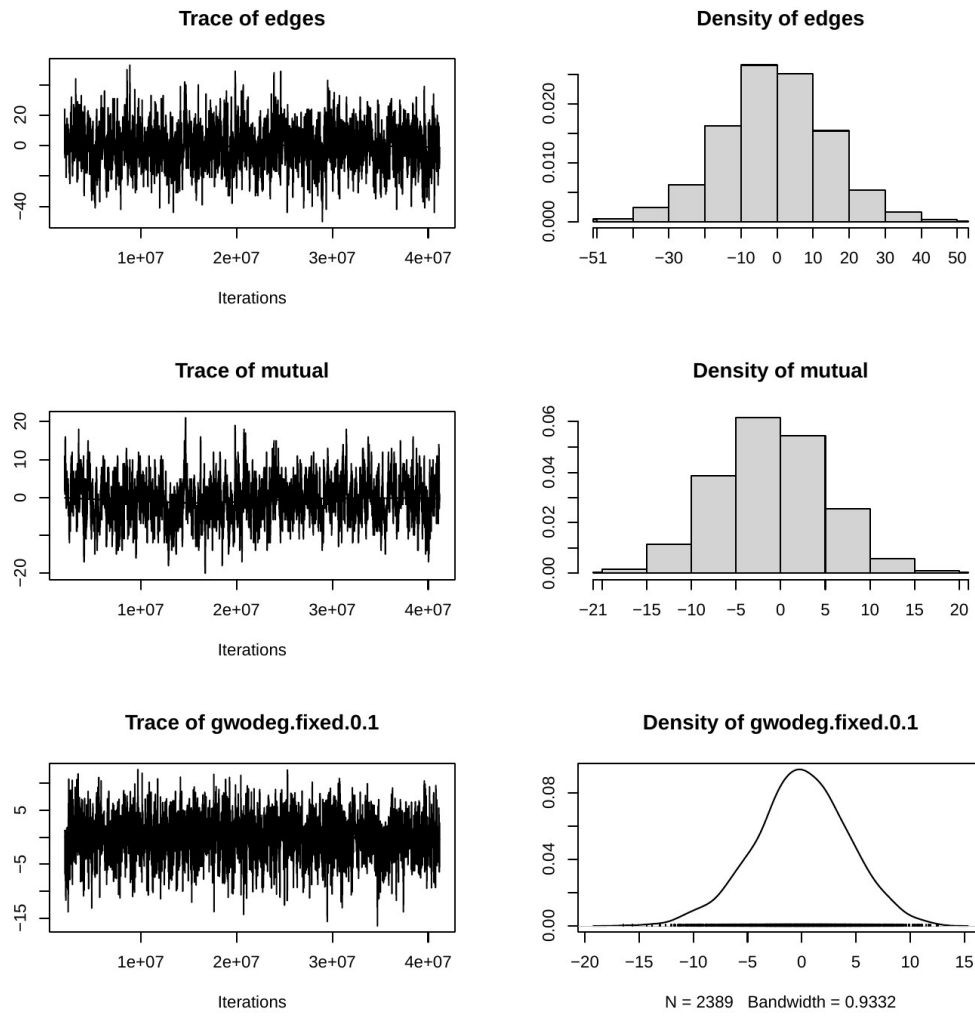
## 4.9 Appendix C

*Table 4.8 ERGMs Models Comparison*

|        | AIC  | BIC  |
|--------|------|------|
| Model1 | 4021 | 4120 |
| Model2 | 4043 | 4143 |
| Model3 | 3978 | 4078 |
| Model4 | 4002 | 4102 |

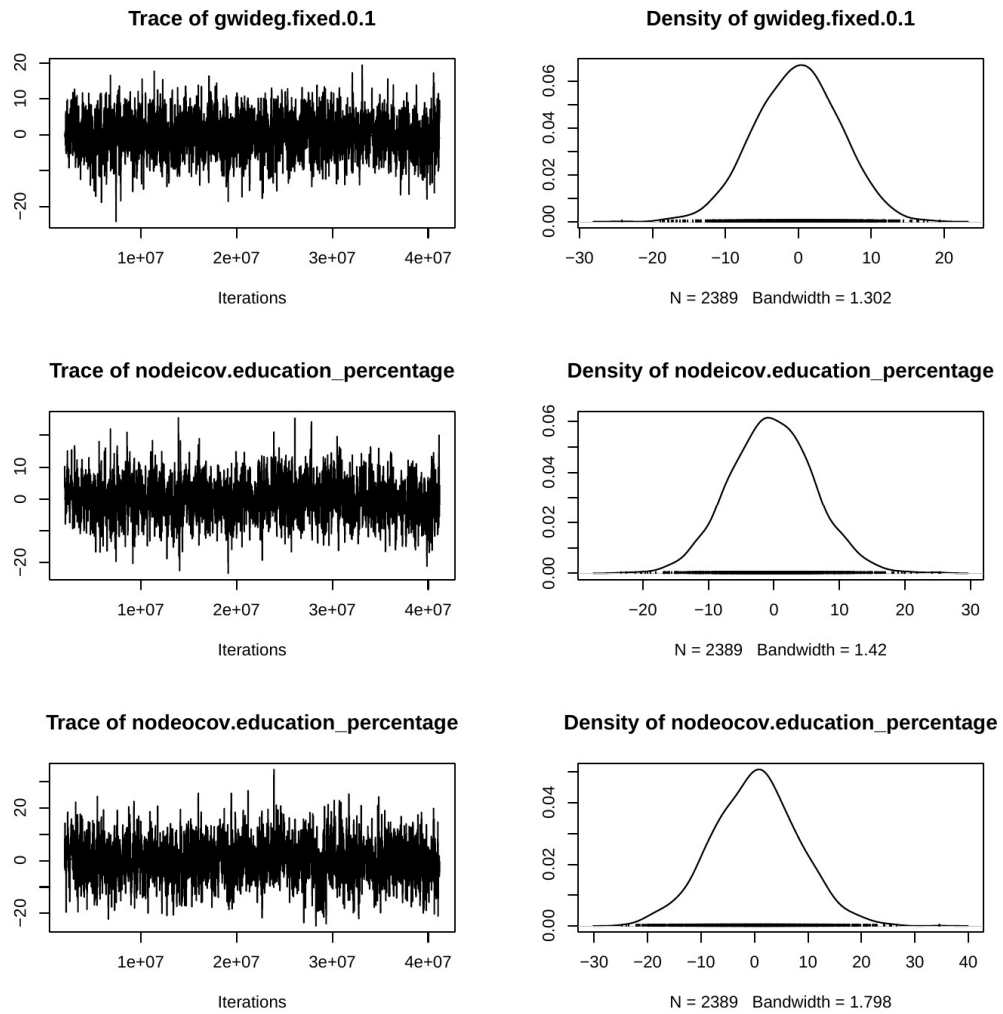
*Model 1 and Model 2 set the decay parameter of the geometrically weighted degree terms at 0.5, whereas Model 3 and Model 4 set it at 0.1. Model 1 and Model 3 estimate the effect of the share of education-oriented institutions involved, while Model 2 and Model 4 focus on those of a public nature.*

Figure 4.16 MCMC Diagnostics for edges, mutual and gwodeg



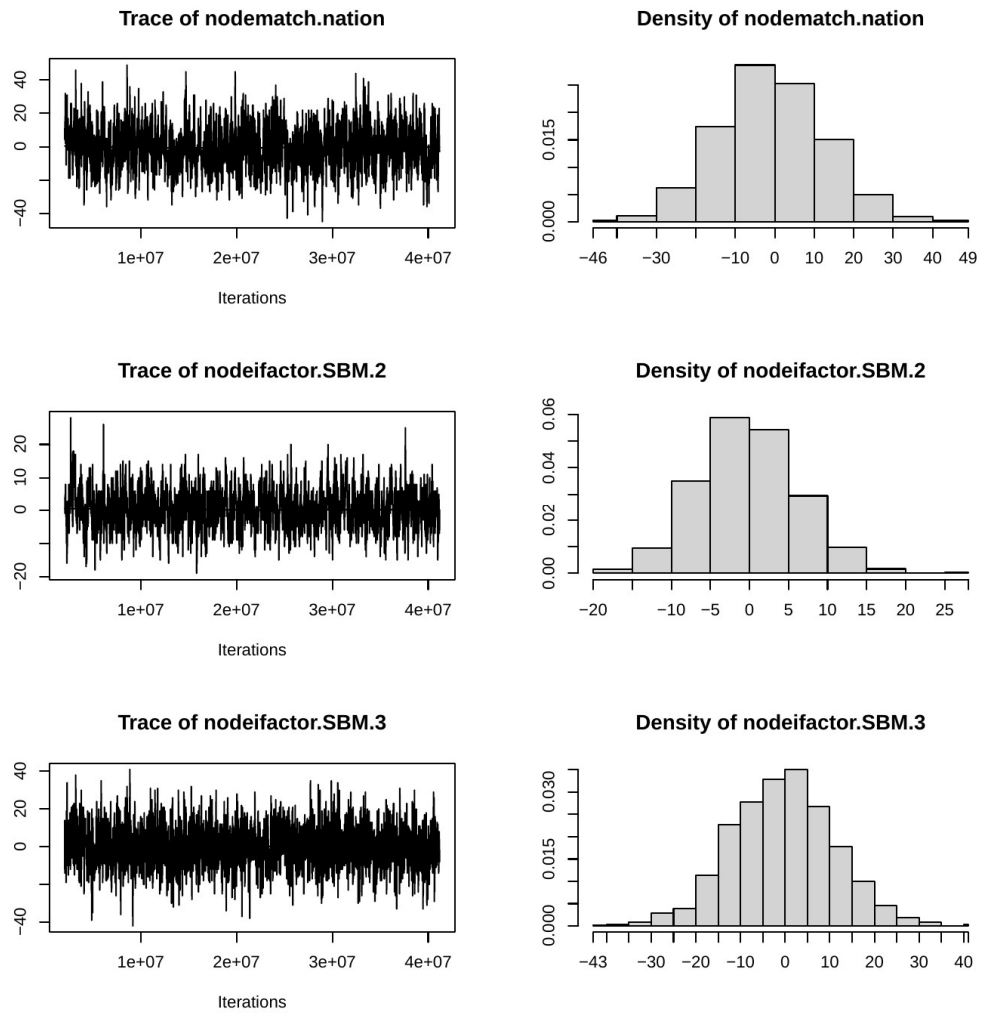
The figure shows the stability of the estimated parameters in the simulations for the variables edges, mutual, gwodeg

Figure 4.17 MCMC Diagnostics for gwideg and education\_percentage



The figure shows the stability of the estimated parameters in the simulations for the variables `gwideg` and `education_percentage`

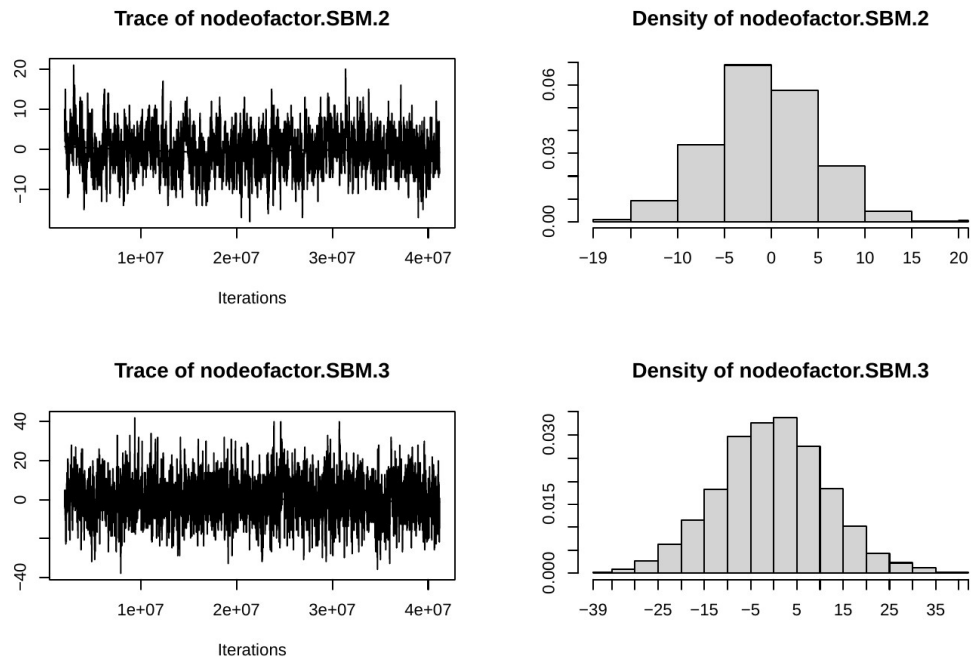
Figure 4.18 MCMC Diagnostics for nation, SBM.2 and SBM.3 inflow



The figure shows the stability of the estimated parameters in the simulations for the variables nation, SBM.2 and SBM.3 inflow

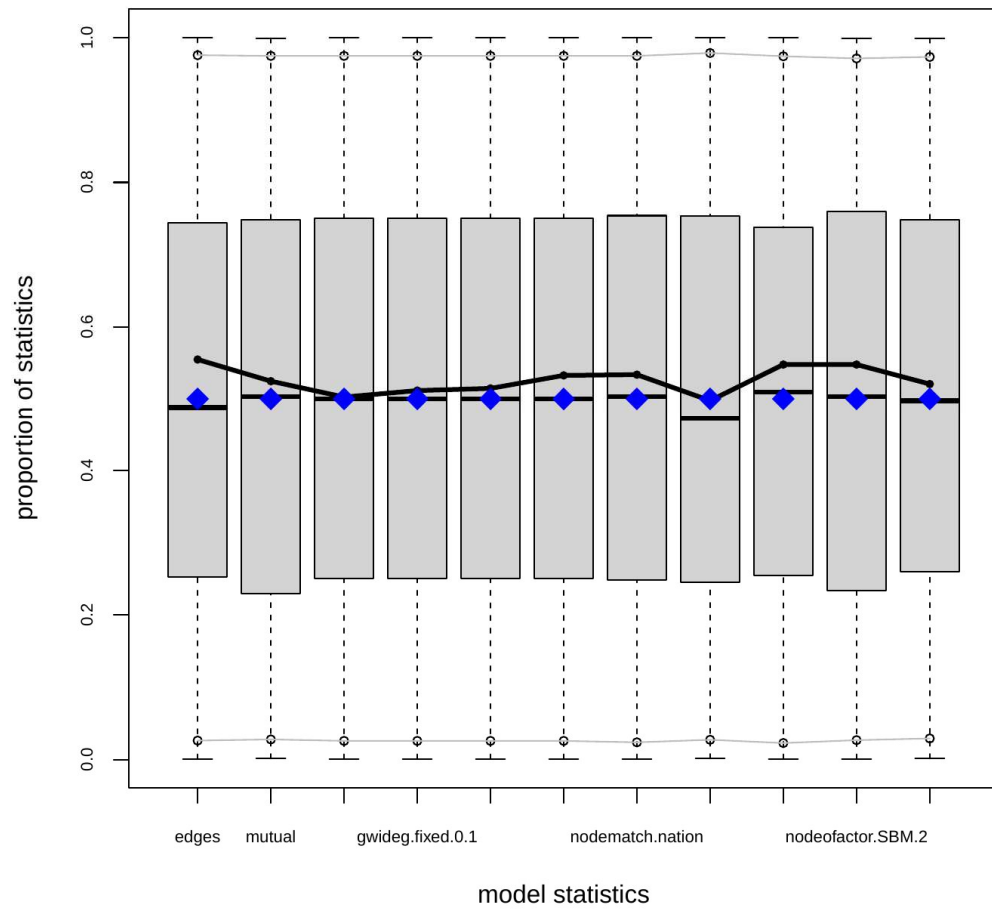


Figure 4.19 MCMC Diagnostics for SBM.2 and SBM.3 outflow



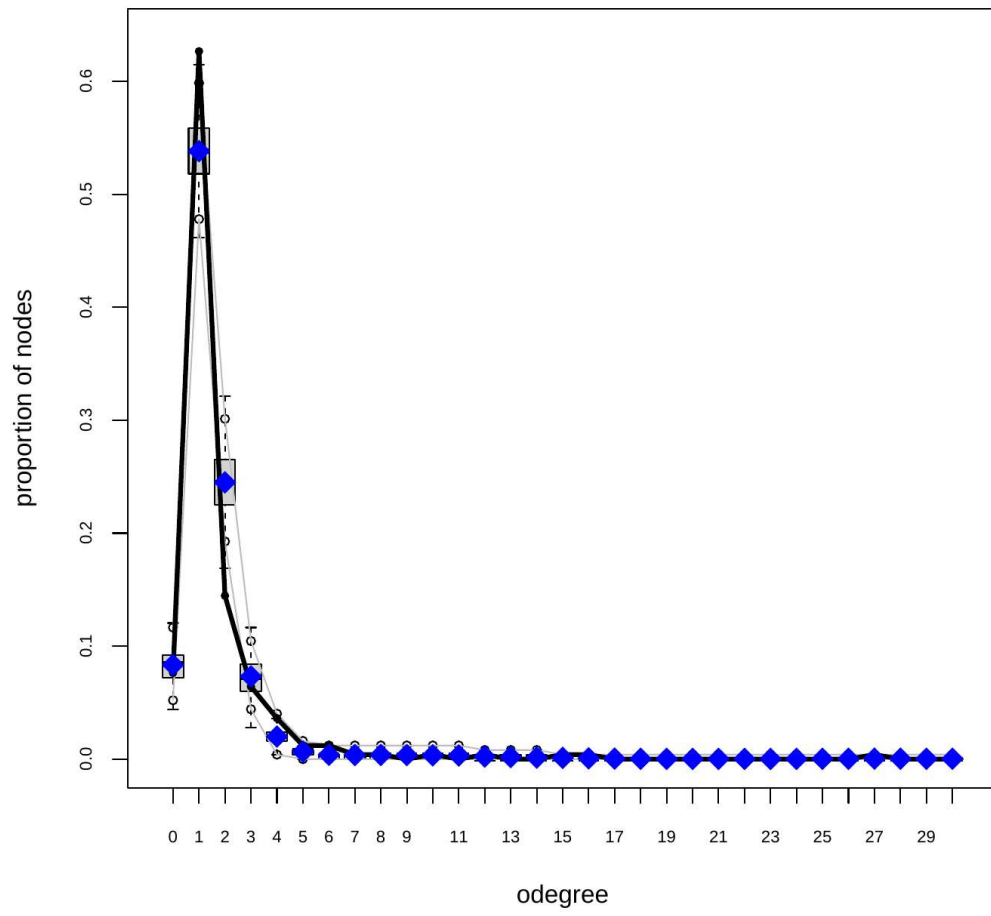
The figure shows the stability of the estimated parameters in the simulations for the variables SBM.2 and SBM.3 outflow

Figure 4.20 Model statistics comparison between real network and simulations



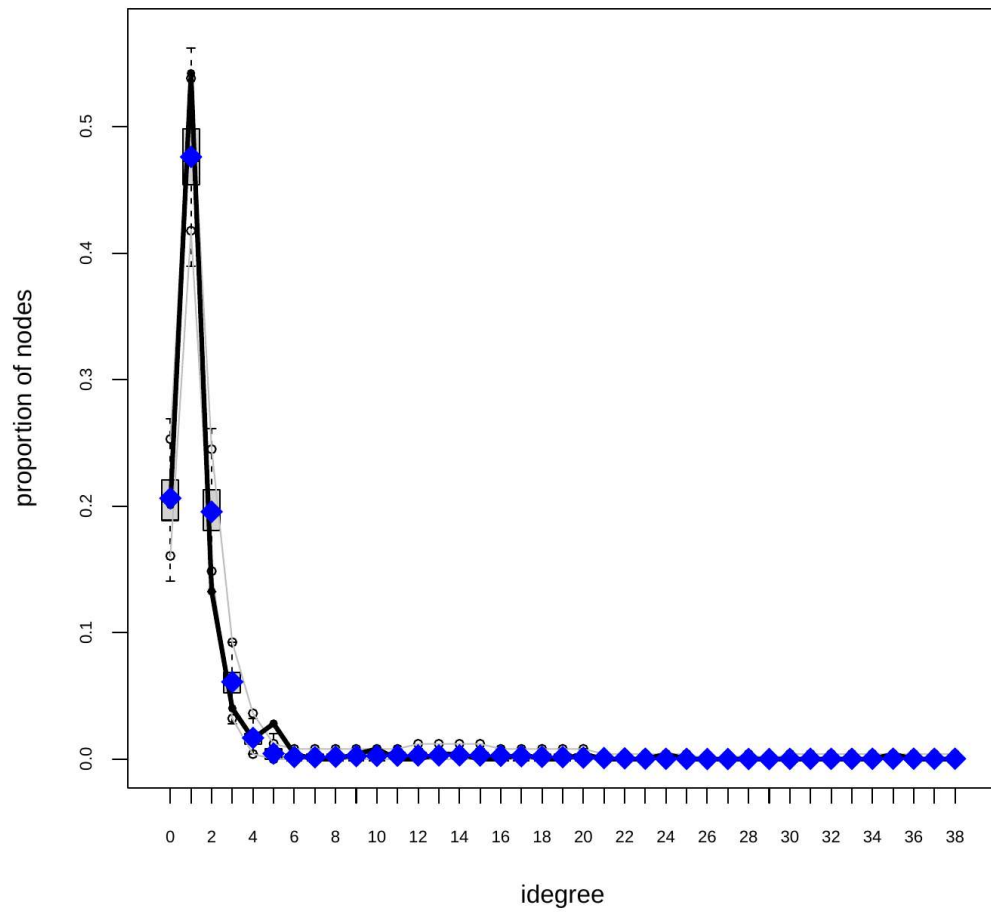
The figure shows the comparison between observed values (blue dots) and simulated values (grey boxes) for the model statistics.

Figure 4.21 Outdegree distribution comparison between real network and simulations



The figure shows the comparison between the real outdegree distribution (blue dots) and the simulated one (grey boxes).

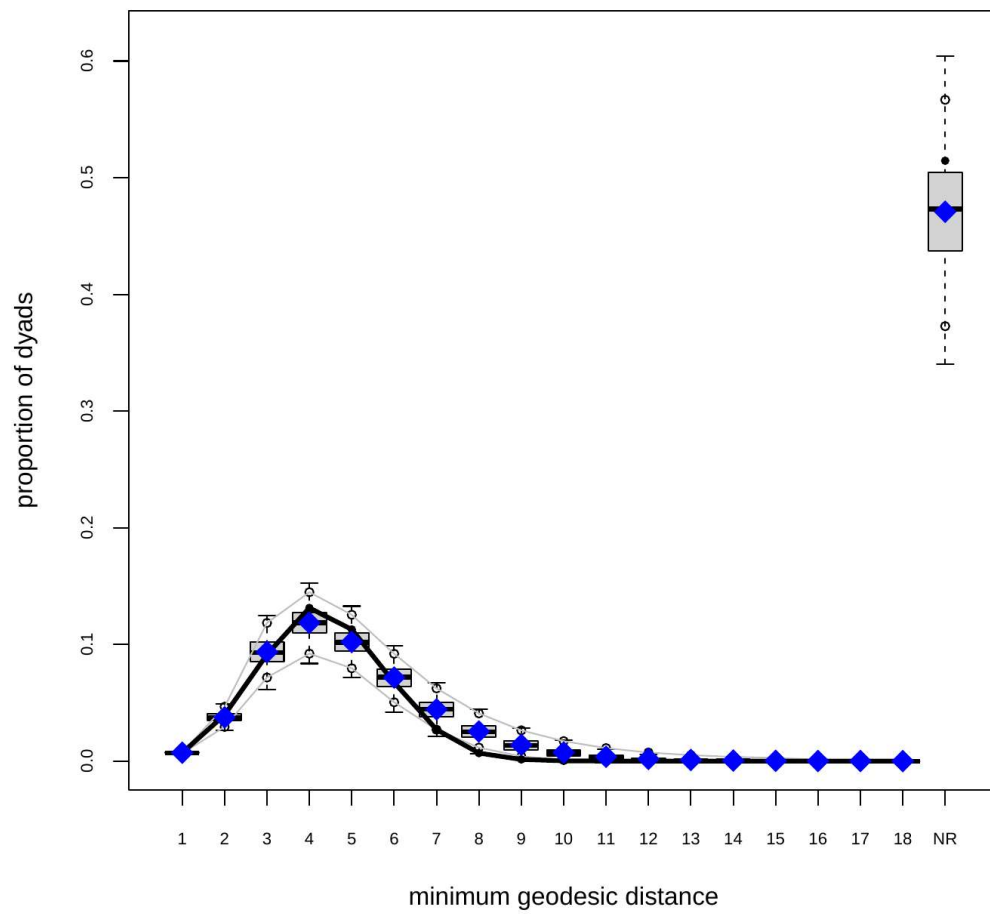
Figure 4.22 Indegree distribution comparison between real network and simulations



The figure shows the comparison between the real indegree distribution (blue dots) and the simulated one (grey boxes).

Figure 4.23 Minimum geodetic distance comparison between real network and simulations

## Goodness-of-fit diagnostics



The figure shows the dyadic minimum geodetic distance distribution between real network (blue dots) and simulations (grey boxes).

# Chapter 5

## 5 Networks in motion: Fifty years of inventor mobility shaping mRNA vaccine innovation

### 5.1 Introduction

The innovation process is a critical area of study for those interested in the mechanisms that transform new knowledge into marketable technologies. Evolutionary theory explains technical change and innovation as occurring within ‘technological paradigms’, through a co-evolutionary interplay between scientific advancements, new technological opportunities, and market structure (Dosi, 1982a; Nelson & Winter, 1982). Empirical works have later shown that these processes tend to differ across industries (Freeman & Soete, 1997; Malerba, 2002; Pavitt, 1984). The so-called linear model of innovation has provided a simple basis for studying innovation as a process in which basic research is the pillar upon which subsequent developments are carried out. This is usually coupled with a division of labour, where the public sector is primarily responsible for basic and fundamental research, while the business sector tends to intervene once technological opportunities become clearer and profit opportunities start to materialise (Balconi et al., 2010). This view has been challenged by studies which have highlighted how quite often the innovation process is not that ‘linear’ inasmuch as there are several feedback stemming from technological developments that go backward towards basic research (Kline & Rosenberg, 1986). Overall, this vast body of research has clarified in many respects how the innovation process works.

One of the aspects which has been downplayed in this body of research has been the spatial dimension.<sup>2</sup> The latter has been instead taken up by economic geography which has explored the spatial dimension of the generation, accumulation and diffusion of knowledge and innovation, as well as the patterns of business agglomeration across the space (Antonelli, 2001; Feldman, 1999; Iammarino, 2005; Martin & Sunley, 2006). This research has broadened our understanding about the spatial properties of innovation mostly in terms of agglomeration economies, that is by exploring how knowledge is accumulated and diffuse over time in specific territories over time depending on the properties of knowledge on the one hand and on the characteristics of the territories – e.g. industry specialization and technological capabilities – on the other hand (Ascani et al., 2020; Döring & Schnellenbach, 2006; Iammarino & McCann, 2006).

This study contributes to the debate about the spatial nature of the innovative process by examining the spatial patterns of the vaccine industry, specifically mRNA vaccines, through a network analysis of mobility and innovation trajectories. By employing a network analysis based on the mobility of the inventors I add the *relational* dimension as a driver of the spatial patterns of innovation. I take an evolutionary perspective in which the spatial patterns of innovation co-evolve and are endogenous within the process of discovery of the vaccine. In my approach I posit that the spatial characteristics of the innovative process are driven by the co-evolution between three elements: (i) the degree of technological and innovation (profit) opportunities; (ii) the relationships between the places involved

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<sup>2</sup> In innovation studies both countries and regions have been characterized mostly for their institutional settings and technological capabilities endowments (Asheim & Gertler, 2006; Balland et al., 2019).

in the discovery; (iii) the path-dependent nature of the stock of knowledge generated along the process.

In order to explore the patterns of the spatial dimension in the discovery of the mRNA vaccine I study the mobility of inventors involved in the patenting activities along all process. I employ a network analysis of the mobility of 4,412 inventors across 46 countries and 1,281 cities in the period between 1984 and 2020, and 24,442 patents. The analysis covers the innovation process from the very basic research activity to the marketable of mRNA COVID-19 vaccines by employing a temporal network analysis to the international mobility of inventors. My unique source of data allows to address some key research questions about the geography of the innovation process such as: how does the mobility of inventors shape the spatial dimension of the innovative process? How does the distribution (i.e. concentration/dispersion) of knowledge change when new technological and innovation opportunities arise? How does the network change over time?

The pharmaceutical industry is a good candidate for such a study for multiple reasons. As a matter of fact, there is a long tradition of studies of innovation in the pharmaceutical and biotechnology industries.<sup>3</sup> Firstly, although the linear model has been revised in the light of more recent findings in some industries, it is true that science-based industry fits quite well with the main characteristics of the model (Balconi et al., 2010). Particularly in the case of the vaccines, their initial development rests upon basic research and fundamental knowledge which is usually carried out in the public sector. While in this phase some biotech firms can contribute to basic research, the big pharma tend to step in when their in-house scientific and technical capabilities allow them to start pilot-plant, trials and full-scale manufacturing (Galambos & Sturchio, 1998; Gambardella, 1992). The history of the pharmaceutical industry over the past decades is filled with advances in science that provided the base for subsequent targeted pharmaceutical R&D activity, such as the breakthrough in microbial biochemistry and enzymology in the 1940s and 1950s and the later biotech revolution and the development of genomics (Galambos & Sturchio, 1998; Zucker & Darby, 1995). Secondly, patents are a very effective tool for the protection of innovations in this sector (Hall, 2004). Hence, relying on the mobility of inventors designated in patents is an effective way to study the spatial evolution of innovation in the industry, following on several previous empirical research (Bahar et al., 2020; Breschi & Lissoni, 2009; Miguelez & Noumedem Temgoua, 2020).

Lastly, innovation is the essence of this industry and R&D is the core activity in the drug business. The innovation process has historically shaped the evolution of the market structure of the industry, its close relationship with public-funded basic research in universities and research centres, including the rising of the biotech sector in the 1990s.

I show that the evolution of the structural characteristics of the network of inventors' mobility changes depending on the dynamic interplay of technological and innovation opportunities along the process of discovery. The network becomes more dense, hierarchical and depending on a few central nodes only when innovation and profit opportunities jointly arise. The most relevant cities not only attract more inventors but also release them, thus acting not just as attractors but rather as hubs for the circulation and amplification of knowledge. Finally, the path-dependence nature of past accumulated knowledge is stronger when technological opportunities are higher than innovative ones, while it becomes less relevant when profit opportunities start to kick in and technological opportunities reduce.

The chapter is organised as follows. In the following section, I introduce the theoretical framework of the analysis based on evolutionary theory of innovation, I then illustrate the process of discovery

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<sup>3</sup> Among the several works by Gambardella see his (Gambardella, 1992, 1995), and among many others (Henderson et al., 1999; Orsenigo et al., 2001).

of the mRNA vaccine and introduce the relevance of inventors' mobility from a spatial perspective and discuss how it serves as a valuable lens for network analysis aimed at understanding the geographical evolution of the innovation process.. Section three presents the data and empirical design of the study, also showing some preliminary descriptive statistics. Section four presents the results of the network analysis and the estimation of a temporal econometric model of network formation. Finally, section five discusses the findings and offers concluding remarks.

## **5.2 The patterns of the spatial dimension in the process of innovation of the mRNA vaccine**

### **5.2.1 Technological change and its spatial characteristics**

Evolutionary theories of innovation studies have long characterized the process of technological change and innovation development as a co-evolution between advancements in science, technological opportunities and market conditions (Dosi, 1982a; Nelson & Winter, 1982). Firstly, several empirical studies about various industries, such as chemical, semiconductors and the drug industry among others, have shown that some key advancements in science drive the rise of new technological opportunities where innovation gets generated (Dosi, 1997; Freeman & Soete, 1997). A fundamental distinction can be drawn here between technological opportunities and innovation opportunities. By technological opportunities, I refer to the frontier of capabilities generated by scientific advances that make further technical developments possible; for this reason, they are tightly linked to scientific and technological progress. Innovation opportunities, by contrast, refer to what can actually be realized given market conditions, and are therefore tied to the feasibility of producing something that is commercially viable. Put differently, technological opportunities are a necessary—but not sufficient—condition for innovation: innovation also requires the presence of innovation opportunities and appropriability.

In this science-push view scientific progress is a *sui generis* exogenous factor, in the sense that even though it is driven by scientific and intrinsic motivations, in fact the direction of scientific progress is often affected by the feedback that receives from technological progress and profit opportunities. Secondly, opportunities and incentives are also key to explain the rate and direction of technological change, particularly the involvement of the business sector. Within each scientific paradigm, the technological opportunities change over time affecting the scope for innovation activities (innovative opportunities) and the ease with which they cost structure for technological advancements (Rosenberg, 1976). Thirdly, a key drive of the business involvement in technical change is appropriability. The latter is defined as the capacity to extract profits from innovations, for instance by the use of Intellectual property rights (IPRs); this is particularly key in the drug sector where patents are extremely effective. The joint presence of strong technical opportunities and a sufficient degree of appropriability account for the willingness of business enterprise to engage in R&D and innovation activities.

The aim of this study is to explore the *spatial* and *relational* characteristics of the process of innovation in the case of mRNA vaccine within the process described above. I describe the process of discovery as characterized by *i*) technological opportunities; *ii*) innovation opportunities; and *iii*) the degree of appropriability. I also identify two main sub-periods along the process: the first is dominated by investment in basic research, low technological opportunities and low innovation opportunities, and little appropriability, the second is instead characterised by increasing technological and innovation opportunities, and higher degree of appropriability.

I investigate how the pattern of the spatial dimension of the discovery process co-evolves with the characteristics of the underlying technical change process itself and the relevance of knowledge



generated within it. By looking at the dynamic of the spatial concentration of innovation and the patterns of the mobility of the inventors, I aim to investigate to what extent the spatial patterns of the innovative process: (i) are dependent upon the state of art of the technological and innovation opportunities; (ii) are endogenously determined in a path-dependent fashion by the past accumulation of knowledge in specific places.

### **5.2.2 The process of discovery of the mRNA vaccine: from basic research to market innovation**

Although already discussed in Chapter 2, in this section I want to recall the essence of the case study since the empirical design of this chapter is strictly related to it. The discovery of the mRNA vaccine has a long history, as it is the case for many other vaccines, punctuated by new scientific advancements, innovative methods and failures. The whole process, which initiated somewhere in 1960 with the discovery of the RNA messenger, has been carried out by several research centres and universities, a long list of biotech start-ups, and a fundamental role of large players in the pharmaceutical industry in the last period.

The innovative content of the mRNA vaccine lies in the fact that it uses a copy of a molecule called messenger RNA (mRNA) to produce an immune response. The vaccine delivers molecules of antigen-encoding mRNA into cells, which use the designed mRNA as a blueprint to build foreign protein that would normally be produced by a pathogen. The mRNA is delivered by a co-formulation of the RNA encapsulated in lipid nanoparticles that protect the RNA strands and help their absorption into the cells—the importance of that will be clear in a minute. mRNA vaccines are advantageous because, given their peculiar nature, they are easy and quick to design, with lower costs of production given a high degree of standardization in the manufacturing process. The length of the discovery process dependent upon the fact that the mRNA technology required several scientific contributions one depending upon the success of the other.

The story can start in the 1960 when the existence of a messenger protein, the mRNA, which delivered the information towards the ribosome, was discovered in two different places, the Caltech and Harvard together with the Pasteur Institute. A second fundamental step was the discovery of the liposome, which is used as a vehicle for the drugs in the body. This was the first step towards the fundamental employment of the liposomal nanoparticles as the vehicle of the mRNA that will be discovered nearly thirty years later in 1989.

It is important to recall that in this initial phase the interest in mRNA was purely scientific in that it was possible to envisage its use as a drug. In fact, until 1984 it was not yet possible to produce the mRNA in laboratory. This changes in 1984 when two scientists at Harvard manage to synthesize the mRNA in their laboratory. Notwithstanding these steps forward, the new technology was still considered unstable the use of the mRNA for vaccine was far from being envisaged. As a matter of fact, Harvard was not interested in patenting the new invention and gave it away to the biotech Promega Corporation. As the story goes, in return of the patent Harvard got a modest amount of royalties and case of good Champagne.

By the end of the 1980s the possibility to employ the mRNA as a vaccine against the HIV started to be explored. During the first half of the 1990s some large producers of vaccines, such as Merk & Co., start investing in the use of the mRNA in some vaccine applications. However, in the following years the projects came to a halt because of the high costs and high instability of the technology, diverting their attention towards DNA type of vaccines. In 1995 a team led by Robert Conry developed what can be defined as a first version of a mRNA vaccine as a cure for the cancer. However, when Conry

asked a company active in the field, Ambion in Texas, the latter drop the idea on the ground of little expected economic returns.

The year 2000 marks a watershed for the development of the mRNA vaccine. Drawing from his PhD dissertation, Ingmar Hoerr in Tübingen got enough financial resources—from the university—to fund a start-up called Curevac which can be regarded as the first company to employ a mRNA vaccine in 2003 for the skin cancer. In the same years, two other scientists, Katalin Kariko and Drew Weissman in the United States made a fundamental discovery, although in that period there was little understanding of its real importance. They started using the pseudo-uridine which avoided the inflammatory reaction of the body to the delivery of the mRNA.

As mentioned above the mRNA needs a means of transport. The key application was the discovery of the lipid nanoparticles, in which the RNA gets encapsulated, as a result of the work by Pieter Cullis from the University of British Columbia, Canada, over the years 2000s. By the end of the year 2000s the combinations of the latest discoveries and scientific advancements allowed the manufacturing of the vaccine scalable for the large drug manufacturer companies. This in turn attracted the interest of the large, big companies. The Swiss Novartis started in 2008 a research centre for the development of mRNA vaccines. In 2012 the DARPA—Defence Advanced Research Projects Agency in the United States—started funding several large firms, including Novartis, AstraZeneca, Sanofi and Pfizer, to work on mRNA vaccines, although the various projects were abandoned later on.

However, the impetus for the business had started. In 2010 the start-up Moderna—which stands for *modified rna*—was established, helped by a substantial amount of financial resources from venture capital and DARPA. In the meantime, another start-up—BioNtech—has accumulated knowledge and patents in the years 2014-2019, collaborating with Pfizer and Genentech from the drug industry, and the universities of Warsaw and Mainz (respectively Germany and Poland). In the meantime, Curevac was still working on mRNA, also thanks to a large funding from a public-private foundation to work on the development of platforms for vaccines.

In January 2020, when the virus SARS-CoV-2 was still limited to China, the three companies—Moderna, BionTech and Curevac—were already at work. Moderna was the first to produce and get its vaccine approved by the Food and Drug Administration in the U.S. in 2020, and in the early 2021 in Europe. Thanks to the collaboration with Pfizer, BioNtech also managed to get its vaccine approved in late 2020.

### **5.2.3 Technological opportunities, innovation opportunities and appropriability in the discovery process of the mRNA vaccine**

As illustrated above, the process of discovery of the mRNA vaccine took some decades. It required a great deal of basic research carried out in universities and research centres, it gave rise to the establishment of many biotech start-ups, and later on in the involvement of a few large drug companies. As usual in scientific discoveries, the process also took place with many trials and errors, several attempts and failures, and a great deal of complementary discoveries and advancements made in various part of the world and as a result of research carried out in parallel by many research teams. Notwithstanding the complexity of the process, we can single out two key characteristics. First, a number of scientific advancements in basic research has played a fundamental role to expand the technological opportunities of the mRNA. Secondly, we can identify two main breakthroughs, namely the discovery of the pseudo-uridine and the discovery of the lipid nanoparticles, which made it possible to envisage the use of mRNA to develop marketable drugs.

We can illustrate the process of discovery of the mRNA vaccine as follows (see Figure 5.1). The figure depicts the three factors characterizing the process of technological change as discussed above.

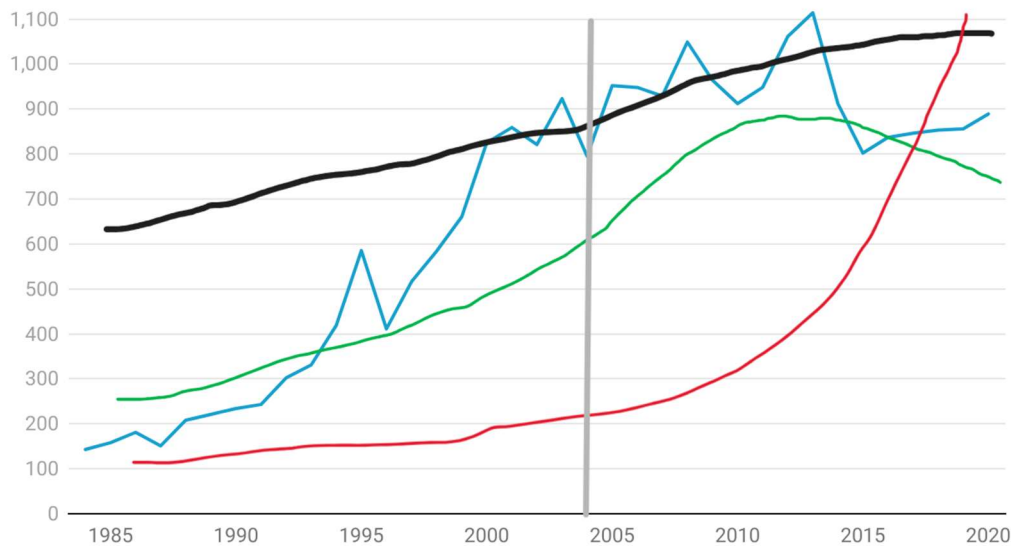
The figure shows the trend of *technological opportunities* which grows steadily ever since 1984 as a result of the biotech revolution. In the 1980s and early 1990s the new techniques of recombinant DNA technique came to represent an “enabling technology” opening up new opportunities for technological development: in fact, “scientific and technological opportunities were expanding more rapidly than they had at any time in the industry’s history” (Galambos & Sturchio, 1998, p. 271; Gambardella, 1995). A fundamental breakthrough occurs in 2004, when two key discoveries made it easy to produce mRNA and reduce the costs of its manufacturing thanks to the standardization of the procedure. After that in the late years technological opportunities decline, as also witnessed by the declining trend of patents (see below). In 2013 the vaccine started the first clinical trials. The turning point of the technological opportunities is driven by a combination of inventions—the modified mRNA with the pseudo-uridine and the lipid nanoparticles—became the dominant technology for the production of the vaccine while the other attempts failed.

The trend of the *innovation opportunities* differs significantly with respect to that of technological opportunities. In fact, during the 1980s and early 1990s the pharmaceutical industry was overall reluctant (or incremental) in acquiring the new scientific and technological capabilities needed to master the biotech revolution. On the one hand the costs were substantial, and there was uncertainty about the future of the biotech applications as well as their patentability (Galambos & Sturchio, 1998; Zucker & Darby, 1995). This was also the case relatively to the mRNA vaccine. As reported above in several cases the pharmaceutical companies drop investments in mRNA since they did not envisage enough profit opportunities. More generally, in this period the large pharmaceutical incumbents were still making substantial investment in previous technological trajectory—microbial biochemistry and enzyme inhibition—and were not ready to shift substantial resources into the new trajectory of molecular genetics and rDNA (Galambos & Sturchio, 1998). Regarding the mRNA vaccine the key turning point for profitability is the year 2004 when, as described above, it becomes possible to produce mRNA in the lab and becomes possible to standardize its production. This would trigger innovation opportunities for large companies driven by the technical possibility to produce mRNA vaccine in-house and the economic opportunity to benefit from scale economies in manufacturing that typically characterize the business model of the large pharma companies. In a nutshell, since 2004 the enabling technology of mRNA becomes a prospective marketable and profitable innovation. Thirdly, the trend of *appropriability* grows steadily over time. Because of high expenditures on research, development, and clinical testing and because new drugs could be imitated easily, patent protection has been particularly relevant for the development of the industry and for its competitiveness. In fact, even though at the onset of the biotech revolution there was some degree of uncertainty about the possibility to patent genetic innovations, in 1980 the U.S. patent system allowed patentability of artificially engineered genetic organisms (Hall, 2004). Ever since patents have been an effective tool to protect innovation in the drug sector. In fact, the pharmaceutical industry is considered as the most important industry in terms of degree of appropriability that can be obtained by IPRs (Gambardella, 1995; Grabowski, 2002).

The characterization of the discovery process of the mRNA vaccine can be thus summarised as follows. The lack of innovation opportunities during the first period is reflected by the low level of involvement of the large drug companies as well as the unwillingness of venture capital companies to fund mRNA-related projects. During this period much of the research is carried out by basic research and funded by public bodies, coupled with several biotech start-ups that used to work in tandem with universities—in fact they were often university spin-offs. Even in the event that some incumbents started a project that was soon or later dropped because of high uncertainty and high costs—that is because of low innovation opportunities. It is only when a high degree of appropriability is coupled with growing innovation opportunities (from 2004 onward) that we observe

(i) the rise of funding towards the largest biotech companies, coupled by (ii) the significant involvement of some of the large incumbents in R&D projects.

Figure 5.1 Technological opportunities, innovation opportunities and appropriability along the discovery of mRNA vaccine



Blu line represents patents production, green line the trend of technological opportunities, red line innovation opportunities and black line appropriability. Source: authors' elaboration.

We can now summarise the aim of the analysis. In what follows I am going to explore the pattern of the spatial dimension along the process depicted in Figure 5.1. The main argument of this study is that the geography of technological innovation (as proxied by patents and inventors' mobility) co-evolves—i.e. is endogenous—with technological and innovation opportunities. More specifically, I explore the evolution of the spatial network generated by inventors' mobility and how the accumulation of knowledge affects the spatial evolution of the process.

#### 5.2.4 Inventors' mobility and its role in the geography of innovation

The research aiming to understand the spatiality of innovation has identified inventors and their mobility as a crucial factor for addressing various aspects of the phenomenon. Inventors can be considered carriers of tacit knowledge—sticky and resistant to long-distance diffusion—which is embodied in the inventors themselves and follows their spatial dynamics. This characteristic makes inventors' mobility the primary channel through which knowledge can transfer across space, with higher inventors' mobility corresponding to greater opportunities for diffusion (Breschi & Lissoni, 2009).

The importance of this phenomenon goes beyond mere knowledge diffusion: through the recombination and reuse of incoming knowledge with local knowledge, and by leveraging international collaborations that mobility helps to initiate (Diemer & Regan, 2022; Scellato et al., 2015), significant benefits can be achieved in terms of productivity and diversification, even triggering technological change (Bahar et al., 2020; Miguelez & Morrison, 2023; Pellegrino et al., 2023). Furthermore, inventors' mobility not only impacts the innovative capacity—and consequently the productivity—of destination regions, but also creates ties between origin and destination regions, reshaping what can be defined as the geography of the innovation process through collaboration networks, knowledge remittances, and circular mobility (Breschi et al., 2017; Miguelez & Noumedem Temgoua, 2020; Saxenian, 2005).

This makes the phenomenon particularly interesting and desirable, raising the question of what drives inventors to move and how such mobility can be enhanced. At first glance, inventors tend to seek destinations already endowed with a sufficient stock of human capital, in order to benefit from knowledge spillovers, increase their own productivity, and thus improve their economic returns (Kerr et al., 2016). At the same time, inventors seek to minimize migration costs to ensure that the benefits outweigh the burdens. As a result, they are more likely to choose destinations that are geographically, technologically, and culturally proximate, as well as those more easily accessible through their existing social networks (Dorner et al., 2016; Gorin, 2016).

From the perspective of this study, focusing on inventors' mobility is both advantageous for the analysis and consistent with the research objectives. It allows to observe the evolving spatiality of the innovation process not only in terms of the geographic distribution of outputs (e.g. patents) but also as a relational process that connects cities and co-evolves with technological opportunities, innovation opportunities, and the degree of appropriability. Inventors are not only a proxy for the flows of knowledge occurring between cities, but they also contribute to connect cities and so to shaping a geographic structure that reveals the multidimensional complexity of innovation, thereby enabling the analysis of how it co-evolves along the innovation process itself.

As already noted, the economic geography literature argues that this phenomenon can foster unrelated diversification through the recombination and reuse of local knowledge with incoming knowledge (Choudhury & Kim, 2019; Miguelez & Morrison, 2023). Opposing this view, some scholars claim that incoming inventors merely reinforce regional specialization, as they tend to be attracted to places that are already leaders in their field (Caviggioli et al., 2020). These two perspectives are not necessarily contradictory; rather, they may reflect different roles that inventors' mobility plays at various stages of the innovation process, and thus different spatial dynamics it generates. The analysis of the innovation process can therefore clarify how these two seemingly opposing functions of inventors' mobility may, in fact, coexist when the evolution of mobility is examined alongside the trajectory of technological and innovation opportunities that characterize the process itself.

In sum, as a dynamic and relational indicator, inventors' mobility provides a bridge between individual dynamics and structural changes in the geographic network of innovation, making it a suitable lens for studying the spatial evolution of the innovation process.

### **5.2.5 The use of network analysis for inventors' mobility**

In recent years empirical research on the mobility of inventors and high-skilled researchers has experienced important methodological and conceptual developments. These advances have been driven by the growing availability of fine-grained patent and publication data, as well as the increasing adoption of sophisticated network-analytic approaches (Bahar et al., 2024; Chang, 2024). A central focus has been the role of mobility in shaping knowledge diffusion and innovation with particular attention to how co-invention and co-patenting network structures mediate these effects. Studies have shown, for instance, that mobile inventors often act as brokers of novel knowledge flows, transferring both tacit and codified knowledge beyond the boundaries of their firms and regions (Wang et al., 2024; Zacchia, 2018). At the same time, scholars have highlighted the unequal geography of these benefits: mobility tends to favour leading global cities and elite institutions, thereby reinforcing existing hierarchies within the global innovation system (Filippetti & Zinilli, 2023; Jonkers & Tijssen, 2008; Verginer & Riccaboni, 2021).

This pattern aligns with well-established preferential attachment mechanisms, whereby inventors tend to move toward and collaborate with organizations and regions already rich in knowledge resources and prestige, reinforcing cumulative advantage and path dependencies in scientific and

technological careers (Barabási & Albert, 1999; Vaccario et al., 2020). Such mechanisms explain the non-randomness of mobility flows and the persistent concentration of innovation activities in global hubs. This has shifted the analytical lens toward the structural constraints that shape mobility decisions and outcomes, such as institutional prestige, geographic proximity, and historical career trajectories. To capture these dynamics more precisely, recent studies have embraced dynamic, multilayer, and higher-order temporal network models, which allow for the identification of path dependencies, network memory effects, and multi-scalar influences in mobility patterns (Liu et al., 2024; Pinto et al., 2021; Vaccario et al., 2020). These models reveal how previous career moves affect future opportunities and how different relational dimensions, such as co-invention ties, institutional affiliations, and geographic locations, interact over time to shape mobility trajectories.

Empirical evidence confirms that the institutional and regional context matters significantly: inventors who relocate to established innovation hubs often experience a boost in patent productivity, largely due to the dense and layered networks they become embedded in, which provide better access to complementary knowledge, collaboration opportunities, and innovation resources (Chang & Matsumoto, 2025; Moretti, 2021). Moreover, longitudinal network analyses have documented that the timing and sequence of moves, as well as ties to “star inventors” or key brokers, critically influence career success and innovation output, highlighting the interplay between individual choices and the structural features of the innovation system (Argyres et al., 2025; Liu et al., 2021).

Other studies have taken a closer look at the micro-foundations of mobility, exploring how factors such as patent protection regimes, individual inventor performance, and relative firm attractiveness influence mobility decisions and inter-firm moves. Using network approaches, this line of research links team composition, collaboration structures, and prior achievements to future career trajectories and inventive output (Argyres et al., 2025; Melero et al., 2017)). For example, strong patent protections may incentivize inventors to remain within firms or geographic areas where their intellectual property rights are best enforced, while high-performing inventors often attract offers from multiple competing innovation centers, further reinforcing preferential attachment patterns.

### **5.3 Data and empirical design**

#### **5.3.1 Data**

This section explains the data sources and procedures used to capture the inventors’ mobility throughout the innovation process that led to the implementation of mRNA COVID-19 vaccines. In the literature, mobility is often captured as a dummy variable (“move” vs. “not move”; “migrant” vs. “non-migrant”) and analyses are typically limited to specific geographical areas and/or technological sectors (Miguélez & Fink, 2023). This study takes a different approach: the aim is to geographically map the mobility along the innovation process. For this reason, I adopted a different data collection strategy, although patents remain the primary source.

The first step is to reconstruct the innovation process. This challenge was made possible thanks to the work of Gaviria and Kilic (2021), who identified the key patents useful for the vaccines production. Through web-scraping on Google Patents, I collected all the patents cited by the key patents to reconstruct the knowledge sources that contributed to the innovation. The set of all these patents (key plus cited patents) constitutes the representation of the innovation process, from which I extracted all inventors.

To reconstruct the inventors’ mobility, I collected all patents associated with each inventor. Here, I encounter the well-known “John Smith Problem”, referring to the difficulty of unambiguously identifying the patent ownership of inventors with common names (Trajtenberg et al., 2006). To

mitigate this issue, I included only patents with CPCs codes related to biotechnology and pharmaceuticals (see Table 5.3 Appendix B), and I considered only patents that listed the inventor with an exact name match. This approach may underestimate mobility, as the same inventor could appear under different name variations (e.g., “John Smith,” “John Dr. Smith,” “Smith John” and so could refer to the same inventors).

Once each inventor was matched to their list of patents, the publication date of each patent provided the temporal dimension, while the assignee location served as the spatial reference. Following (Verginer & Riccaboni, 2021), I define an inventor’s geographic move as a change in affiliation in their next patent. The location of assignees was identified using USPTO data when available; otherwise, I manually extracted location information from the address listed on the patent. In cases multiple assignees were listed with different locations, I only considered the first assignee.

With the resulting dataset, I can more accurately trace the inventors’ mobility who contributed to this innovation over time, shaping a global mobility network that connects all involved cities. Some limitations remain, several of which were already mentioned. The “John Smith Problem” cannot be fully resolved, though I took measures to avoid significant overestimation of mobility. Additionally, it is not possible to trace inventors’ mobility beyond their patenting activity, nor can I claim that the entire innovation process is fully captured through patents data alone. While using assignees as geographic coordinates is not flawless, it allows for more accurate tracking of mobility compared to other available data sources. Although the economic-geography literature on inventors’ mobility typically relies on inventors’ addresses to identify moves, the assignee-location approach is more suitable for two reasons. First, on technical grounds, the patents I analyze span multiple patent offices and a long time horizon, and the availability and consistency of inventor-address information vary both over time and across authorities (Doherr, 2016). Second, given the purpose of the study, I use inventors’ mobility as a proxy to reconstruct the relational geography that emerges along the innovation process; therefore, even temporary inventors’ relocations are relevant for this analysis.

### 5.3.2 Method: Temporal exponential random graph models (TERGMs)

To analyze the evolution of inventors flows throughout the innovation process, I adopted Temporal Exponential Random Graph Models (TERGMs), a longitudinal extension of ERGMs—already used in the previous chapter—that allows estimating the probability of observing a specific network based on endogenous and exogenous attributes. As an extension of ERGMs, TERGMs account for the dependence between nodes and dyads, which often occurs in empirical networks, a dependency that leads to the failure of traditional linear models. To achieve this, ERGMs, and consequently TERGMs, assume that edges are conditionally dependent through the so-called Markov dependence (Robins et al., 2007). Moreover, TERGMs account for intertemporal dependence between networks (Hanneke et al., 2010; Leifeld et al., 2018), making them suitable for longitudinal studies like this, which involve a sequence of networks observed at regular time intervals.

Another method for analyzing temporal network sequences is the SAOM model (Stochastic Actor-Oriented Model) (Balland, 2012). However, this model relies on the assumption of actor-based behaviour, leading to choose TERGMs as a more appropriate approach for spatial analysis.

From an analytical perspective, we can derive the formulation of TERGMs starting from ERGMs, which view the probability of observing a given network as dependent on the network statistics  $h$  of the network  $N$ .

$$P(N, \theta) = \frac{\exp(\theta^T h(N))}{c(\theta)}$$

Where  $c(\theta)$  is the normalization constant.

To apply this formulation, it is necessary to make a Markov assumption, stating that the network  $N^t$  is independent from  $N^1, \dots, N^{t-2}$  given  $N^{t-1}$ :

$$P(N^2, N^3, \dots, N^t | N^1) = P(N^t | N^{t-1}) P(N^{t-1} | N^{t-2}) \dots P(N^2 | N^1)$$

We can therefore generalize ERGMs for a sequence of temporal networks as follows:

$$P(N^t | N^{t-k}, \dots, N^{t-1}; \theta) = \frac{\exp(\theta^T h(N^{t-1}, \dots, N^{t-k}))}{c(\theta, N^{t-k}, \dots, N^{t-1})}$$

Since the usual maximum pseudo-likelihood estimation (MPLE) underestimates variance, I adopt bootstrapped MPLE (Leifeld et al., 2018) to correct errors in TERGMs. In this analysis, I sampled 500 network sequences while preserving their temporal order. An alternative to bootstrapped MPLE is MCMC-MLE (Markov chain Monte Carlo maximum likelihood estimation). Although MCMC-MLE is accurate and consistent, it is computationally demanding, making its use impractical for this analysis.

### 5.3.3 Empirical design

The dependent variable in the models is the transfer of an inventor from one city to another, which translates into the formation of an edge between two nodes in our networks. The explanatory variables can be classified into endogenous and exogenous variables: the former refers to structural characteristics of the network, while the latter pertain to node attributes.

Endogenous variables include:

*Mutual*: Represents the tendency in the network to form dyads with reciprocal links between nodes.

*Geometrically Weighted Edgewise Shared Partner Statistic (GWESP)*: Captures the tendency for transitivity within the network, indicating whether the nodes of a dyad are both connected to one or more common nodes. The decay parameter, set to 0.1 and 0.5 (following Leifeld et al. (2018) and Wang et al. (2024)) mitigates the influence of highly dense triads. In both cases, parameters remain consistent.

*Cyclicalities*: Measures the tendency to form three-node cyclic patterns (i connected to j, j connected to k, and k connected to i).

*Geometrically Weighted Indegree Statistic and Geometrically Weighted Outdegree Statistic (Gwidegree and Gwodegree)*: Help to assess the impact of degree distribution on the formation of incoming and outgoing edges. They are used to identify the presence of preferential attachment (if coefficients are negative) or anti-preferential attachment (if coefficients are positive) (Hunter, 2007). I set the decay parameter first to 0.1 and then to 0.5 (following Wang et al., (2024)) to verify consistency.

*Memory*: Incorporates the network inertia or temporal dependency, capturing the persistence of edges (or absence of edges) from time t-1 to time t between every dyad.



*Time trend*: Controls for the linear temporal trend in edges formation.

Exogenous variables include:

*Country*: Indicates the country to which a node belongs. It will be used to assess homophily and so to understand whether edges are more likely to form between cities in the same country.

*GDP per Capita*: Captures the effect of overall economic performance on the probability of forming incoming and outgoing edges.

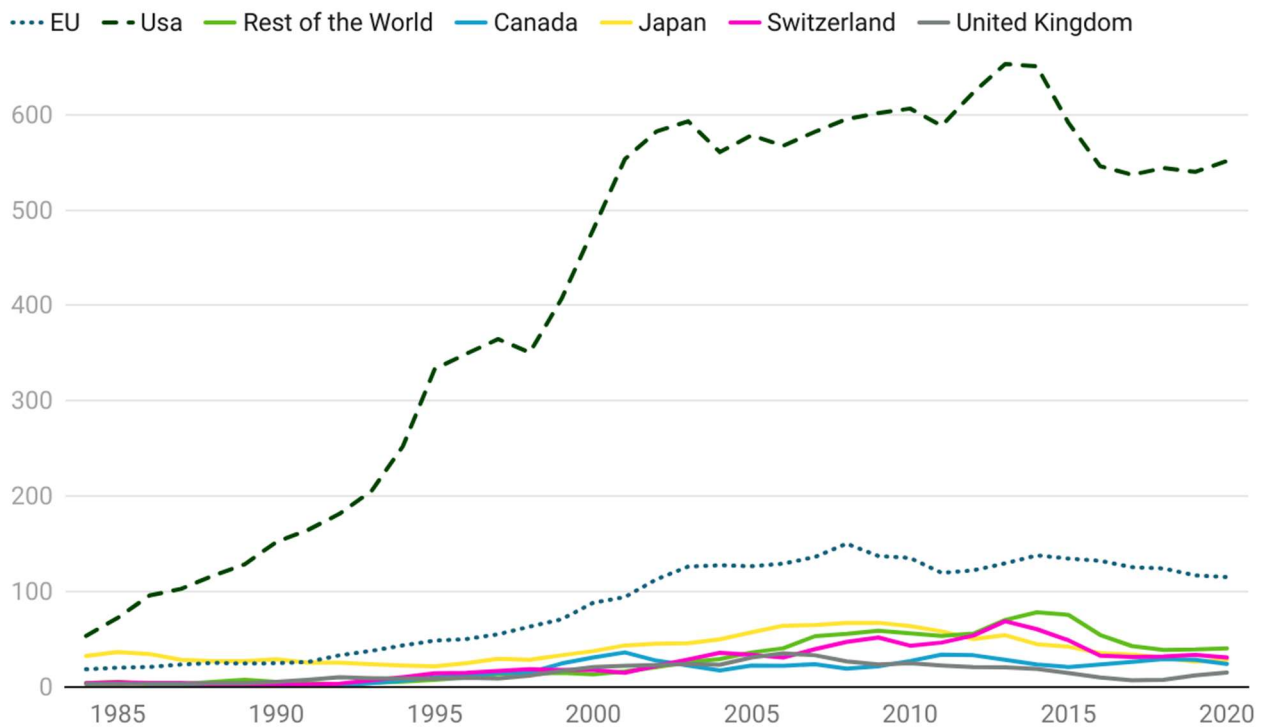
*Patents Stock*: Measures the probability of forming an incoming or outgoing edge based on the cumulative patents production of the cities. It captures the role of past innovative production and so the path-dependency of the process. Since patents are the source of information on mobility—where a relocation is recorded when an inventor files a patent in a different location than the previous one—I use the cumulative number of patents up to the year preceding the reference year, in order to mitigate distortions.

The analysis covers the entire innovation process from the first in vitro production of mRNA in 1984 to the final production of COVID-19 vaccines in 2020. To capture potential temporal discontinuities due to different phases of the innovation process, I divide the entire timeframe into two representative periods: (1) 1984–2004: From the first in vitro production of mRNA to the discovery of pseudo-uridine. During this period, mRNA becomes potentially usable for clinical purposes, attracting industrial interest despite prevailing scepticism due to the inherent characteristics of mRNA. (2) 2005–2020: The discovery of pseudo-uridine enables the introduction of mRNA into the human body without triggering inflammatory reactions. This period marks the final effort leading to the development of vaccines.

#### **5.3.4 Descriptive statistics**

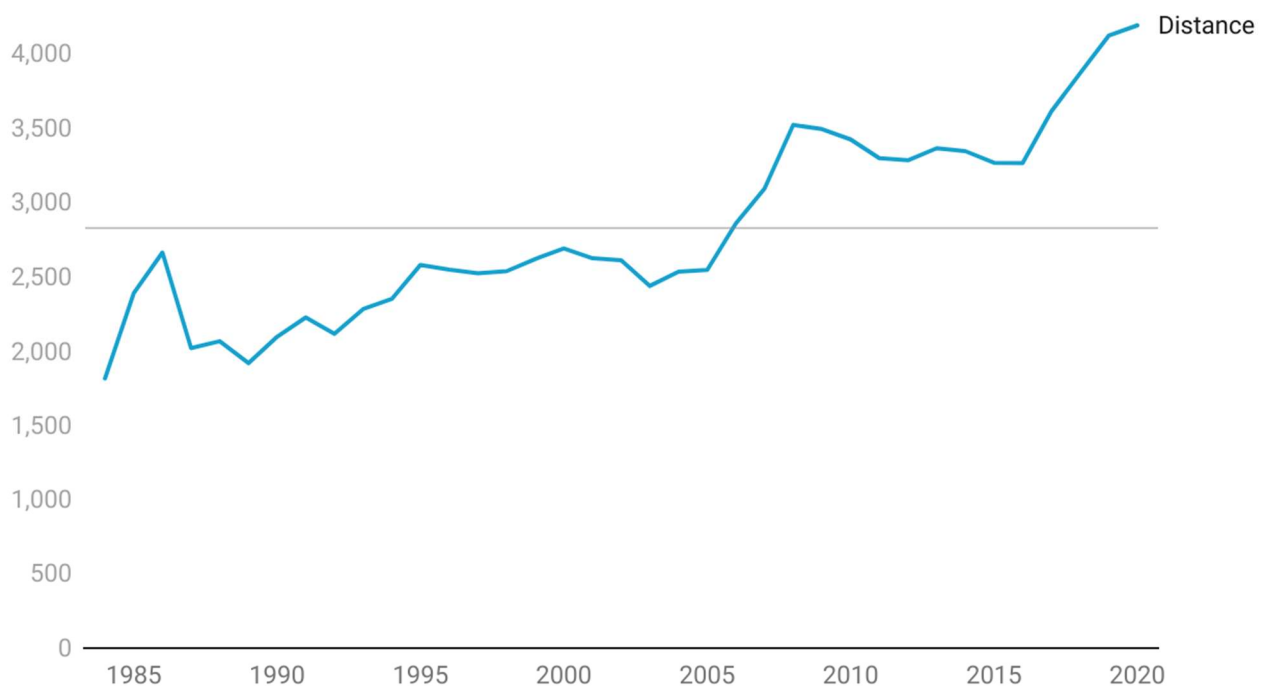
In this section I discuss some descriptive of the data. Next figure (Figure 5.2) shows the number of patents application and the number of inventors over the considered period grouped by the geographical areas. Overall, we observe a steady growth of patents until 2013 and a subsequent decline. Note that at this time the technology required for the implementation of vaccine platforms was already available, and it was precisely in 2013 that the first clinical trials began. After this year it is likely that the technological opportunities decline. The second information derived from the chart is the lion's share of the U.S. in mRNA patenting (equal to 62% in the whole period), followed by the European Union (17%) with Germany weighting from half of the patents. It is also evident that the U.S. researchers are the first movers, followed by the European ones in the 1990s, and Asian countries later on with China started patenting in the year 2000. This is also reflected by the average distance travelled on average each year by the inventors (see figure 5.3). The increased distance is possibly driven by the fact that the geography of the innovation process broadens over time ending up involving the whole globe in the years 2000s.

Figure 5.2 Patents production by country along the innovation process



The chart shows the patents production trends of countries involved in the innovation process

Figure 5.3 Average distance travelled by inventors



The chart shows the average distance travelled by inventors along the innovation process. The grey horizontal line indicates the overall average distance (around 2800 km).

The number of cities involved reflects the geographical trends illustrated above, with 572 American cities, 269 European cities, up to a total amount of 1282 cities across the entire period. These numbers also suggest a higher concentration of patents for the American cities (on average 30.9 patents per city) with respect to the case of Europe (13.8), Canada (23.43) and Japan (24.11).

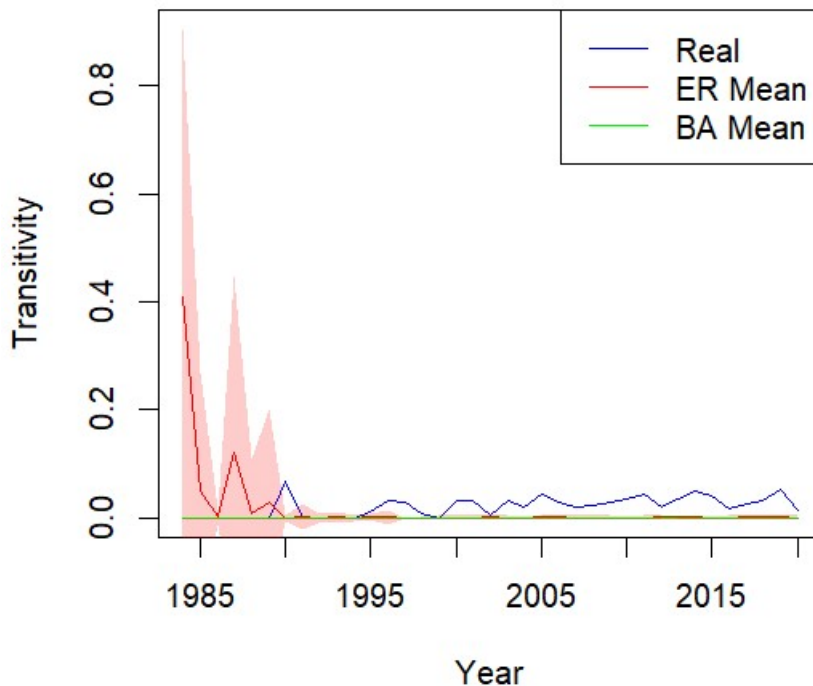
## 5.4 Results

### 5.4.1 Spatial patterns evolution over time

Here I report the trend of some statistics characterizing the evolution of the network which are compared with two generative models —Erdős–Rényi (ER) and Barabási-Albert (BA)—simulated to match the same nodes and edges. The former generates a random network, in which every node has the same likelihood of being connected. The latter is a generative model that creates a network by adding one node at a time and where nodes no longer have the same probability of being connected, but the probability of connection increases as the degree of the node increases: the greater the number of connections that the node has already received, the greater the probability that it will receive another connection (preferential-attachment).

Figure 5.4 shows the transitivity comparison over the years which measures the propensity of the nodes to form a closed triad—i.e. A is connected with B, B is connected with C, and then A connects with C. It suggests if the link between A and C takes place thanks to the mediation of B. In the first period the transitivity of the real network resembles that of a random model; it only starts becoming different, and higher, from the late 1990s

Figure 5.4 Transitivity comparison per year

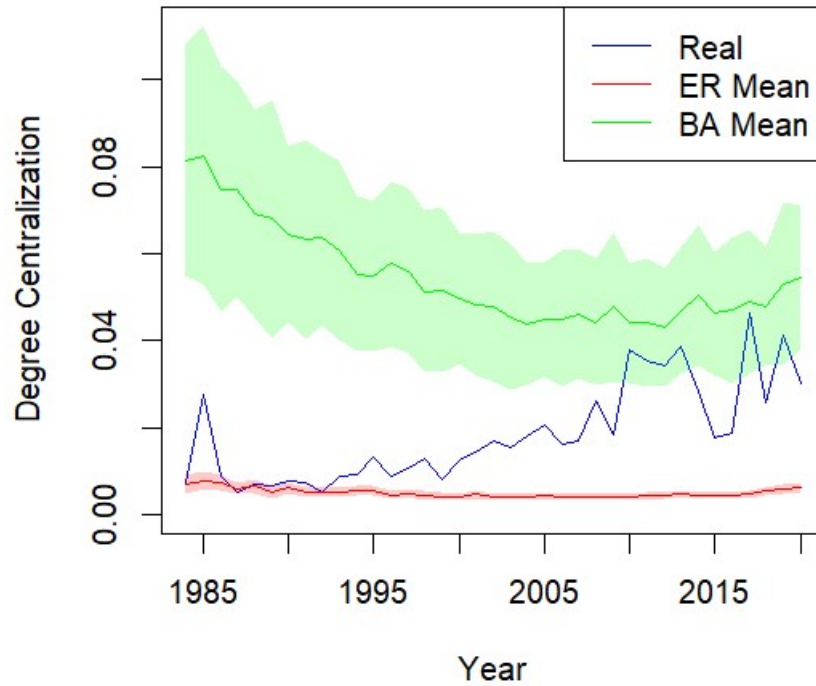


The figure shows the comparison between transitivity values over time for real mobility network (blue) Erdős–Rényi simulations (red) and Barabási-Albert simulations (green)

The following charts (Figure 5.5 and 5.6) report the degree centralization and betweenness centralization over the years. Degree centrality measures the number of both inward and outward linkages of each node (city); betweenness centrality assigns higher values to those nodes that act as intermediaries between other nodes. These measures suggest to what degree the network depends upon the nodes with higher centrality. In both cases in the first period our network is similar to a

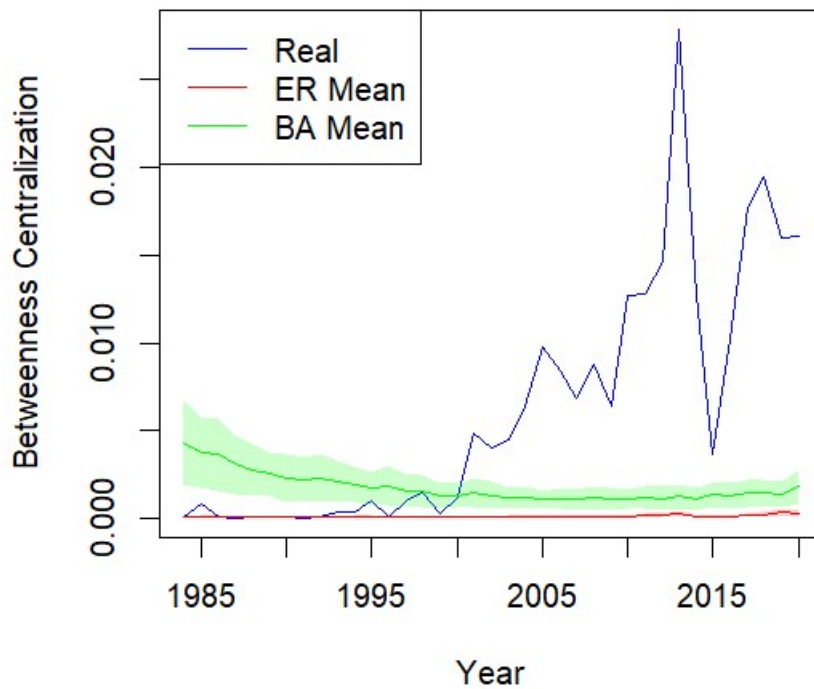
random one, while starting from the 2000s it detaches from the random model taking higher values for both the indicators. In particular, the network tends to exhibit increasing degree centralization with clear signatures of preferential-attachment, reaching levels consistent with a Barabási–Albert structure.

Figure 5.5 Degree centralization comparison per year



The figure shows the comparison between degree centralization values over time for real mobility network (blue) Erdős–Rényi simulations (red) and Barabási–Albert simulations (green)

Figure 5.6 Betweenness centralization per year

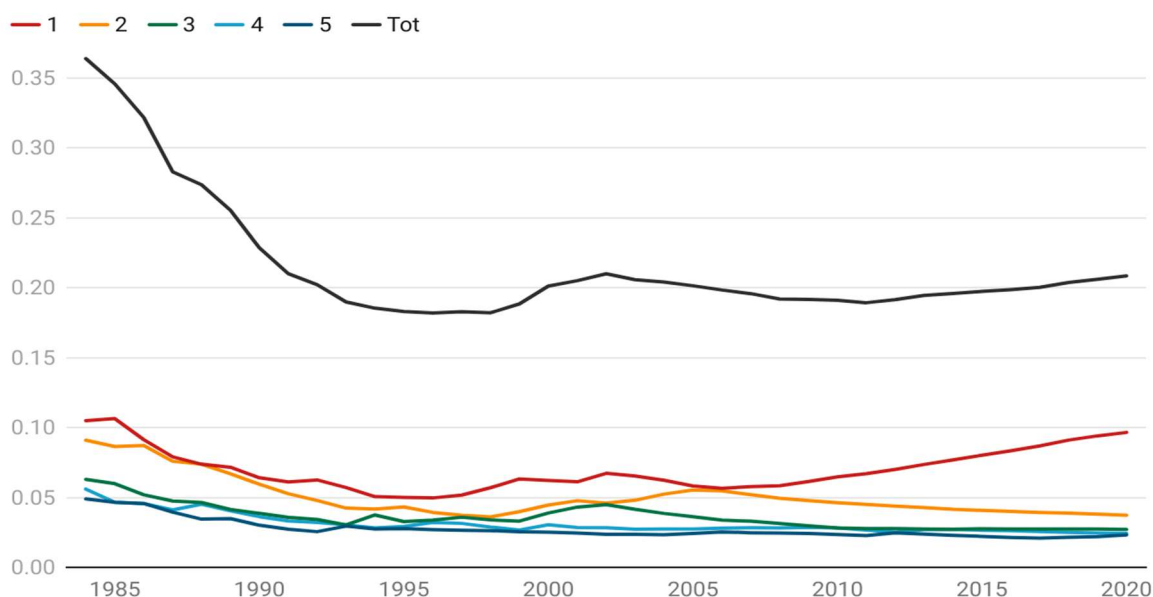


The figure shows the comparison between betweenness centralization values over time for real mobility network (blue) Erdős-Rényi simulations (red) and Barabási-Albert simulations (green)

Figure 5.7 reports the concentration over time, calculated as the share of patents of the five cities that show the higher average of patenting across the whole period. The 5-cities concentration (black line) shows two distinct trends. First a steady decline from 1985 to 2000, and then a stable trend. This reflects the fact that in the first decades new cities enter in the process; while since 2000 there is no clear sign of an increase in the concentration, although the top-five cities retain some more than 20% of the total amount of patents. In fact, the number of active nodes (cities) shows a continuous increase until year 2008 and after a decline (Figure 5.12 in Appendix A).

Figure 5.7 Patents geographic concentration over time

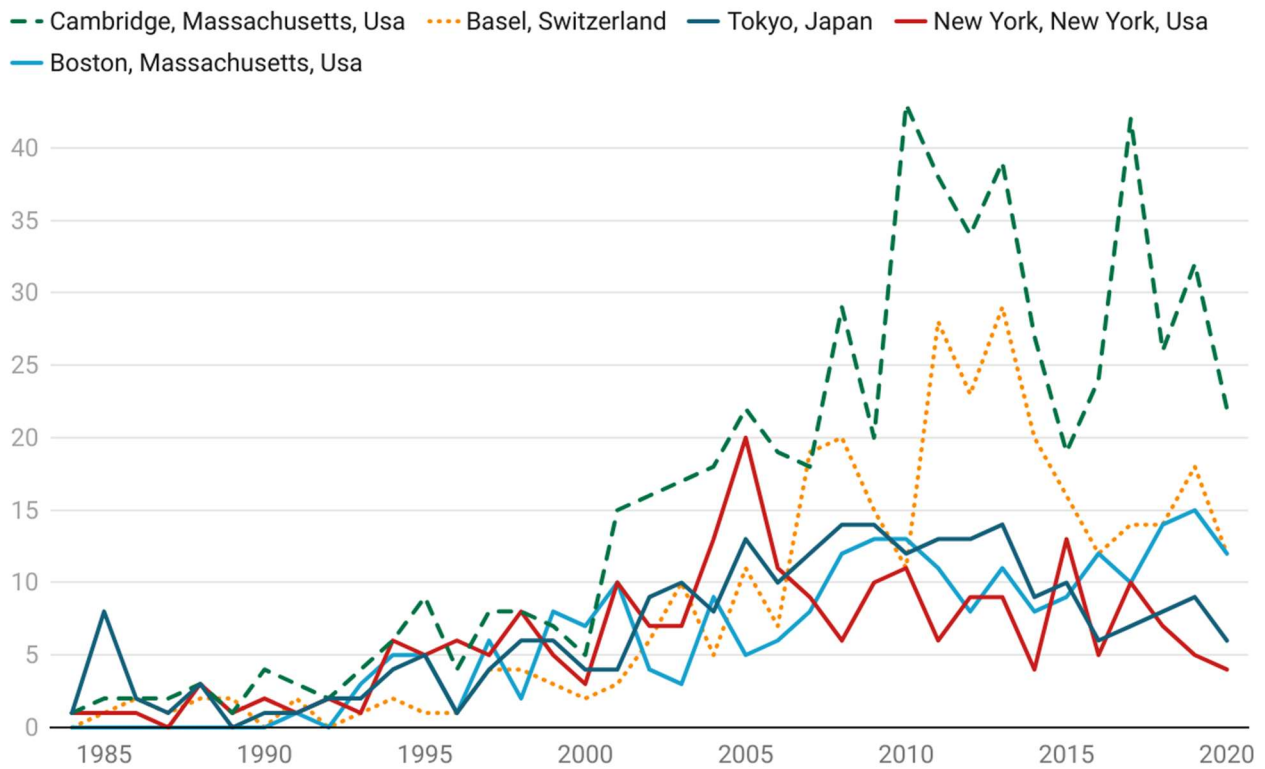
## Geographic Concentration Over Time



The figure shows the geographic concentration over time of patents share between the first five cities. The black line represents the total share of the five cities, the other lines represent the ranked cities.

By looking at the degree of centrality of the top-five cities—calculated as the number of incoming and outgoing links generated by inventors’ mobility for each city—(Figure 5.8) we observe a clear trend consistent with other characteristics of the network illustrated below. The top-five start to become ‘central’ in the network only starting by the early 2000s. Note that the degree of centrality is extremely similar by looking at both *inward* centrality and *outward* centrality (Figure 5.13-5.14 Appendix A).

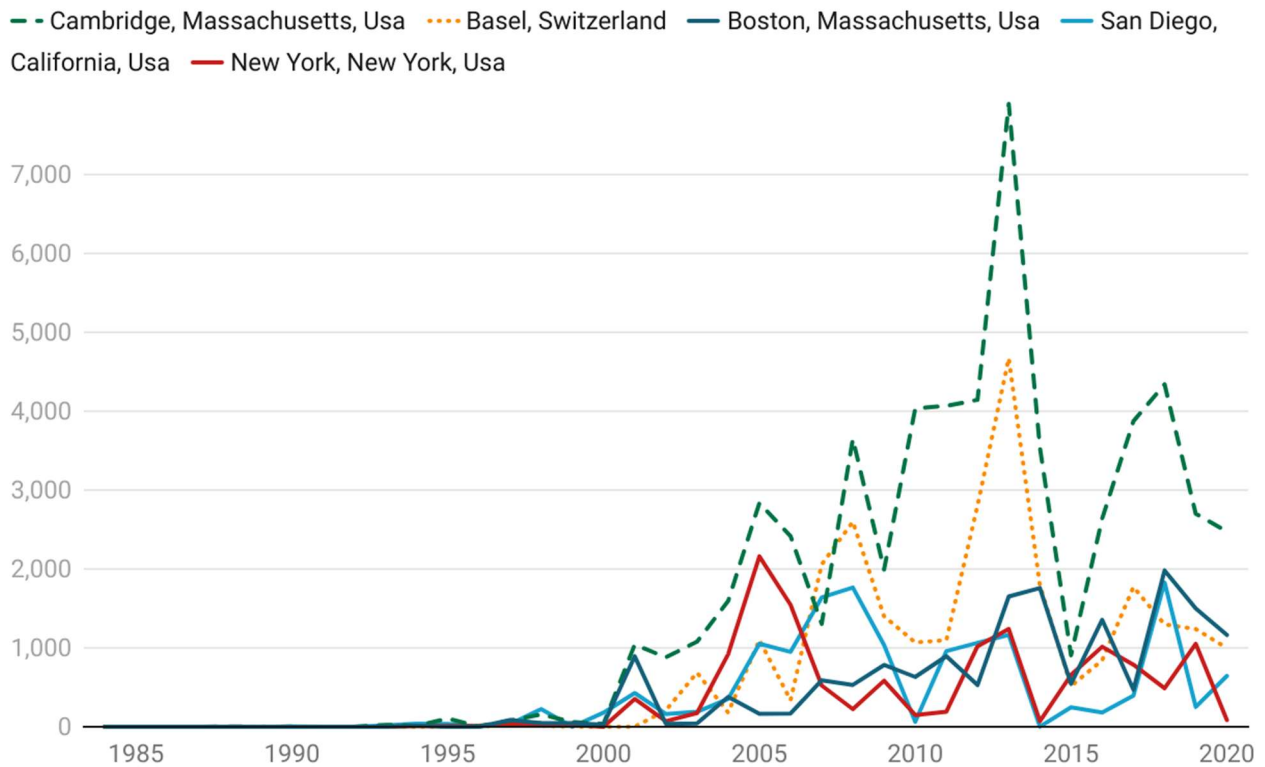
Figure 5.8 Top-five cities degree centrality



The chart shows degree centrality values of the top-five cities per average centrality over all the innovation process.

A very similar fashion is followed by the degree of betweenness centrality, which measures how a city works as a gatekeeper between two nodes (Figure 5.9).

Figure 5.9 Top-five cities betweenness centrality

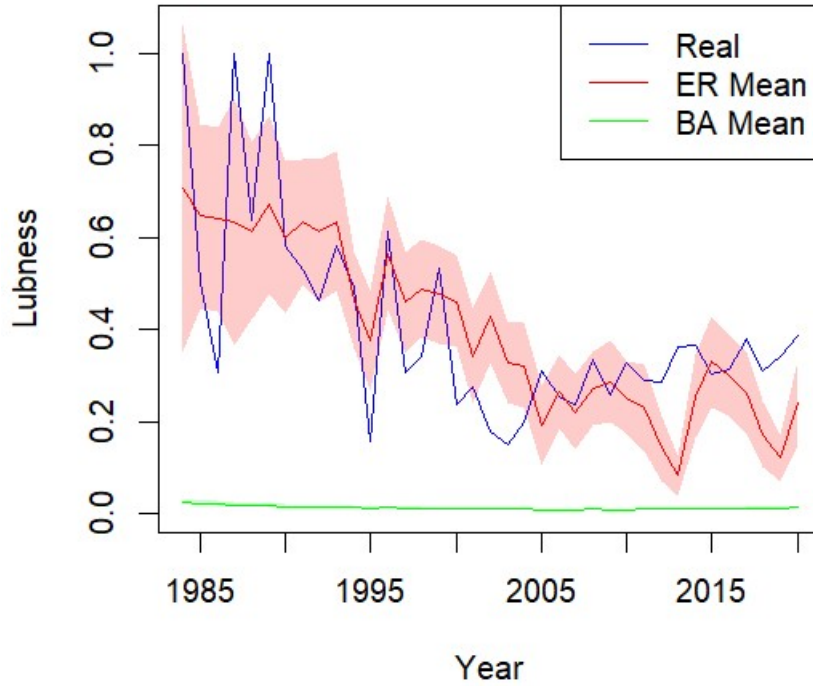


The figure shows betweenness centrality values of the top-five cities per average centrality over all the innovation process.

The next chart (Figure 5.10) reports the measure of the LUBness (Least Upper Boundness). This indicator is a measure of the hierarchy of the network, and it is based on the number of couples that share the same node. The chart shows that for the first period the network overlaps with a random model. However, again starting from the years 2000s the value increases, thus suggesting a growing and significant hierarchy in the relationships between the cities.



Figure 5.10 LUBness comparison per year

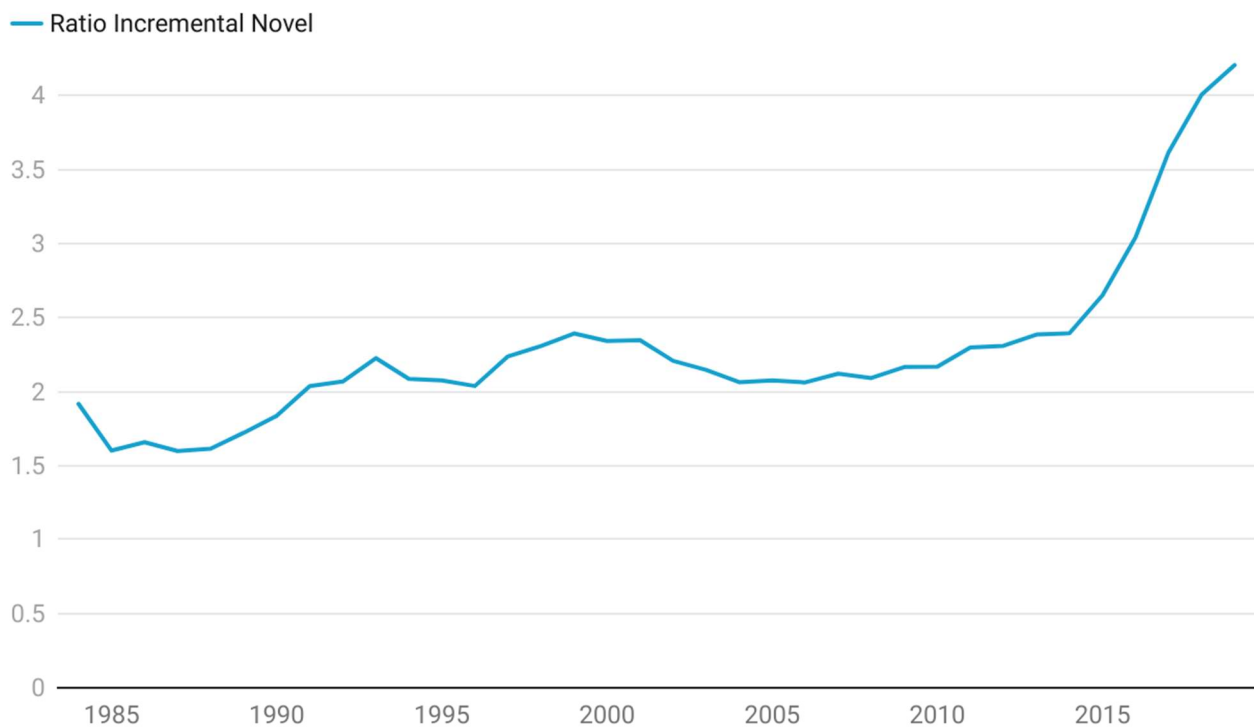


The figure shows the comparison between LUBness values over time for real mobility network (blue) Erdős–Rényi simulations (red) and Barabási-Albert simulations (green)

The Figure 5.11 reports the ratio between incremental versus novel knowledge production. To identify patents that contain incremental or novel knowledge, I follow Arts et al. (2021), applying natural language processing (NLP) techniques to calculate novelty and impact indicators based on patents abstracts. Only patents in the innovation process with abstracts available in English were used. Specifically, for each patent, I compute backward\_cosine and forward\_cosine. The first measure the similarity of the focal patent with patents filed in the preceding five years and the second with patents filed in the following five years.

In line with the original authors, I use the ratio forward\_cosine/backward\_cosine ( $F\_B\_Ratio$ ) as an indicator of impact, serving as a proxy for identifying novel knowledge. A higher value of this index suggests a patent that introduced concepts more widely used afterward than in the past. Unlike the authors, who use  $1 - \text{backward\_cosine}$  as a measure of novelty, I use the backward\_cosine (*Backward\_sim*) value itself as a proxy for incremental innovation, since a higher value of this index indicates a stronger conceptual connection to prior knowledge.

Figure 5.11 3 Years Moving Average Incremental-Novel Knowledge Ratio



The chart shows a moderate stability in the first period and a substantial increase in the final stage of innovation. This trend is consistent with the fact that after the “dominant design” of the mRNA vaccine has been established a greater share of knowledge is generated within the specific technological trajectory which has been selected.

Summing up, results suggest overall the presence of a significant change in the structure of the network along the innovation process. As shown above the number of patents, inventors and mobility transfer grow steadily from the beginning to the year 2015 and then show a decline. Instead, the dynamic of the network follows a different pattern, characterized by two periods 1984 – 2000s, and 2000s onward. In the former period (i) the structure of the network resembles that of a random model; (ii) the centralization of the network is low/negligible (low preferential attachment); (iii) the degree and betweenness centrality of the most relevant nodes (cities) are still low. Starting from the 2000s the structure of the network changes, by detaching significantly from a random network. The latter assumes a higher hierarchical stance, the network becomes more dependent upon the centrality of some nodes, and this gets reflected in the higher centrality of the top-five cities. Note that centrality increases both *inward* and *outward*. This reflects the fact that a number of nodes become more central not because they simply attract more inventors. Their centrality takes the form of being *hubs* of knowledge in that a growing number of inventors enter and exit, that is transit, from these nodes. This is consistent with the fact that they act also as intermediated between secondary nodes. Hence the story is much more complex than simple attraction of inventors and accumulation of knowledge, but is instead more a story of relational value and knowledge circulation. Interestingly enough, this is not reflected in the concentration of patents; the latter in fact remains stable in the top-five cities, with the exception of the city of Cambridge MA which emerges as the winner in the mRNA race.

#### 5.4.2 Knowledge and mobility: TERGMs estimation

In this section, I present the results of the TERGMs estimations for two different models, divided into two time periods representing distinct phases of the innovation process under observation.

The first model includes all endogenous variables tied to the network's structure, alongside exogenous variables attributable to the country's attributes in which each city-node is located. This model serves as the baseline for estimating the second model, which adds a city-level variable. Specifically, the second model includes the variable *Patents\_stock*, which captures the effect of past cumulated knowledge (measured by the number of patents filed until that year) of each city.

I do not interpret coefficients as causal effects in the econometric sense; rather, I estimate conditional associations consistent with co-evolutionary dynamics, controlling for network dependence and temporal inertia.

Turning to the estimation results (Table 5.1), the variable *Edges* is negative and significant. This variable accounts for the number of links actually formed in the network compared to the number of potential links. A negative coefficient in both timeframes thus indicates a sparse network with low density, a common characteristic in real-world networks. However, this coefficient becomes smaller in the second period, suggesting that inventors' mobility contributes to creating a denser network of links in the second stage.

The variable *Mutual* captures the number of bidirectional ties between dyads. The coefficient is positive and significant, confirming—as also highlighted in the descriptive analysis—that mobility tends to generate reciprocal relationships between cities. However, the decrease in the coefficient in the second period suggests that this tendency is more prominent during the first phase.

*GWESP* measures the tendency to form triadic closures in the network, better known as transitivity. In a directed network such as the mobility one, this refers to the greater likelihood of a direct link forming between two nodes when there is already an indirect (mediated) path between them. For example, if there is a link from node A to node B and from B to C, a triadic closure occurs when there is also a link from A to C. In this case, the coefficient is not significant, confirming the low or near-zero transitivity observed in the descriptive analysis.

However, it would be incorrect to conclude that there is no clustering in the network: it simply takes a different form. The positive and significant coefficient of *Cyclicalities* captures the tendency to form circular flows between nodes. Returning to the previous example, a circular flow occurs when there are links from A to B, from B to C, and from C back to A. This coefficient also decreases in the second period, indicating that such circular flows between cities are more prominent in the phase of technological exploration.

These findings become even more insightful when considered alongside the coefficients for *GWIDEG* and *GWODEG*, both of which are negative and significant. These results indicate a tendency toward centralization around nodes with higher in-degree and out-degree. This centralization effect becomes more pronounced in the second period, suggesting that as profit opportunities increase, mobility not only generates a denser, less reciprocal, and less cyclical network—as discussed above—but also reinforces the role of innovative hubs, particularly in attracting inventors.

The variable *Edge Memory* is positive and significant suggesting the presence of temporal inertia in the ties generated by inventors' mobility which tend to persist across both periods. At the same time, the non-significance of the variable *Timecov* suggests that the process cannot be adequately described as a linear trend over time.

Turning to country-level characteristics and their impact on inventors' mobility, we can first observe a national homophily effect, captured by the *Country* variable. This indicates a strong tendency for mobility to occur between cities within the same country, although this effect weakens in the second

period; this can depend on a higher propensity to travel abroad looking for the major hubs and/or because the number of countries involved grows over time.

The control variable *GDP\_per\_Cap*, representing the per capita GDP of the country to which each city belongs, is significant only in the first period. This can be explained by the previously noted strong influence of intra-national mobility, as well as the possibility that international mobility could be facilitated by a certain degree of economic proximity.

We now can turn our attention to the estimate related the variable which proxy the knowledge generated by cities. The variable *Patents\_stock* captures the effect of the accumulated stock of knowledge in the nodes (cities) on inventors' mobility—inflows and outflows. I expect to find a positive relation between the inflows of inventors and the cumulated stock of knowledge in the cities. To the extent that the latter represents a strong signal of close-to-the-frontier research carried out in the mRNA vaccines inventors are likely to be attracted by it. Regarding the outflows of inventors two options are possible. On the one hand, inventors might be reluctant to leave a place where they can engage in top class research. On the other hand, it is possible that inventors are also likely to leave these places once they have benefitted enough from working in a top research environment; the latter is consistent with research on skilled migrants that are inclined to leave the more innovative regions after some time (Champion & Gordon, 2021; Fielding, 1992).

By looking at Model 2 (Table 5.2) two elements are worth stressing regarding the variable *Patent\_stock*. First, both the coefficients of inward and outward mobility are positive and have a similar magnitude. This shows that the past accumulation of knowledge of a city does not make the latter only an attracting place for inventors, but rather a 'hub'; that is, inventors not only are attracted by these cities, but they also tend to leave them after some time—i.e. they live there for at least one year. Second, the magnitude of the coefficient is significantly reduced in the second period. This suggests that the path-dependent effect of knowledge become relatively less important when innovation opportunities arise. This second result needs to be discussed in contrast with the fact outlined above that over time the centrality of some nodes of the network increases. We can interpret these two findings as follows: it is true that a few cities become more central, that is they act as hubs in the second part of the period, but the role of knowledge is relatively less relevant in attracting inventors. That is, these cities become *hubs* not only for their innovative capacity but also for other factors that could be described as complementary assets. By the latter I mean those assets, such as big labs, specific equipment, testing and manufacturing capabilities, that are necessary in carrying out applied (closer to the market) research and ultimately producing the vaccine.

Table 5.1 TERGMs estimation Model1

|                        | 1984-2004 |           |         |         |   | 2004-2020 |           |        |        |   |
|------------------------|-----------|-----------|---------|---------|---|-----------|-----------|--------|--------|---|
|                        | Estimate  | Boot mean | 2,50%   | 97,50%  |   | Estimate  | Boot mean | 2,50%  | 97,50% |   |
| edges                  | -12,807   | -13,080   | -16,418 | -10,814 | * | -3,337    | -3,440    | -5,851 | -1,517 | * |
| mutual                 | 5,979     | 5,996     | 5,600   | 6,427   | * | 4,585     | 4,588     | 4,276  | 4,888  | * |
| Gwesp (0,5)            | -0,324    | -0,335    | -0,974  | 0,152   |   | 0,068     | 0,070     | -0,104 | 0,233  |   |
| cyclicalities          | 0,977     | 0,971     | 0,647   | 1,256   | * | 0,626     | 0,622     | 0,397  | 0,824  | * |
| Gwideg (0,5)           | -2,395    | -2,398    | -2,536  | -2,271  | * | -2,633    | -2,631    | -2,723 | -2,497 | * |
| Gwodeg (0,5)           | -2,404    | -2,400    | -2,631  | -2,203  | * | -2,441    | -2,439    | -2,635 | -2,237 | * |
| memory                 | 1,236     | 1,237     | 1,070   | 1,419   | * | 1,265     | 1,266     | 1,167  | 1,362  | * |
| timecov                | 0,016     | 0,016     | 0,000   | 0,029   |   | 0,004     | 0,004     | -0,002 | 0,009  |   |
| Country (nodematch)    | 1,584     | 1,586     | 1,513   | 1,670   | * | 1,189     | 1,187     | 1,109  | 1,274  | * |
| GDP_per_Cap (nodeicov) | 0,704     | 0,726     | 0,488   | 1,055   | * | -0,190    | -0,176    | -0,436 | 0,128  |   |
| GDP_per_Cap (nodeocov) | 0,983     | 1,022     | 0,711   | 1,487   | * | 0,007     | 0,016     | -0,167 | 0,223  |   |

Table 5.2 TERGMs estimation Model2

|               | 1984-2004 |           |         |         |   | 2005-2020 |           |        |        |   |
|---------------|-----------|-----------|---------|---------|---|-----------|-----------|--------|--------|---|
|               | Estimate  | Boot mean | 2,50%   | 97,50%  |   | Estimate  | Boot mean | 2,50%  | 97,50% |   |
| edges         | -10,888   | -10,949   | -11,732 | -10,311 | * | -9,063    | -9,088    | -9,818 | -8,429 | * |
| mutual        | 5,005     | 5,027     | 4,764   | 5,316   | * | 3,996     | 3,994     | 3,738  | 4,256  | * |
| Gwesp (0,5)   | -0,134    | -0,141    | -0,701  | 0,381   |   | 0,022     | 0,025     | -0,144 | 0,188  |   |
| cyclicalities | 0,618     | 0,625     | 0,372   | 0,859   | * | 0,433     | 0,428     | 0,226  | 0,595  | * |
| Gwideg (0,5)  | -0,617    | -0,602    | -0,856  | -0,279  | * | -1,274    | -1,273    | -1,409 | -1,129 | * |
| Gwodeg (0,5)  | 0,011     | 0,020     | -0,293  | 0,335   |   | -0,459    | -0,451    | -0,693 | -0,183 | * |
| memory        | 0,870     | 0,868     | 0,717   | 1,039   | * | 0,959     | 0,962     | 0,877  | 1,053  | * |

|                          |        |        |        |          |        |        |        |          |
|--------------------------|--------|--------|--------|----------|--------|--------|--------|----------|
| timecov                  | -0,032 | -0,032 | -0,047 | -0,017 * | -0,055 | -0,056 | -0,070 | -0,044 * |
| Country (nodematch)      | 1,461  | 1,467  | 1,367  | 1,604 *  | 0,869  | 0,871  | 0,786  | 0,948 *  |
| GDP_per_Cap (nodeicov)   | 0,040  | 0,041  | -0,020 | 0,103    | 0,037  | 0,039  | -0,028 | 0,119    |
| GDP_per_Cap (nodeocov)   | 0,047  | 0,049  | -0,017 | 0,129    | 0,004  | 0,006  | -0,032 | 0,049    |
| Patents_Stock (nodeicov) | 1,433  | 1,446  | 1,307  | 1,650 *  | 1,040  | 1,040  | 0,975  | 1,099 *  |
| Patents_Stock (nodeocov) | 1,852  | 1,865  | 1,703  | 2,021 *  | 1,434  | 1,438  | 1,362  | 1,512 *  |

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## 5.5 Discussion and conclusions

Notwithstanding the great progress that research has made on the patterns of the innovation process, the study of its spatial characteristics has revived research in this area of the past years. A great contribution has come from the economic geography of innovation which has broadened our understanding of key characteristics of innovation, such as knowledge diffusion and accumulation, the concentration of innovation, the patterns of regional industrial dynamics, including the contribution of the multinational corporations.

However, I believe that the application of the network approach to a longitudinal study of the innovative process can make further improvement in this area. This approach can make two central contributions compared with previous research. First, it adds the *relational* dimension to the geographical dimension usually employed in empirical research which merges innovation studies with (new) economic geography. Second, it provides a better representation of the *evolution* of the geography of innovation by looking at the evolving characteristics and properties of the network itself over time.

This study has contributed to this direction by exploring the evolution of the network of inventors of mRNA vaccine over five decades. The evidence about the dynamic of the network gives us some key messages. Firstly, in the first phase of the innovative process we do not observe a hierarchical or well-structured network. By contrast, for a considerable span of time we can observe a decentralised network in which no cities emerge as a central hub and in which preferential attachment is weak. This is increasingly interesting even when considering that research on mRNA almost certainly started out across already pre-existing networks formed by those cities and research institutions that had the necessary scientific knowledge and technical expertise. And yet we can observe how the network evolves in a decentralised fashion. Secondly, at some point, some events trigger a change in the structure of the network which start evolving into a hierarchical type, with growing hubs and strong preferential attachment. From this point onward the network evolves into a structured network much centred around a few central hubs. This helps to account for the apparent contradictions in the literature, where inventors' mobility seems capable of both diffusing and concentrating knowledge in space, and of generating both regional diversification and specialization. Along the innovation process, mobility appears to play different roles depending on the phase. In the early stage, inventors' movements are more strongly knowledge-oriented, contributing to the spatial diffusion and recombination of knowledge, and thereby fostering diversity. In the later stage, by contrast, mobility becomes less directly driven by knowledge and tends to concentrate in places that are already highly specialized in the development of biopharmaceutical products.

Secondly, I connect this process to the co-evolution of the technological opportunities, innovation opportunities and the degree of appropriability with which the theory describes the evolution of technological progress. I add a spatial/relational dimension to the three dimensions already identified by the literature to characterize how science, technological progress and marketable innovation co-evolve over time in the space. The finding is consistent with an evolutionary logic in which during the first period a decentralised and non-hierarchical network reflects the explorative phase. Here basic research is the main engine of progress, and it works into different directions in parallel within an environment of great uncertainty. By contrast, during the second phase the characteristics of the network are more consistent with a situation in which progress is driven by applied research and complementary assets (e.g. manufacturing capabilities and financial capital). The presence of some focusing devices—i.e. some key inventions which increase the effectiveness of the vaccine—reduces technological uncertainty and narrows down the focus of research along few trajectories. At this stage, preferential attachment and centrality start playing a role and set in motion those self-reinforcing patterns of mobility which makes the network more structured and hierarchical.

Summing up, the evolution of the network of inventors seems to replicate (and it is functional to) the characteristics of the scientific and technological space. A decentralised and non-hierarchical (quasi random) structure is more suitable with the initial phase of trials and errors and curiosity-driven exploration into a broad and uncertain technological space; whereas a hierarchical and well-structured network is more suitable to a focused activity of applied research and to exploit local strong complementary assets necessary to scale up experimentation and clinical trials, as well as cost-efficient manufacturing. A key qualification of this evidence is that the drug industry exhibits a distinctive pattern of innovation: a strong science base, a central role for public institutions, and extensive use of patents. Comparative research in other industries is needed to further understand the spatial characteristics of long innovation processes.

This has policy implications. My evidence points to a more cautious approach toward concentrating funding in science policy. The evolution of the network I analyze suggests that before a few nodes emerged as the key actors in the invention and development of the mRNA vaccine, there were several years in which research progressed in a relatively diffuse and uncoordinated manner. The discoveries that enabled the shift to the commercialization phase were possible because of numerous prior developments carried out in second-tier cities, universities, and research centers. Thus, my findings run counter to science and technology policies based on “picking winners” or resource concentration. Instead, they are more consistent with an approach that preserves slack, creates some redundancy, and encourages diversification across multiple pathways, embracing learning from failures—especially during the exploratory phase of the innovation process, when technological opportunities are expanding but innovation opportunities remain limited.



# 5.6 Appendix A

Figure 5.12 Active nodes per year

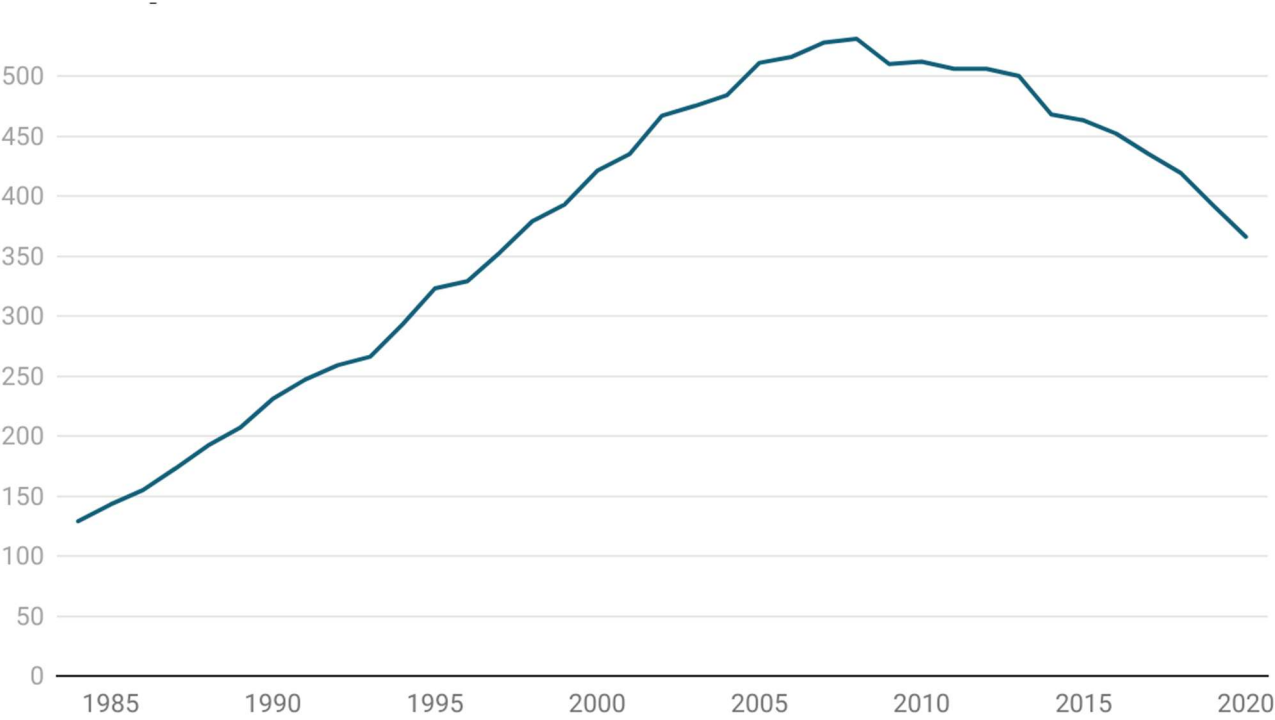
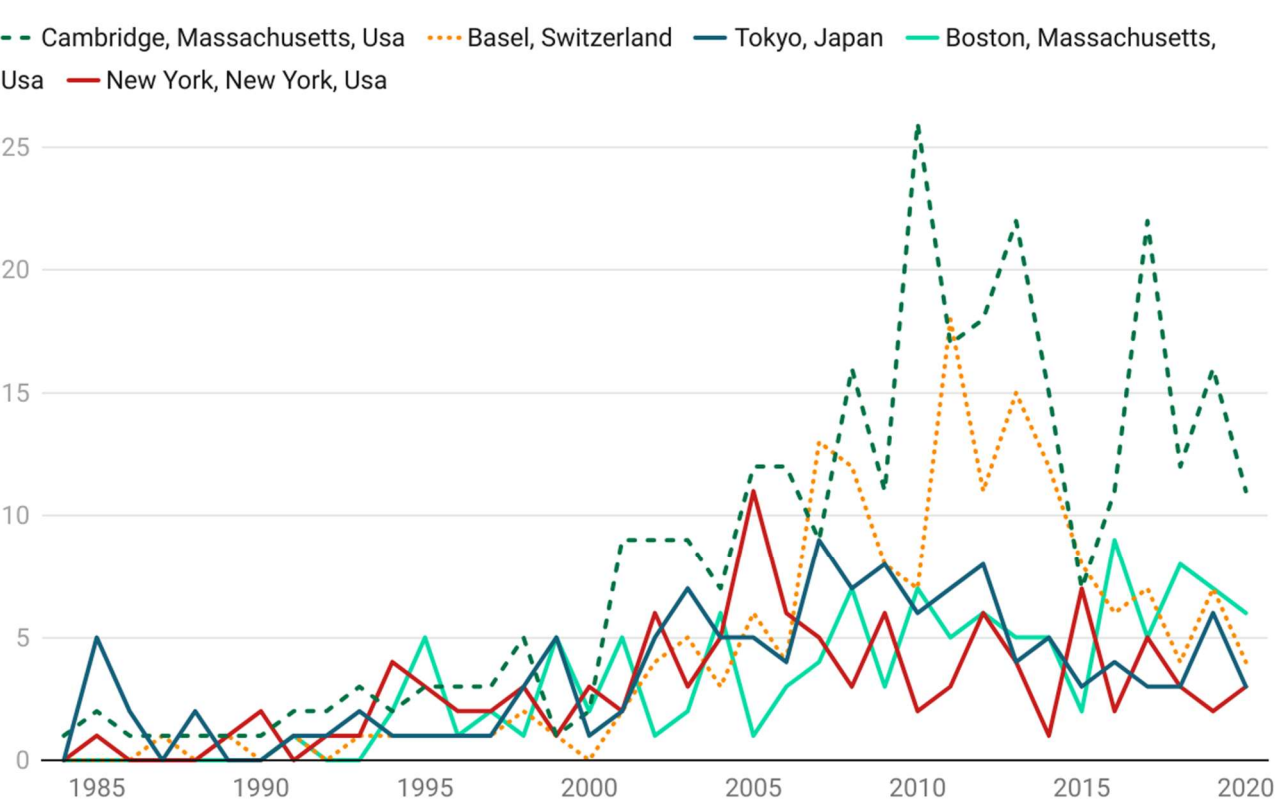
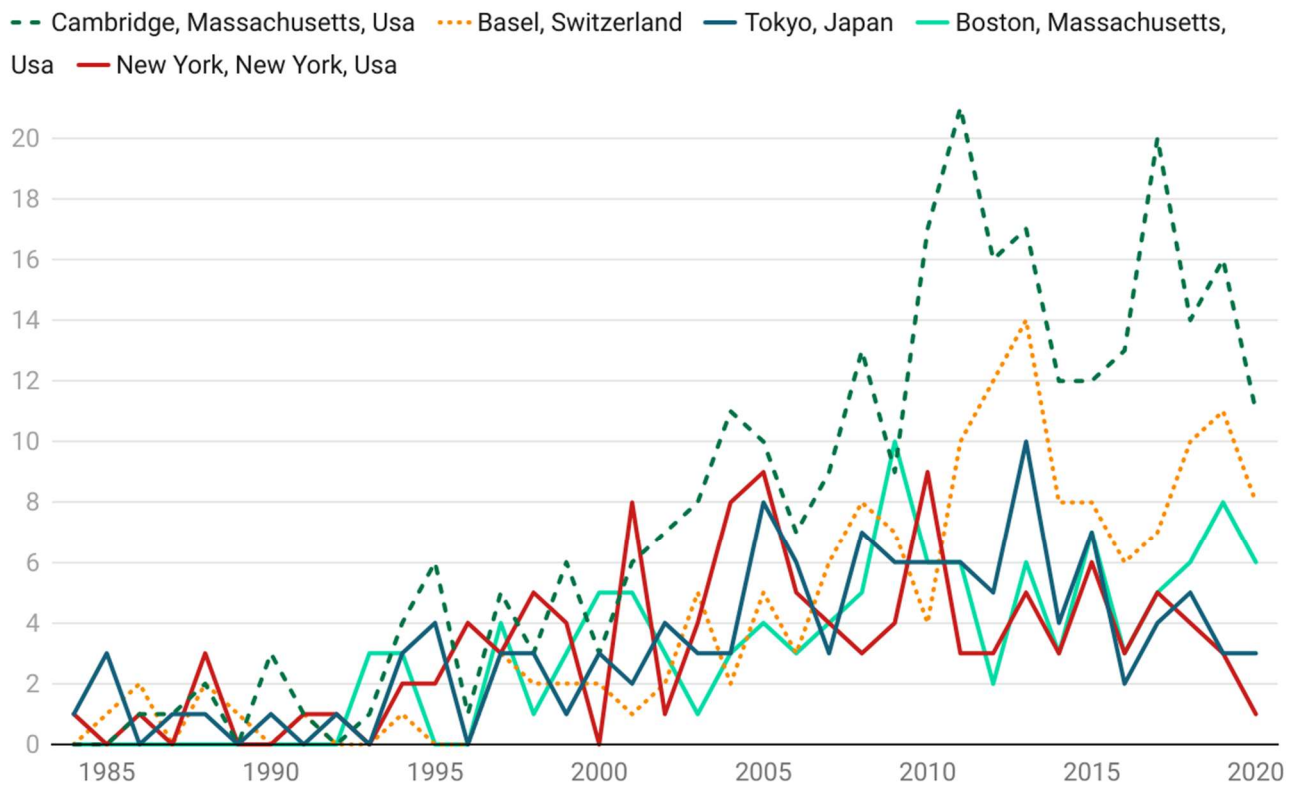


Figure 5.13 Top-five cities indegree centrality



The chart shows indegree centrality values of the top-five cities per average centrality over all the innovation process

Figure 5.14 Top-five cities outdegree centrality



The chart shows outdegree centrality values of the top-five cities per average centrality over all the innovation process

## 5.7 Appendix B

Table 5.3 CPCs for biotechnology and pharmaceutical innovation

| CPC  | Description                                                                                                                                                                                 |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| A61K | PREPARATIONS FOR MEDICAL, DENTAL OR TOILETRY PURPOSES                                                                                                                                       |
| A61P | SPECIFIC THERAPEUTIC ACTIVITY OF CHEMICAL COMPOUNDS OR MEDICINAL PREPARATIONS                                                                                                               |
| B01B | BOILING; BOILING APPARATUS                                                                                                                                                                  |
| B01D | SEPARATION                                                                                                                                                                                  |
| B01F | MIXING, e.g. DISSOLVING, EMULSIFYING OR DISPERSING                                                                                                                                          |
| B01J | CHEMICAL OR PHYSICAL PROCESSES, e.g. CATALYSIS OR COLLOID CHEMISTRY; THEIR RELEVANT APPARATUS                                                                                               |
| B01L | CHEMICAL OR PHYSICAL LABORATORY APPARATUS FOR GENERAL USE                                                                                                                                   |
| B81B | MICROSTRUCTURAL DEVICES OR SYSTEMS, e.g. MICROMECHANICAL DEVICES                                                                                                                            |
| B81C | PROCESSES OR APPARATUS SPECIALLY ADAPTED FOR THE MANUFACTURE OR TREATMENT OF MICROSTRUCTURAL DEVICES OR SYSTEMS                                                                             |
| B82B | NANOSTRUCTURES FORMED BY MANIPULATION OF INDIVIDUAL ATOMS, MOLECULES, OR LIMITED COLLECTIONS OF ATOMS OR MOLECULES AS DISCRETE UNITS; MANUFACTURE OR TREATMENT THEREOF                      |
| B82Y | SPECIFIC USES OR APPLICATIONS OF NANOSTRUCTURES; MEASUREMENT OR ANALYSIS OF NANOSTRUCTURES; MANUFACTURE OR TREATMENT OF NANOSTRUCTURES                                                      |
| C07B | GENERAL METHODS OF ORGANIC CHEMISTRY; APPARATUS THEREFOR                                                                                                                                    |
| C07C | ACYCLIC OR CARBOCYCLIC COMPOUNDS                                                                                                                                                            |
| C07D | HETEROCYCLIC COMPOUNDS                                                                                                                                                                      |
| C07F | ACYCLIC, CARBOCYCLIC OR HETEROCYCLIC COMPOUNDS CONTAINING ELEMENTS OTHER THAN CARBON, HYDROGEN, HALOGEN, OXYGEN, NITROGEN, SULFUR, SELENIUM OR TELLURIUM                                    |
| C07G | COMPOUNDS OF UNKNOWN CONSTITUTION                                                                                                                                                           |
| C07H | SUGARS; DERIVATIVES THEREOF; NUCLEOSIDES; NUCLEOTIDES; NUCLEIC ACIDS                                                                                                                        |
| C07J | STEROIDS                                                                                                                                                                                    |
| C07K | PEPTIDES                                                                                                                                                                                    |
| C11B | PRODUCING, e.g. BY PRESSING RAW MATERIALS OR BY EXTRACTION FROM WASTE MATERIALS, REFINING OR PRESERVING FATS, FATTY SUBSTANCES, e.g. LANOLIN, FATTY OILS OR WAXES; ESSENTIAL OILS; PERFUMES |
| C11C | FATTY ACIDS FROM FATS, OILS OR WAXES; CANDLES; FATS, OILS OR FATTY ACIDS BY CHEMICAL MODIFICATION OF FATS, OILS, OR FATTY ACIDS OBTAINED THEREFROM                                          |
| C11D | DETERGENT COMPOSITIONS; USE OF SINGLE SUBSTANCES AS DETERGENTS; SOAP OR SOAP-MAKING; RESIN SOAPS; RECOVERY OF GLYCEROL                                                                      |
| C12M | APPARATUS FOR ENZYMOLOGY OR MICROBIOLOGY                                                                                                                                                    |
| C12N | MICROORGANISMS OR ENZYMES; COMPOSITIONS THEREOF; PROPAGATING, PRESERVING, OR MAINTAINING MICROORGANISMS; MUTATION OR GENETIC ENGINEERING; CULTURE MEDIA                                     |
| C12L | PITCHING OR DEPITCHING MACHINES; CELLAR TOOLS                                                                                                                                               |
| C12P | FERMENTATION OR ENZYME-USING PROCESSES TO SYNTHESISE A DESIRED CHEMICAL COMPOUND OR COMPOSITION OR TO SEPARATE OPTICAL ISOMERS FROM A RACEMIC MIXTURE                                       |

|      |                                                                                                                                                                                                                                               |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| C12Q | MEASURING OR TESTING PROCESSES INVOLVING ENZYMES, NUCLEIC ACIDS OR MICROORGANISMS; COMPOSITIONS OR TEST PAPERS THEREFOR; PROCESSES OF PREPARING SUCH COMPOSITIONS; CONDITION-RESPONSIVE CONTROL IN MICROBIOLOGICAL OR ENZYMOLOGICAL PROCESSES |
| C12R | INDEXING SCHEME ASSOCIATED WITH SUBCLASSES C12C - C12Q, RELATING TO MICROORGANISMS                                                                                                                                                            |
| C12Y | ENZYMES                                                                                                                                                                                                                                       |
| C40B | COMBINATORIAL CHEMISTRY; LIBRARIES, e.g. CHEMICAL LIBRARIES                                                                                                                                                                                   |
| G01N | INVESTIGATING OR ANALYSING MATERIALS BY DETERMINING THEIR CHEMICAL OR PHYSICAL PROPERTIES                                                                                                                                                     |
| G16B | BIOINFORMATICS, i.e. INFORMATION AND COMMUNICATION TECHNOLOGY [ICT] SPECIALLY ADAPTED FOR GENETIC OR PROTEIN-RELATED DATA PROCESSING IN COMPUTATIONAL MOLECULAR BIOLOGY                                                                       |
| G16C | COMPUTATIONAL CHEMISTRY; CHEMOINFORMATICS; COMPUTATIONAL MATERIALS SCIENCE                                                                                                                                                                    |
| G16H | HEALTHCARE INFORMATICS, i.e. INFORMATION AND COMMUNICATION TECHNOLOGY [ICT] SPECIALLY ADAPTED FOR THE HANDLING OR PROCESSING OF MEDICAL OR HEALTHCARE DATA                                                                                    |

*The table shows CPCs (Cooperative Patents Classification) representing patents technological classes used to filter for biotechnological and pharmaceutical innovations.*

5.8 Appendix C

Figure 5.15 Goodness-of-fit TERGMS estimation Modell period 1984-2004

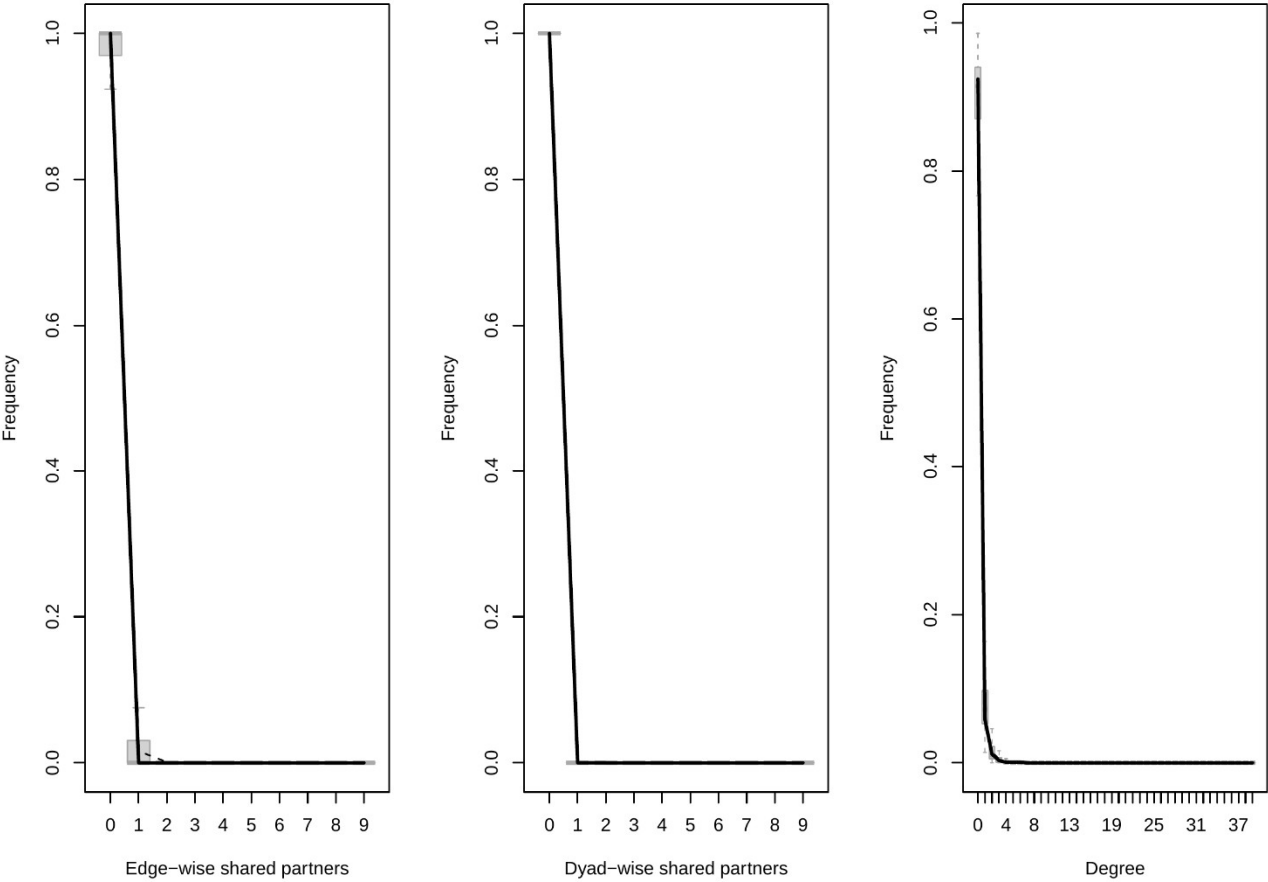


Figure 5.16 Goodness-of-fit TERGMS estimation Model2 period 1984-2004

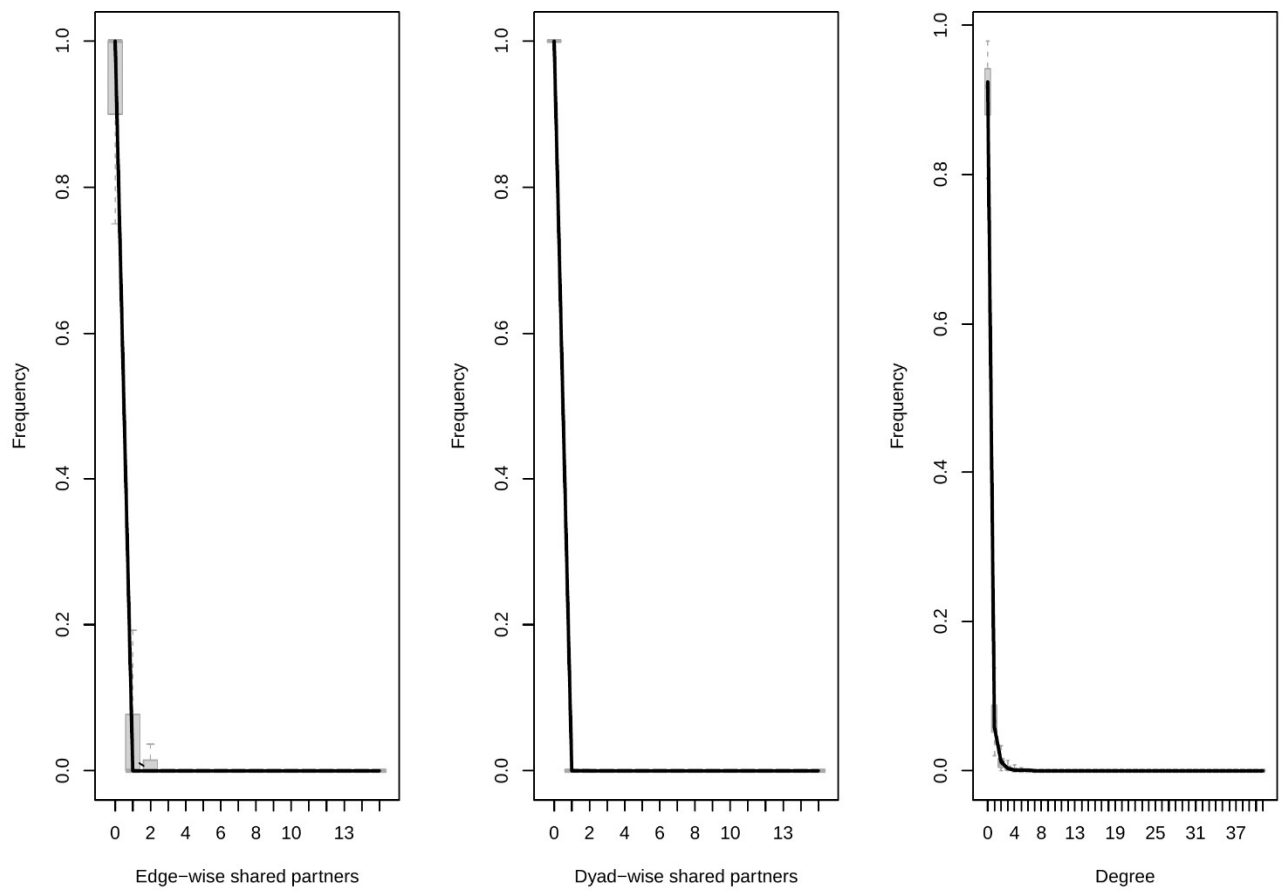


Figure 5.17 Goodness-of-fit TERGMS estimation Modell period 2005-2020

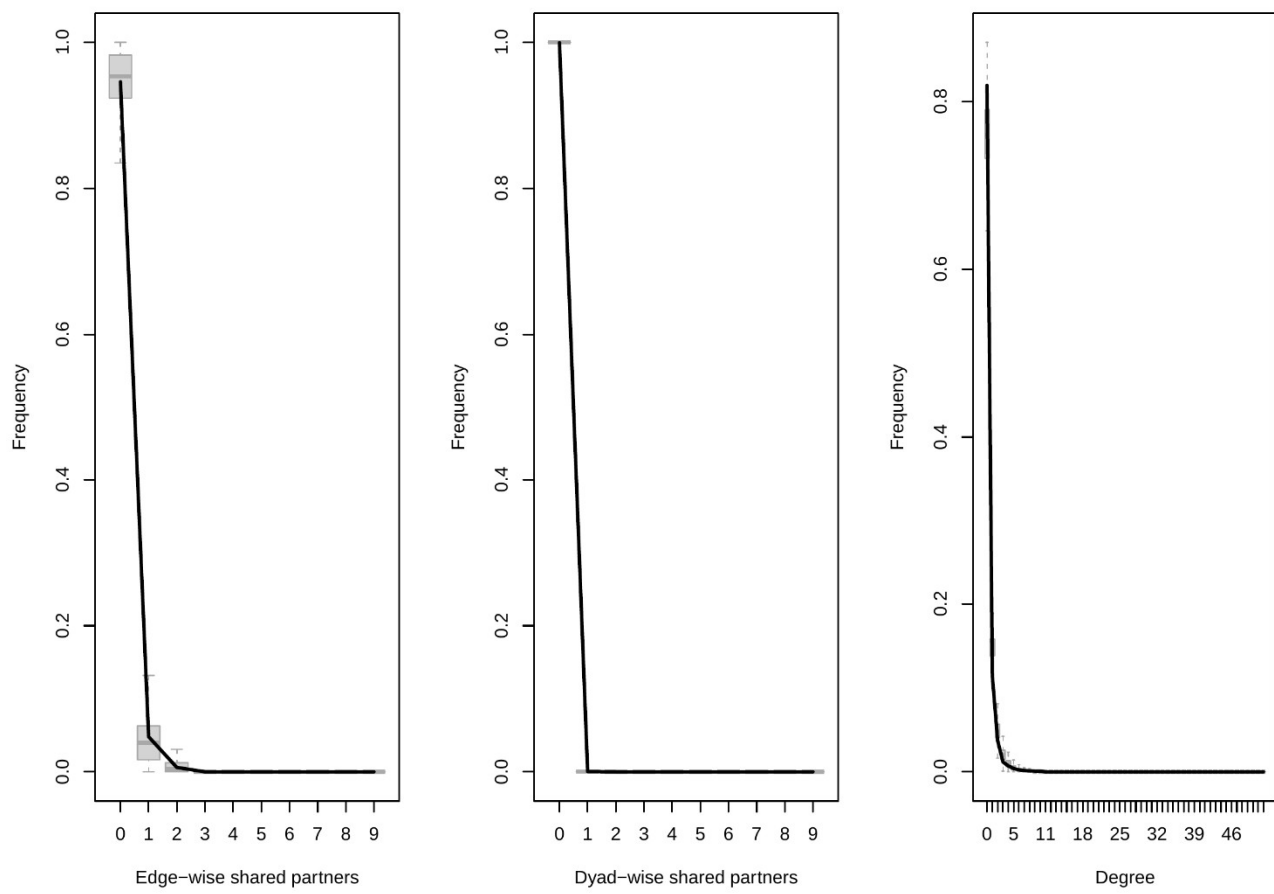
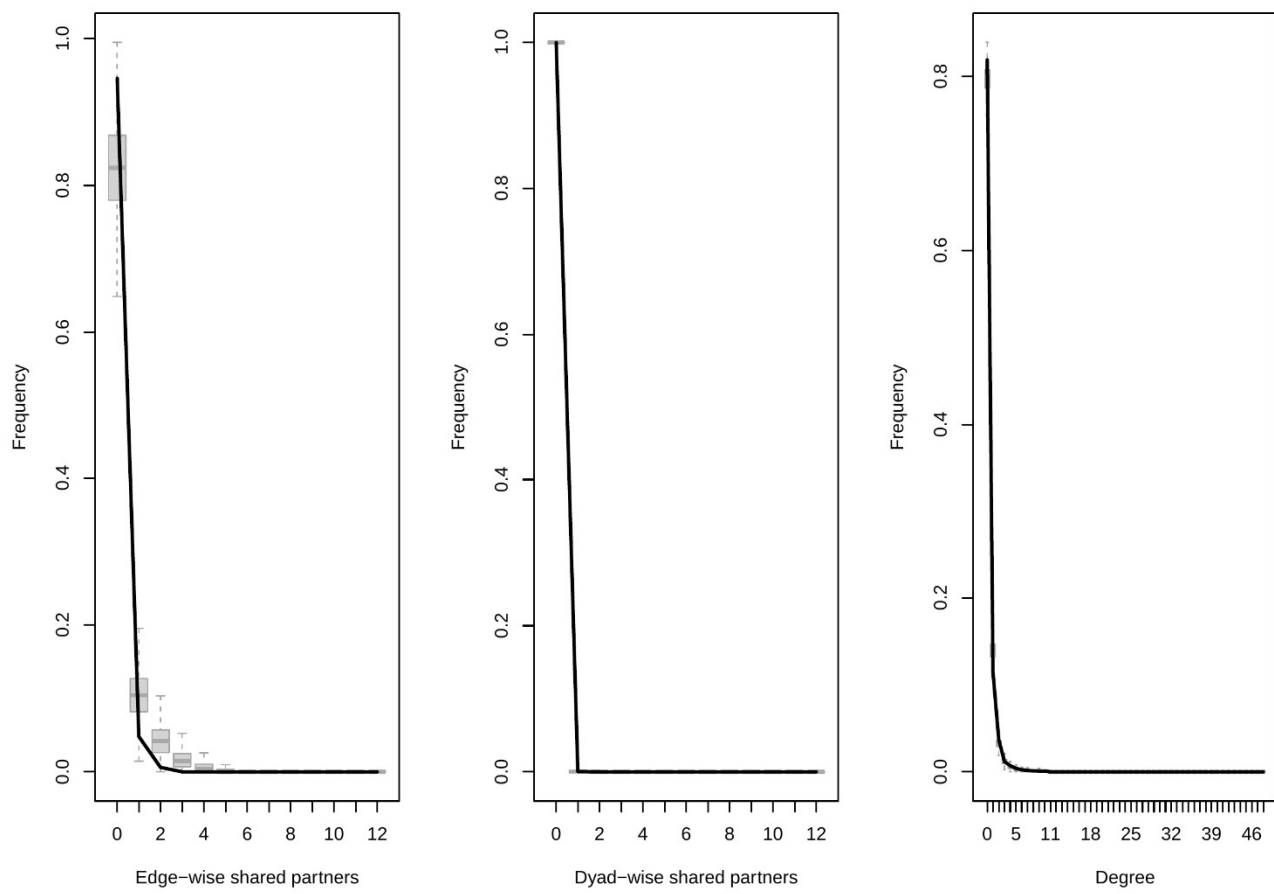


Figure 5.18 Goodness-of-fit TERGMS estimation Model2 period 2005-2020





# Chapter 6

## 6 Inventors' journeys: a life histories analysis to grasp mobility drivers

### 6.1 Introduction

Inventors' mobility is one of the main channels for the spatial circulation and diffusion of knowledge (Breschi & Lissoni, 2009), as well as a powerful driver of technological change (Miguelez & Morrison, 2023). Understanding the factors that influence it is crucial not only for theoretical reasons, but also as an instrument to design effective policies that can leverage this phenomenon.

To date, the literature on inventors' mobility—approaching the issue mainly from a microeconomic perspective—has highlighted how career opportunities, social networks, and various forms of proximity shape inventors' migration trajectories (Dorner et al., 2016; Gorin, 2016; Kerr et al., 2016). However, focusing exclusively on external-objective variables, while important, risks reducing inventors' decision-making processes to a deterministic exercise, ignoring the unique story of those involved. This approach tends to underestimate the subjective dimension through which inventors interpret, weigh, and assign meaning to these factors. In other words, understanding why an inventor chooses to relocate (or not) requires looking not only at what is “rationally” convenient, but also at what the inventor perceives as meaningful in the pursuit of their aspirations and in giving value to their work.

This study aims to address this knowledge gap by adopting a qualitative approach based on the life histories of eleven inventors who contributed to the development of mRNA COVID-19 vaccines. The goal is to uncover, through their narratives, the factors they consider relevant in their decision-making processes, and how these choices shaped their careers and the resulting geographies of innovation. This leads to the following research questions: Which factors do inventors consider decisive in their location choices across their career path, and how do these factors influence the spatial configuration of the innovation process? Answering these questions serves a dual purpose. On one hand, it aims to deepen our understanding of the factors that guide talented individuals in choosing their location in different career stage, by exploring their subjective decision-making processes and positioning them within a debate largely dominated by structural and microeconomic approaches. The use of life histories, integrated with an evolutionary perspective, bridges a more systematic framework with an interpretative one, providing a more comprehensive basis for future research. Life histories, in fact, offer insight into why and how mobility decisions are made, while an evolutionary perspective helps explain how these individual choices co-evolve with—and are reciprocally shaped by—socio-spatial contexts, producing recurrent patterns that evolve over time. On the other hand, it seeks to offer insights for policies aimed at attracting and retaining highly skilled human capital in the context of the “war for talent” (Michaels et al., 2009) which implications are exacerbating nowadays. By distinguishing and analyzing the relationship between objective and subjective drivers of mobility, this work offers input for an understanding of inventors' mobility drivers that combines structural conditions and economic incentives with the fulfilment of individuals' inner aspirations.

The analysis shows that inventors' choices are primarily guided by intrinsic, open-ended motivations—curiosity, the pursuit of discovery, and problem-solving—which are shaped by the socio-spatial context. This interaction generates a dialectical, co-evolutionary dynamic closely tied to the innovation process and its spatial dimension. The resulting self-reinforcing dynamic contributes to a perceived spatial division of the innovation process within a geography where “moving is part of the game”. At the same time, inventors point to potential risks, as the current trajectory increasingly lead the avoidance of highly uncertain, high-impact research. These findings imply the need for policy measures that, on the one hand, secure the pursuit of high-risk research through multi-year, person-based funding and, on the other, promote the circulation of inventors—rather than mere attraction and retention—by reducing the costs associated with mobility.

The chapter is organized as follows: the next section presents the theoretical background on the drivers of mobility from different perspectives; section three outlines the data-collection process and details the methodology; section four reports the results; and the final section discusses their implications.

## **6.2 Theoretical Background**

The scientific literature on inventors' mobility has highlighted that it is one of the main channels for the spatial diffusion of tacit knowledge (Breschi & Lissoni, 2009) and, as already mentioned, a key driver of regional technological change (Migueluez & Morrison, 2023). As such, inventors' mobility plays a crucial role not only in avoiding lock-in effects caused by the path-dependent nature of innovation processes (Dosi, 1982b), but also in opening new trajectories for regional development. Given its importance for innovation and, by extension, for regional economic development, research has increasingly sought to identify the factors that drive this specific type of mobility. Specifically, understanding these factors can be an indispensable asset for policy-makers because, in what has been termed the “war for talent” (Michaels et al., 2009), the capacity to attract and retain highly qualified human capital is pivotal for enhancing territorial competitiveness, sustaining innovation, and ensuring long-term economic growth. The most widespread approach in the literature is a microeconomic one, where the inventor is conceptualized as a boundedly rational agent (Tunali, 2000) who decides whether to migrate based on a cost–benefit calculation aimed at maximizing gains and minimizing losses.

It is important to note that for inventors, just the act of migrating is often itself a benefit, as it has been shown to increase their productivity (Van Der Wouden & Rigby, 2021) and potentially lead to higher wages. Yet this is not enough: even when framed in this narrow economic perspective, the decision to relocate will only be made if the expected benefits outweigh the costs of moving. Key incentives for migration include a strong wage differential between origin and destination, better job opportunities, and the chance to enhance one's skills (Kerr et al., 2016). At the same time, inventors seek to minimize relocation costs, which often influences destination choice, leading to a preference for countries with geographical, cultural, technological, or institutional proximity (Gorin, 2016).

Another key concern for inventors is minimizing the costs associated with information asymmetries. In this regard, social networks play a critical role. Dorner et al. (2016), leveraging the natural experiment of German reunification after the fall of the Soviet Union, showed that the large migration wave of inventors from East to West Germany was facilitated by the presence of social ties. These not only reduce the costs linked to information asymmetries but also serve as an additional incentive for inventor mobility when such networks are ethnically diverse (Campo et al., 2022), as inventors can benefit from the externalities generated by diversity.

Straightforward economic calculations often overlook those intangible factors that are hard to observe and quantify yet can be highly appealing to highly skilled workers such as inventors. The issue gained prominence with Richard Florida (2002) conceptualization of the “creative class,” which highlighted how immaterial factors can serve as powerful attractors for these “creatives” through his 3T framework (Technology, Talent, Tolerance). Following this line of inquiry, numerous studies have employed various proxies to show that intangible factors—such as quality of life and social tolerance—also exert a strong pull in attracting high skilled workers (Acs & Megyesi, 2009; Florida, 2014; Rao & Dai, 2017). Nonetheless, these studies face several limitations, among which there are opposing views suggesting reverse causality, namely, that amenities follow people rather than the other way around (Albouy & Stuart, 2020).

The factors discussed so far mainly concern objective influences—economic or otherwise—on inventors’ choices. However, decision-making is a highly subjective process, and limiting the analysis to external factors risks offering a deterministic interpretation of inventors’ mobility. Some efforts have been made to integrate individual characteristics into the analysis, such as individual productivity (Di Lorenzo & Almeida, 2012), skill diversification (Haller, 2022), and risk preferences (Bisset et al., 2024). Still, these contributions are not sufficient to fully bridge the gap between inventors’ subjectivity and the broader economic, social, and geographic context. These studies tend to focus on a single factor that influences individuals’ choices, thereby minimizing the actual complexity of the decision-making process. In addition, they fail to consider how this process evolves over time and interacts with different socio-spatial contexts.

Since the decision to migrate is highly subjective and constrained by circumstances that vary from one individual to another, the starting point for understanding it must be intrinsically biographical (Findlay & Li, 1997; Halfacree & Boyle, 1993).

For this reason, this study adopts a life history approach to explore the decision-making processes of inventors over time and how these processes interact with external factors.

While this approach has been more widely used in migration and mobilities studies, it has been less commonly applied to the mobility of highly skilled workers. Existing studies have for example focused on the perception of the migration experience (Kōu & Bailey, 2014), the social dynamics following such trajectories (Kōu et al., 2015), the female migration driven by non-work-related motivations (Liversage, 2009), the evaluations of attraction and retention policies (Toma & Villares-Varela, 2019), and return migration (Ma et al., 2023). Here, by contrast, I use the analysis of the life stories of inventors who contributed to the innovation process, delving into their motivations and viewing external factors through their eyes, in order to reconstruct the dynamics that shaped their trajectories and the resulting territorial patterns.

Without denying the contributions that, on the one hand, microeconomic approaches and, on the other, qualitative migration studies have made to our understanding of this phenomenon, this chapter focuses exclusively on inventors’ mobility—an empirical case that differs from more general forms of migration in at least three respects. First, inventors’ spatial mobility is more closely tied to their career trajectories and often consists of multiple moves rather than a single migratory event. Second, it is strongly shaped by organizational and institutional contexts that determine where research can be conducted. Third, as discussed in the previous chapter, the geography of opportunities available to inventors tends to evolve alongside the innovation process, and the meanings inventors attach to specific places may vary over time, even beyond the own personal economic return.

In addition, I adopt an evolutionary approach in a generalized sense: the goal is not to import biological detail, nor the determinism often associated with it; rather, I use abstract principles such as variation, selection, and retention to frame the mechanisms linking individual choices to the broader socio-spatial context (Campbell, 1965; Hodgson & Knudsen, 2010; Nelson & Winter, 1982).

Inventors' life histories allow both a view of the “variation” expressed by their intrinsic, subjective motivations and an understanding of how they perceive the objective factors that influence—and “select”—their choices. More importantly, an evolutionary perspective highlights the co-evolutionary dynamics between individual decisions and socio-spatial contexts, in which the former, though dependent on the latter, can reshape future capacities and opportunities (Arthur, 2009; Boschma & Frenken, 2006; Boschma & Martin, 2010; Murmann, 2003). In evolutionary economic geography, “co-evolution” is used to explain how regional development unfolds through reciprocal feedbacks between path development and institutional change, yet the concept has often remained too vague for direct empirical application. Benner (2022) proposes to retheorizing co-evolution as a multidimensional framework that distinguishes (i) industrial–institutional co-evolution (the interplay between industrial/organisational dynamics and institutions), (ii) path multiplicity (multiple co-existing and interacting paths within a territory), and (iii) multiscalar/nestedness (the embedding of these dynamics across spatial scales and interscalar relations). In this chapter, I use this lens to interpret inventors' mobility as part of a broader co-evolutionary dynamic between (a) the evolving innovation process, (b) socio-spatial contexts and institutions, and (c) inventors' career trajectories. This approach helps connect life histories to the emergent spatial regularities identified in the quantitative chapters, such as the role of hubs and the co-existence of circulation and concentration.

### 6.3 Methods and positioning

#### 6.3.1 Data

This study adopts a qualitative approach based on the life histories of inventors who contributed—either directly or indirectly—to the development of mRNA COVID-19 vaccines.

The sampling process involved several stages. First, all patents relevant to this innovation were identified, starting with those listed by Gaviria & Kilic (2021) as essential to vaccine production, and including all patents cited by these core documents. From this patent set, all inventors listed in the documents were extracted, allowing the inclusion of both those directly involved in the final product and those who contributed at earlier stages of the innovation process. Publicly available contact information was then used to reach out to the inventors. Out of approximately 600 contacted individuals, only 11 agreed to be interviewed<sup>4</sup>.

In line with the qualitative framework, the goal was not statistical representativeness, but rather to obtain a heterogeneous group of interviewees that would allow for a deep understanding of different perspectives. Table 6.1 shows the demographic profile of the interviewees. While there is a predominance of male participants over the age of 65, this reflects the nature of the population under study. Among the eleven inventors, seven had lived in a country different from their origin country, while three of the remaining four had experienced intra-national mobility.

The unstructured biographical interviews were conducted between October 2024 and March 2025 via video calls to accommodate geographic distance, time zone differences, and the interviewees' schedules. Interviews lasted in a range of 23 and 73 minutes (mean 52 minutes). All were audio-recorded and transcribed using Microsoft Word's dictation tool, followed by manual verification for

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<sup>4</sup> The low participation rate was strongly influenced by the low response rate. Because inventors' contact details were gathered manually and consisted of professional/work email addresses, participation requests were, on the one hand, sometimes blocked by corporate policies that restrict external emails for security reasons and, on the other, failed to reach recipients who had changed jobs and no longer used the listed address.

accuracy. The interviews were open and informal, encouraging inventors to discuss topics they personally considered relevant.

*Table 6.1 Inventors' Demographic Information*

| ID | Gender | Age   | Education | Patents | Employment           | Origin Country | Current Country |
|----|--------|-------|-----------|---------|----------------------|----------------|-----------------|
| 1  | M      | 65+   | PhD       | 50      | Vice President       | Italy          | Canada          |
| 2  | M      | 65+   | PhD       | 35      | CEO                  | United Kingdom | Canada          |
| 3  | M      | 35-50 | PhD       | 21      | Project Manager      | Germany        | Germany         |
| 4  | M      | 65+   | PhD       | 7       | Professor            | France         | France          |
| 5  | M      | 35-50 | PhD       | 1       | CEO                  | Canada         | Canada          |
| 6  | M      | 50-65 | PhD       | 5       | Professor            | Turkey         | United States   |
| 7  | M      | 65+   | PhD       | 116     | Director             | France         | France          |
| 8  | M      | 65+   | PhD       | 102     | Retired              | United States  | United States   |
| 9  | F      | 35-50 | MD        | 3       | Professor            | Italy          | United States   |
| 10 | F      | 65+   | PhD       | 2       | Senior<br>Researcher | Italy          | Italy           |
| 11 | M      | 65+   | PhD       | 27      | Professor            | Romania        | United States   |

### 6.3.2 Analysis

In line with the biographic interviewing guidelines, the analysis was conducted entirely manually, without the use of coding software, following an iterative process of reading, annotating, and synthesizing that prioritized direct engagement with the voices of the interviewees. Coding was inductive and data-driven: initial codes were generated directly from the transcripts rather than imposed a priori from the literature. The literature served only as sensitizing context at a later stage, helping to interpret and situate the emergent patterns.

Transcripts were read multiple times, with marginal notes used to capture key observations and organize the stories. Significant segments were then highlighted and assigned provisional codes corresponding to broader thematic areas. These codes were revised and refined through repeated comparison, ultimately leading to a final coding structure based on four macro-themes: intrinsic motivation, socio-spatial context, co-evolution of mobility and geographies, and spatial division of innovation process.

This process made it possible to preserve the richness narrative of the interviews and allowed greater flexibility during the analytical phase.

### 6.3.3 Researcher Positioning

As an Italian PhD candidate in economic geography, based at an Italian university, I do not share a disciplinary background with the interviewees. However, we are connected through our engagement in scientific research and, to some extent, experiences of mobility.

Three of the interviewees were also born Italians, a proportion that is relatively high given the overall population. This self-selection, likely due to a sense of affinity with a fellow national, facilitated understanding of specific institutional and cultural references and enriched the data collection.

Regarding the relationship established between myself and the interviewees, and the power dynamics involved, my younger age and earlier stage in the academic career helped reduce the risk of influence and fostered a more informal, sometimes “pedagogical” dynamic in which inventors often assumed the role of mentors. This dynamic enabled a deeper understanding of the complexities in their life

trajectories, although it was necessary during analysis to distinguish between lived experience and advice directed at a young researcher.

Additionally, some of the interviews took place while I was temporarily residing outside my home country for research purposes, and others were conducted shortly after my return. This experience of being a “researcher in transit” sharpened my sensitivity to elements in the interviewees’ narratives that might otherwise have gone unnoticed.

## 6.4 Results

### 6.4.1 Blind vocation and intrinsic motivations

The analysis of inventors’ life histories allows for a deeper understanding of the motivations behind their decisions and how these shape not only their mobility and career trajectories but also the nature of the innovative outcomes they produce. In doing so, the inventors’ narratives offer the opportunity to observe aspects not directly related to their location choices—such as their aspirations—which nonetheless serve as an internal compass driving their decision-making process.

It is particularly interesting to examine what might be called the genesis of their career paths or the emergence of their professional aspirations. Some interviewees, such as inventor 1, reported having always known that they would pursue research in a specific field:

*“You know, whether or not you believe it, I became interested in chemistry at 7 and I got my first chemistry set at age 8. At age 8, I was certain I wanted to be a chemist.”*

This drive appears to be almost irrational, as it is not based on understanding or knowledge. Some inventors report that, at the beginning of their careers, they “vaguely” wanted to become researchers, while “not really understanding and know what it is”. Driven by this inner drive, they later realize, in retrospect, that becoming researchers with certain specific interests happened through a kind of “snowball effect.”

This typically emerges at a young age, initially taking the form of a hobby that would later guide their professional choices, for example, inventor 4 spoke of “collecting insects, plants.” Some of them recall the exact moment when this realization occurred, as in the case of inventor 5:

*“What really got my mind on fire, was learning about DNA code and how it's translated into proteins through mRNA. So to me this was kind of a really important moment where I realized that pretty much anything and everything can be changed”*

In other cases, this unfolds through what inventor 2 described as an “organic process,” without a clear turning point.

What is particularly striking is that, at the foundation of their life trajectories, there often lies a kind of “blind” vocation that, while certainly shaped and mediated by context, carries a strong element of contextual indeterminacy and uncertainty.

To better understand this, it is essential to examine the values that emerge from the inventors’ narratives. Foremost among these is curiosity and the desire to understand and learn. Some of them “never thought of research as work” but rather as “a great pleasure and an opportunity”. It was the opportunity to discover and learn new things about nature — facts that no one had yet discovered or realized. Very often, this is the “driving force” they mention behind their choices.

This is sometimes accompanied by motivations that could be described as social oriented, especially in relation to the specific field of innovation under study, this can have a “potential to the lives of real people”, which brings a “big emotional aspect” to their work.

At times, this “blind” vocation manifests as a strong desire to solve problems, as exemplified by inventor 1, who sees himself as a “mechanic” capable of fixing chemical structures. Ultimately, the primary drive influencing inventors’ decisions appears to be what is commonly referred to as intrinsic motivation (Sauermann & Cohen, 2010).

This perspective helps explain why models of individual decision-making based solely on economic utility maximization fall in fully accounting mobility. This is not to say that economic considerations play no role—they certainly do, particularly in terms of “opportunity”—but rather that their role should be seen as enabling the fulfilment of inventors’ intrinsic motivations, rather than serving as the main drivers, at least accordingly with the self-perception and self-representation of inventors.

Indeed, the inventors themselves often recall instances in which their choices were not driven by economic incentives alone, for example, inventors 7’s decision to turn down a corporate position, that would have given him a higher salary, but he nevertheless decided to decline the offer, having realized that he “wanted to remain an academic”.

Other examples include inventor 2’s refusal to relocate even though “they pay you to go,” or inventor 1’s sense of fulfilment in having contributed, despite not receiving any formal recognition:

*“So subsequently for intellectual property reasons, I had to stop contributing to that effort [...] The compound, by the way, is called [chemical compound name]. They called it [chemical compound name]. You know, with the initials of my name.”*

The blind vocation and intrinsic motivations underpinning inventors’ work shape not only their life trajectories but also the very nature of the innovation processes they help generate.

Their life stories appear far from linear, often chaotic and marked by elements of chance. A clear example of this is the flexibility and sudden shifts in academic fields experienced by some of them, as illustrated particularly well by inventor 7:

*“In the beginning, I wanted to become a mathematician. Works in physics. So I graduated in engineering school. That was targeted to mathematics and physics, but I found that there were maybe more, for my point of view, sighting and fastly moving innovation in biology. So why? Why I moved? Because I found many new concepts appear. Maybe, more cruising speed, much more than in mathematics and physics.”*

Inventors often describe these seemingly random turns in their paths as functional and ultimately beneficial to their work.

The role of chance becomes even more apparent when looking at the innovation process itself. It is well known that serendipity plays a fundamental role in innovation—particularly in drug discovery (Ban, 2006)—and inventors appear acutely aware of this.

For many of them, curiosity-driven research—guided by the intrinsic motivations discussed above—is seen as essential. Their inventions or discoveries are frequently described as purely accidental: some consider themselves simply “lucky,” like inventor 4, while others place stronger emphasis on serendipity, such as inventor 1, who described their most important discovery by stating: “I’d like to say that we were right, for the wrong reason”.

Some of them, like inventor 6, seem aware of the parallel between their own lives and scientific work, both marked by a foundation of chance and uncertainty:

*“So, one sentence or one word: adaptation. be adaptive, right. Because life evolves, cancer cells evolve right when you expose them to therapy, they evolve. Individual scientists, we have to adapt. We have to evolve and we have to be on top of mountain and see the scenery and identify other peaks and opportunities. For personal growth and also to be impactful”*

Ultimately, the primary force driving inventors to action can be identified as a diverse set of intrinsic motivations, a blind and seemingly indeterminate vocation seeking expression.

Starting from this apparently random internal drive, it is the encounter with the socio-spatial context that shapes their choices and, indirectly, the outcomes of their work.

#### **6.4.2 Socio-spatial context and selection**

The inner subjective drive represented by inventors’ intrinsic motivations takes shape as concrete choices when it interacts with the socio-spatial context.

It is at this point that the contextual and structural variables—those most extensively explored in the literature—come into play.

The inventors’ narratives offer valuable insight into which of these factors are perceived as most important. One factor clearly stands out as central in shaping both life and mobility decisions throughout their careers: the need for funding. This economic imperative appears to be the most influential contextual factor. Inventor 6, for instance, illustrates how the search for funding shaped the trajectory of their career:

*“I followed up on my PhD advisor's guidance that he said, If I want to be a successful, you know, life scientist, probably, I should go into more research fields involving in human health, rather than just focusing on a very narrow biotechnology field, because there aren't much funding opportunities.”*

The same inventor highlights how this need can lead to extreme mobility decisions—for example, “went to the Netherlands by hitchhiking”.

The need to secure funding affects not only inventors’ mobility and life choices, but also their ability to conduct research, especially when they decide to start a company, as exemplified by inventor 5, who reports that, in the first years after founding his company, it is not really possible to do science; rather, there is a need to find investors, demonstrate feasibility through small projects, and, at the same time, work in order to support oneself.

Funding, then, proves to be essential not so much for maximizing individual utility, but rather as a prerequisite for assuming the risks inherent in an uncertain activity like research.

Inventor 3 illustrates this well, emphasizing how limited resources place a greater burden of responsibility on individual researchers:

Carrying such responsibilities naturally makes inventors less willing to take risks. Conversely, having a secure financial position allows them to take chances—even the risk of failure—in a process where mistakes are seen as steps forward, as inventor 4 explains:

*“What I also papers on this time there was something like 6 or 7 examples in the world. Nothing else. And so people were interested but, well, glad to see. Nevertheless, I decided to continue. What the*



*hell no? I was completely crazy. And I must say something else: I was already a professor at the university, so I had a safe position so I could take big risks.”*

The same inventor also emphasizes that resources do not merely provide better tools for research but also create opportunities for exploration “in terms of different topics around”.

Another frequently recurring factor relates to human relationships, which can be broadly divided into family ties (including romantic relationships) and professional or social networks, categories that are not necessarily mutually exclusive.

The impact of this human dimension on inventors’ choices, and therefore on their mobility, is not linear. In many cases, having a partner and children has led inventors to limit their mobility for the sake of their loved ones, as reported by inventors 3, 5, and 7. They report that, in their life choices, they also had to consider the well-being of their family, safeguarding their partners’ careers and realizing that, most likely, dragging their family around the world according to their individual career needs “was not really going to work.”

In other cases, family relationships did not hinder mobility, as stated by inventor 1, who reports that, since his family consists only of himself and his partner, “moving is really a non-issue,” or at least “easier than for a lot of people.”

At other times, emotional ties serve as an additional reason for mobility, as explained by inventor 9:

*“The other reason was that my then-boyfriend, who would later become my husband, was already in Boston doing research, so that served as an additional motivation. Still, I have no regrets.”*

Professional networks, which have received considerable attention in the literature, remain an important channel for the spatial movement of inventors, as acknowledged by inventor 2:

*“There are certain decisions I made that had a profound impact on where it went next. But certainly, the decision to come to Vancouver to work with [colleague name] was instrumental because he, I think, had the recognition that academic research could be applied to clinical development at a time where almost nobody was sort of thinking along those lines”*

However, these are not the only human ties that inventors consider in their decision-making processes. Often overlooked are other forms of connection that, as shown, may have an even greater impact.

Among the additional external factors influencing inventors’ decisions, the context of their origin country plays a prominent role. Inventor 1 recalls making the decision to leave Italy at the beginning of his academic journey, during a period of palpable political tensions and ideological clashes, and a particular event led him to believe that the local environment was not conducive to research, rather it actively discouraged it.

Inventor 9, on the other hand, found herself in a context that did not allow her to do exactly what she wanted, namely, to combine research and clinical practice. As a result, she actively sought out an environment that would enable her to pursue both.

The context in which inventors find themselves can therefore “push them away” when it clashes with their intrinsic motivations—provided they have the opportunity to leave—just as certain environments can encourage them to stay or even attract them.

This is particularly true for settings described by inventors as “international” and “progressive,” where it is easier “to fit in.” Similarly, contexts that support translational research are also seen as favourable, as noted by inventor 2:

*“The University of British Columbia certainly, back in the in the 80s and 90s, was very interested in supporting academic researchers in trying to commercialise their technologies and, you know, built out laboratories, you know, office and laboratory facilities that could be used by start-up companies, for example to begin to transition out of the academic environment”*

These factors act as a filter imposed on the initial, generic, and indeterminate drive represented by inventors’ intrinsic motivations, thus shaping and selecting their trajectories.

However, the resulting mobility outcomes generated by this dynamic can, in turn, transform socio-spatial contexts and, by extension, the very selection mechanisms themselves.

### **6.4.3 Co-evolution dynamics**

To understand how inventors’ actions and the socio-spatial context mutually influence one another, it is necessary to start from the localized output they produce: innovation.

Inventors often describe this process as beginning within a small research group that—consciously or not—is in competition with others. For reasons often described as “fortuitous,” one group achieves a breakthrough, and this success feeds back into and transforms the context that produced it, as explained by inventor 1:

*“At that time, there was a very significant pharmaceutical industry in Canada. All that vanished almost overnight during the financial crisis of 2008. It's unbelievable [...] But now, with the advent of the vaccines, you know, there is a huge development of pharmaceutical industry here in the City of Vancouver because that's where those started”*

Localized discoveries—especially those that are broad in scope and disruptive in nature—can also influence other contexts, according to the experience of inventor 4. He recalls having benefited from the results obtained in Chinese laboratories, results he describes as “completely unpredicted” and “discovered by accident”, but which triggered a series of further discoveries in other places as well. Following a discovery, a virtuous cycle is often triggered—characterized by emulation and government intervention—as exemplified by inventor 2:

*“As soon as you have some success, then that just acts as a magnet and other researchers want to emulate that success. And so it just creates a self-sustaining community and it was also the, as I say, the university was supportive, the provincial governments were supportive, they would provide grants to allow researchers to get started. And that led to a fairly strong biotech sector in Vancouver”*

All of this happen because a discovery must leave the lab in order to be transformed into a marketable product.

This stage is often overlooked at first by inventors, who—as already seen—are driven by motivations that differ from purely market-oriented ones. Inventor 8 describes how this transition occurred during a pivotal moment for the field, during the 1970s, when researchers — who had initially disregarded the possibility of collaborating with industry — gradually realized that “if the biotechnology revolution was going to have its full impact,” they needed to become partners with companies.

This transition is not immediate, especially “when nobody has done that and you have to find customers.”

Once again, the socio-spatial context can play a facilitating role in this process through “policy to help the start [of] young companies.”

This virtuous cycle has the power to transform a place, and thus the socio-spatial context that will go on to shape the decisions of future inventors. Evidence of this can be found in the experiences of some inventors who were involved from the very beginning and are therefore able to speak directly about the transformation that occurred over time, such as inventor 3:

*“Nowadays it's quite impressive. It's really an industrial area, so [company name] has built them massively in their big times around COVID. They acquire a lot of money, so they build a lot. But there is also, I think, Amazon and Google and, you know, other tech companies who have their smaller or bigger buildings now occupying this area. So for me, you know, knowing the old days and a lot of empty space and then going there again and recognizing all of those buildings, this was quite impressive.”*

In this process of co-evolution between inventors' actions and the socio-spatial context, mobility plays a fundamental role.

It is well known that mobility enables the transfer of knowledge—often tacit knowledge—across space, bringing benefits to the receiving locations. The life stories of inventors offer additional insights into this phenomenon.

First, they shed light on what is actually being transferred. Rather than referring simply to “knowledge,” inventors often speak first and foremost of “expertise”, which—especially when general in nature—can be more easily transferred. Inventor 1 illustrates this point through a comparison between his work and that of a mechanic:

*“You know, all the mechanic, so to speak, can fix a Fiat or a Jaguar or a Ferrari, right? Yeah. So once you understand how, you know, the mobile works, you can fix any kind of car. Well, it's a little bit like that, you know, given my training in synthetic organic chemistry”*

In other cases, it is possible not only to transfer one's expertise gained elsewhere, but entire technologies developed in a different context, as in the case of inventor 6, who acquired the product that he developed at the previous company and transferred it when he received a better offer.

In addition, especially in the case of highly influential inventors, it is not just their expertise that travels with them, but they are often able to relocate entire research groups, considered the “heart of the laboratory”, making the spatial impact of mobility even more significant, as exemplified by inventor 8:

The role of mobility in advancing the innovation process—and thus impacting the broader context—is acknowledged by inventors not only through their own mobility experiences, but also in reference to key individuals who have made a significant impact.

Inventor 2, for example, reflects on this while speaking about the person widely regarded as the father of a particular invention, with whom they had the opportunity to work:

*“He had done his undergrad and PhD in University of British Columbia. He then went in Cambridge where he learned NMR microscopy and also in Utrecht, where he was working with researchers studying lipids because he wanted to apply biophysical techniques to understand lipid macromolecular structure, and so his postdoctoral travels were really predicated on gaining the knowledge he needed to be able to do the research that he wanted to, and then he was able to take a position at UBC in the Department of Biochemistry, having, as I said, you know, been in Cambridge and Utrecht and being able to sort of bring back that experience and that training to then apply it in his own research group at UBC.”*

Thus, mobility—initially triggered by the encounter between intrinsic motivations and the socio-spatial context—ultimately reshapes that very context, thereby influencing how the intrinsic motivations of future inventors will manifest.

#### **6.4.4 Niches formation, spatial division of innovative process and consequences**

As just seen, inventors' actions can shape the socio-spatial contexts involved in the innovation process.

The very formation of innovation hubs—often considered the geographic engines of innovation—is frequently attributed to the presence and movement of the “very brightest people.” Inventor 8 emphasizes that while these places are excellent for conducting research, as an elite environment, they carry a hidden trap: an excess of comfort that can lead to a narrow scientific vision, ultimately detrimental to the research itself. This is one of the reasons why is essential to inventors to move and “learn for being exposed to another environment”.

The result is a situation in which moving “is part of the game”: regardless of their origin, the role of the scientist is to remain constantly dynamic—to look for opportunities wherever they arise and to be able to adapt—something inventor 7 learned through experience:

*“What I have learned is: a researcher, a scientist, since the field is dynamic, every day we are learning something new. But also, life of a researcher is very dynamic. Not only may have to change your field of interest. You had to be very open minded, very opportunist and you have to have a good... feeling: Where the need is. Where the field is going. And on top of that you have to be very adaptive, not only in scientific field, but where you live”*

The inventor must therefore go where they are needed, even if this comes at a professional cost, such as the loss of social networks or the “influence on the institution” they leave behind, as noted by inventor 11, who claims that after all the gain is greater than the cost, since the researcher would gain “different perspectives, different approaches, different technologies, different areas of research and criteria”, very important in science.

This appears to stem from the fact that, although attention is often focused on innovation hubs, the co-evolutionary process described earlier is not only responsible for their formation, but also for producing a broader geographic division of the innovation process perceived by inventors and based on they make their choice.

Inventors point out that hubs are not always the most suitable environments for training or for the early stages of a research career, compared to other places, as illustrated by inventor 1, who claims that students actually “don't need the Nobel Prize winning professor to teach the basics of chemistry” but rather someone that “can provide an environment” where they can learn. Furthermore, hubs are very expensive for students or early researchers, making the total cost of their education excessive in relation to the benefits.

It thus becomes clear that certain places are perceived as more suitable for training and learning, while others are better aligned with industry-oriented research—focused on product development—or provide the security needed to pursue more uncertain, basic research.

The contrast between the differing aspirations of inventor 5 and inventor 1 highlights how a single location cannot fully meet both sets of needs, often prioritizing one over the other:

*“All of this would have been so much easier if I was American. I don't know how Canada even exists. I give you an example of the stupidity. In Canada, a university is not legally allowed to invest in private enterprises at all. Can you imagine? University [...], where I was working at, it cannot give a private entity any money by law. The University Act of Canada, which has passed more than 100 years ago, does not allow for that to happen because it was thought that universities are entities that are supposed to educate the public. They're not in the business of investing or really innovation. Can you imagine?”*

*“When I moved to Canada, it was no challenge because, you know, seriously, the university environment here is very, very safe. It's practically identical to the US except that the, you know, people don't get fired and don't get terminated as easily as in the US”*

The life stories analyzed reveal that inventors, over the course of their careers, must navigate different stages of the research process. This perceived geographic division of innovation, in a sense, compels them to move according to what they need at a given time, in search of the right place to pursue it. Adding to this is a social pressure to be mobile, as staying too long in one place may lead colleagues to think that you are probably not receiving offers elsewhere, which affects your reputation and, consequently, your actual chances of advancing in your career. Market pressures are also far from negligible, often placing inventors at a crossroads: relocate or face dismissal—as was the case for inventor 2:

*“As with any biotechnology company you go through, you know boom and bust. You know, sometimes it's easy to get funding from the market, sometimes it isn't. And they were going through a tough time and they decided to close down the subsidiary in Vancouver. They wanted the scientists to go and work in Princeton, NJ. But we didn't wanna do that”*

In this perceived geographic division of the innovation process, the market tends to reward more generously the actors and places involved in the final stages of product development, according to the inventors' perspective.

As a result, locations and individuals who have contributed significantly to earlier phases of the process are often not adequately recognized or compensated. On this point, inventor 3 offers a personal reflection regarding the fact that, although he and his team were among the first to work on the potential vaccine in terms of timing, they were overtaken in the final stage and were unable to bring the product to market. In his view, the “winners” of this race possessed the skills and a “pragmatic” attitude needed to finalize the work, due also to the “different background that people had.”

The international and pragmatic nature of hubs facilitates the achievement of success—and thus greater economic recognition—even if they are not the first to act. In fact, they can afford to enter the market at the most promising and least risky stage.

The different inventors perspectives seem always agree about the fact that this market-driven logic imposes a kind of sword of Damocles over the heads of those involved, as only successful research is rewarded. Yet, inventors themselves acknowledge that the most significant discoveries often happen “by accident,” or, in the words of inventor 7, “90% of fundamental research will not lead to any application to benefit for the population, but you need 90% of people doing fundamental research with no application at all. For the 10%, finally”.

It is clear that this research environment—one that some inventors do not hesitate to call “corrupted”—raises significant concerns among inventors.

They observe that the growing focus on “safer” research risks missing major opportunities, especially when this contextual pressure begins to shape the behaviour of younger generations, those who are often the most creative and most willing to take risks. As inventor 11 explains:

*“Young researchers now more than ever are very limited in resources, and the system demands them to be successful in funding, in getting money for research. As opposed to take a risk and develop something new ideas that they have. And therefore, young investigator not only spend much of their creative time in writing grants application for research, but they also, by necessity, focus on research that is expected to be funded, as opposed to what is what is in their heart.”*

It follows that locations overly focused on product-oriented outcomes fail to provide the security inventors need in order to take risks.

On one hand, this drives inventors to seek out destinations where risk-taking is still possible—as inventor 4 did—but such opportunities appear to be increasingly rare. As a result, interviewees claim that there is a growing risk that, over time, even inventors’ core intentions will co-evolve with a context that is increasingly averse to risk.

## **6.5 Discussion and conclusion**

The analysis of the eleven life histories of inventors who contributed to the innovative process leading to the development of mRNA vaccines highlights not only how personal their trajectories are, but also how the innovation process itself—and its resulting spatial dimension—is shaped by their internal drives. At the core of their paths lies a form of blind vocation, expressed through intrinsic motivations such as curiosity, the desire for knowledge, the will to solve problems, and to improve public health. These motivations serve as a compass guiding their journeys. The indeterminate and broad nature of these motivations is reflected in the organic and often chaotic character of their life trajectories, helping to explain the serendipitous nature of the innovation process itself. In other words, motivations and aspirations precede calculation, which nonetheless plays an essential role.

Intrinsic motivations alone, however, are not sufficient to explain how choices are actually made. They interact dialectically with the socio-spatial context, which filters and translates them into concrete decisions. Among the external factors most emphasized by the inventors there is, above all, the need for funding. Financial support is seen crucial for coping with the high level of uncertainty that characterizes innovative activity, particularly basic research. Secondly, interpersonal relationships play a key role. These can either facilitate or discourage mobility, especially in the case of family ties. This reveals the inventors not as an isolated, atomistic individuals, but as part of a social network that influences their choices. Lastly, inventors refer to the importance of environments that allow them the freedom to pursue their work. Being in a restrictive environment is often mentioned as a reason for leaving.

The dialectic between internal aspirations and external contexts does not end there; its outcomes reshape the very contexts that will influence future decisions. In this co-evolution, the inventors’ mobility plays a central role, enabling the transfer of experience, knowledge, and technology and so contributing, for example, to the creation of technological hubs.

Although such hubs are often seen as engines of innovation, inventors also warn of the risks they pose: overly comfortable environments may lead to cognitive lock-ins, ultimately hindering innovation. This reveals the need for inventors to avoid relying solely on these hubs and instead take advantage of opportunities offered by moving across different locations. A perceived geographic division of the innovation process emerges, with certain places being more conducive to specific

stages of innovation (basic, translational, or product-oriented). Inventors can benefit from moving between these locations, though this often comes at a personal cost. The inventors' perspective corroborates the findings presented in the previous chapters, both with regard to the geographic division of the innovation process and to the emergence of geographies and places that are more conducive to exploratory or exploitative forms of research.

Relying on the market to allocate recognition and resources appears problematic, as it tends to favor product-oriented research and the places involved in it. This trend, which several inventors note has become more pronounced over time, raises concerns. Consequently, talent attraction policies should go beyond economic incentives and account for personal factors that are often overlooked in the pursuit of one-size-fits-all solutions. In particular, policies should acknowledge what seems to be the true engine of inventors' decisions: their intrinsic motivations. The opportunity to pursue research aligned with their personal vocation is perhaps the most attractive resource a territory can offer.

To achieve this, a capacity to fund high-risk research—often neglected by the market—is needed. This calls for a more substantial public investment capable of assuming this responsibility (Mazzucato, 2013) by supporting inventors through long-term projects with uncertain outcomes. Rather than calling for “more public money,” the central issue is how those resources are assigned, in order to not reproduce market distortions. First, multi-year person-based funding programs—financing researchers rather than specific projects—are needed, since projects may fail in the short term, while this modality enables pivots and a greater production of novel research (Azoulay et al., 2011). At the same time, to avoid conservatism and cumulative-advantage effects—at both individual and geographic levels—it may be useful to adopt a modified-lottery approach, whereby, after a previous merit screen, funds are allocated by random lottery (Fang & Casadevall, 2016). At the same time, the social networks inventors are embedded in must be taken into account, as these may act as constraints on mobility. Human capital attraction policies should therefore seek solutions that enable inventor mobility without compromising family well-being. Moreover, relocation often entails costs and bureaucratic burdens, particularly in terms of time taken away from research. It is therefore crucial to minimize these obstacles to facilitate easier integration.

Finally, retaining inventors may not be the most realistic goal, as mobility is clearly part of the innovation process and inventors themselves consider it necessary. This was exposed also in the previous chapters, highlighting the role of the hub-cities not as a mere accumulator of human capital, but in function of their ability to exchange knowledge routes. Rather than retention, the true objective should be to encourage inventors to return, bringing novelty and diversity back with them and fostering circular mobility (Saxenian, 2005).

In conclusion, truly forward-looking policies should prioritize funding for high-risk research, facilitate family mobility, and reduce bureaucratic burdens, placing research freedom at the center as the most valuable territorial asset.

## 7 Conclusions

This thesis has examined the relationship between inventors' mobility and the geographies of innovation through the study of the innovation process that led to the implementation of mRNA vaccines against COVID-19. In doing so, it first presented the functioning of this technology and its distinctive history, characterized by a long period of skepticism, repeated attempts and failures, and a final acceleration triggered by discoveries that narrowed the scope of research and enabled a more efficient allocation and concentration of resources. Secondly, it provided a critical review of the literature on inventors' mobility, highlighting contrasting findings and gaps. In particular, it showed that the role of inventors' mobility remains contested: while it appears to diffuse knowledge, it also concentrates it (Breschi & Lissoni, 2009; Kerr et al., 2016); while it fosters diversification, it simultaneously drives specialization (Caviggioli et al., 2020; Miguelez & Morrison, 2023). Equally ambiguous are the regional effects of the phenomenon, especially in relation to origin regions (Beine et al., 2011; Diodato et al., 2023; Marino et al., 2020). Moreover, the literature on the drivers of inventors' location decisions remains largely framed within a microeconomic approach, focusing on cost–benefit maximization and privileging external and objective factors, while neglecting the subjective experiences of the actors themselves.

Starting from this background, this thesis proposed a relational–processual approach, combining methodologies oriented toward the analysis of spatial networks generated by inventors' mobility—to capture the complexity of the resulting geographies and their implications, and reinterpret apparent contradictions in the literature—with a qualitative–biographical approach, which analyzed the life histories of inventors in order to integrate their subjective perspectives into the study of mobility drivers.

The first study revealed the spatial structures that emerge from the career trajectories of the key inventors of mRNA vaccines. Although static in nature, the results show that the network of cities linked by inventors' mobility bears all the hallmarks of a complex system. The emergent geography is strongly centralized around innovation hubs, but contrary to common assumptions, these hubs are not passive accumulators of incoming human capital. Instead, they exhibit strong mutual ties—especially among themselves—and enable circulation rather than unilateral accumulation. The process of concentration must therefore be understood as dynamic and complex: while the net balance of inventors moving in and out of hubs is positive, mobility ensures ongoing circulation and exchange of knowledge. This finding helps reconcile the apparent contradiction between knowledge diffusion and concentration: the two occur simultaneously, as two sides of the same coin. The central position of hubs within the network reinforces this role, enabling them to connect to a wider range of cities and increasing their potential as channels for knowledge flows.

The analysis also highlighted the importance of two often-overlooked factors: intranational mobility and the role of institutions. These are partly connected, as intranational mobility not only generates denser ties among cities but also links places with different institutional profiles, particularly educational cities and work-oriented cities. While at the national level such complementarities tend to balance each other, at the city level an overrepresentation of educational institutions may result in net outflows of human capital, pointing to the importance of maintaining institutional balance even on smaller scales to promote equitable regional development.

In terms of implications, the study showed that the relational pathways connecting cities form a compact and efficient network capable of facilitating knowledge exchange and innovation. This network is robust and resilient to shocks and policies targeting cities at random, but highly vulnerable to disruptions affecting hubs. This reveals another layer of spatial inequality: inventors' tendency to gravitate around hubs not only fosters an unequal distribution of resources but also makes the entire



system highly dependent on them. Consequently, policy-makers are likely to channel resources to hubs to prevent or mitigate shocks, further reinforcing spatial inequalities at the expense of less central cities. Additionally, policies designed to limit inflows or outflows of inventors at the national level were shown to merely reduce the global size of the mobility network without significantly altering its efficiency. Such policies, therefore, are ineffective as tools for retaining human capital and instead are a risk of self-exclusion from the wider system. Finally, the study demonstrated that the geographies produced by inventors' mobility are not neutral: once formed, they feed back into the process, favoring more centralized and direct mobility paths, increasing concentration while reducing circulation—the very mechanism essential for knowledge diffusion and recombination.

The second study extended the analysis by integrating the temporal dimension and situating the evolution of emergent geographies within the broader innovation process. While many of the spatial structures observed mirrored those identified in the first study, here their formation over time and co-evolution with the stages of innovation could be observed. Two distinct phases were identified. In the first, both technological and innovative opportunities were initially low but gradually increased. Here, technological opportunities expanded more rapidly than innovative ones, as new lines of inquiry and potential applications of mRNA emerged, without yet reaching the threshold for commercialization. In the second phase, technological opportunities peaked and then declined, while innovative opportunities surged, marking the final stage of the innovation process. Key discoveries—such as pseudouridine-modified mRNA and lipid nanoparticles—narrowed research trajectories toward more promising avenues, reducing technological opportunities while drastically increasing innovative ones.

Geographically, these phases translated into distinct patterns of inventors' mobility. During the first phase, mobility appeared almost random, generating a dispersed and fragmented network of cities with no clear hierarchy. In the second phase, however, the network became denser and more centralized, with a few cities emerging as intermediaries and consolidating the structure observed in the first study. These results demonstrate that spatial dynamics mirror the broader innovation process: when research is exploratory and basic-science-oriented, mobility creates non-hierarchical and quasi-random ties based on knowledge production; when innovation opportunities dominate, inventors cluster around hubs possessing complementary assets essential for commercialization, generating centralized and hierarchical spatial structures.

The third study shifted the focus to inventors' subjective perspectives, analyzing their life stories to understand the drivers of mobility and their decision-making process, as well as how they perceive and experience emergent geographies of innovation. The analysis revealed that career and mobility decisions are initially shaped by an internal, seemingly indeterminate impulse, often described by inventors themselves as curiosity, the desire to uncover unknown facts and learn from nature, and, in the life sciences and pharmaceutical fields, by an emotional drive to care for others. Decision-making thus begins chaotically in their own inner drivers but takes form when this inner impulse encounters the external socio-spatial context.

External factors act as filters, shaping and constraining decisions. Among these, the most important from inventors' perspective is access to funding, not simply financial gain, but resources to sustain risky, uncertain research without guaranteed outcomes. Social ties also play a critical role: professional relationships often facilitate mobility, while family or intimate ties may discourage or limit it. Moreover, inventors reported witnessing significant transformations in places following the arrival of particular scientists or major discoveries, illustrating how their own decisions can reshape the socio-spatial context in a dynamic of co-evolution. Over time, inventors perceived the geography of innovation as increasingly fragmented, with some places better suited for particular types of research than others. This perception raised concerns, especially in a market-driven innovation system

that disproportionately rewards late-stage, product-oriented research while marginalizing more uncertain, high-risk basic research, despite its crucial role as a foundation for future breakthroughs.

These insights carry important implications for talent attraction and retention policies. Policy-makers should consider inventors' concerns by funding high-risk, curiosity-driven research, which many are eager to pursue, and by addressing their social and family needs through targeted support and integration programs. Moreover, since mobility is costly in terms of time taken away from research, international cooperation to reduce bureaucratic burdens would be highly beneficial.

In conclusion, the mixed-methods approach adopted in this thesis has demonstrated how geographies of innovation emerge relationally from inventors' mobility. Analyzing the complexity of these geographies has shed light on the contradictory dynamics of innovation processes, deepened our understanding of the role of spatial formations such as hubs, and shown how they interact with other places. It has clarified how spatial structures co-evolve with innovation over time, what implications and inequalities these geographies produce, and how inventors themselves interact with and interpret them.

## References

- Acs, Z. J., & Megyesi, M. I. (2009). Creativity and industrial cities: A case study of Baltimore. *Entrepreneurship & Regional Development*, 21(4), 421–439.  
<https://doi.org/10.1080/08985620903020086>
- Agrawal, A., Kapur, D., McHale, J., & Oettl, A. (2011). Brain drain or brain bank? The impact of skilled emigration on poor-country innovation. *Journal of Urban Economics*, 69(1), 43–55.  
<https://doi.org/10.1016/j.jue.2010.06.003>
- Albouy, D., & Stuart, B. A. (2020). URBAN POPULATION AND AMENITIES: THE NEOCLASSICAL MODEL OF LOCATION. *International Economic Review*, 61(1), 127–158. <https://doi.org/10.1111/iere.12419>
- Almeida, P., Phene, A., & Li, S. (2015). The Influence of Ethnic Community Knowledge on Indian Inventor Innovativeness. *Organization Science*, 26(1), 198–217.  
<https://doi.org/10.1287/orsc.2014.0931>
- Antonelli, C. (2001). *The microeconomics of technological change*. Oxford University Press.
- Argyres, N., Rios, L. A., & Silverman, B. S. (2025). On the heels of giants: Internal network structure and the race to build on prior innovation. *Strategic Management Journal*, 46(7), 1728–1761. <https://doi.org/10.1002/smj.3696>
- Arthur, W. B. (2009). *The nature of technology: What it is and how it evolves*. Allen Lane.
- Arts, S., Hou, J., & Gomez, J. C. (2021). Natural language processing to identify the creation and impact of new technologies in patent text: Code, data, and new measures. *Research Policy*, 50(2), 104144. <https://doi.org/10.1016/j.respol.2020.104144>
- Ascani, A., Bettarelli, L., Resmini, L., & Balland, P.-A. (2020). Global networks, local specialisation and regional patterns of innovation. *Research policy*, 49(8), 104031.
- Asheim, B. T., & Gertler, M. S. (2006). *The Geography of Innovation: Regional Innovation Systems*. Oxford University Press.  
<https://doi.org/10.1093/oxfordhb/9780199286805.003.0011>

- Azoulay, P., Graff Zivin, J. S., & Manso, G. (2011). Incentives and creativity: Evidence from the academic life sciences. *The RAND Journal of Economics*, 42(3), 527–554.  
<https://doi.org/10.1111/j.1756-2171.2011.00140.x>
- Bahar, D., Choudhury, P., Miguelez, E., & Signorelli, S. (2024). Global Mobile Inventors. *Journal of Development Economics*, 171, 103357. <https://doi.org/10.1016/j.jdeveco.2024.103357>
- Bahar, D., Choudhury, P., & Rapoport, H. (2020). Migrant inventors and the technological advantage of nations. *Research Policy*, 49(9), 103947.  
<https://doi.org/10.1016/j.respol.2020.103947>
- Balconi, M., Brusoni, S., & Orsenigo, L. (2010). In defence of the linear model: An essay. *Research Policy*, 39(1), 1–13.
- Balland, P.-A. (2012). Proximity and the Evolution of Collaboration Networks: Evidence from Research and Development Projects within the Global Navigation Satellite System (GNSS) Industry. *Regional Studies*, 46(6), 741–756. <https://doi.org/10.1080/00343404.2010.529121>
- Balland, P.-A., Boschma, R., Crespo, J., & Rigby, D. L. (2019). Smart specialization policy in the European Union: Relatedness, knowledge complexity and regional diversification. *Regional Studies*, 53(9), 1252–1268. <https://doi.org/10.1080/00343404.2018.1437900>
- Balsmeier, B., Fleming, L., Marx, M., & Shin, S. R. (2020). *Startups, Unicorns, and the Local Inflow of Inventors* (w27605; p. w27605). National Bureau of Economic Research.  
<https://doi.org/10.3386/w27605>
- Ban, T. A. (2006). The role of serendipity in drug discovery. *Dialogues in Clinical Neuroscience*, 8(3), 335–344. <https://doi.org/10.31887/DCNS.2006.8.3/tban>
- Barabási, A.-L., & Albert, R. (1999). Emergence of Scaling in Random Networks. *Science*, 286(5439), 509–512. <https://doi.org/10.1126/science.286.5439.509>
- Beine, M., Docquier, F., & Oden-Defoort, C. (2011). A Panel Data Analysis of the Brain Gain. *World Development*, 39(4), 523–532. <https://doi.org/10.1016/j.worlddev.2010.03.009>

- Benner, M. (2022). Retheorizing industrial–institutional coevolution: A multidimensional perspective. *Regional Studies*, 56(9), 1524–1537.  
<https://doi.org/10.1080/00343404.2021.1949441>
- Bhagwati, J., & Hamada, K. (1974). The brain drain, international integration of markets for professionals and unemployment. *Journal of Development Economics*, 1(1), 19–42.  
[https://doi.org/10.1016/0304-3878\(74\)90020-0](https://doi.org/10.1016/0304-3878(74)90020-0)
- Biernacki, C., Celeux, G., & Govaert, G. (2000). Assessing a mixture model for clustering with the integrated completed likelihood. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 22(7), 719–725. <https://doi.org/10.1109/34.865189>
- Bisset, J., Czarnitzki, D., & Doherr, T. (2024). Inventor mobility under uncertainty. *Research Policy*, 53(1), 104896. <https://doi.org/10.1016/j.respol.2023.104896>
- Borjas, G. J., & Doran, K. B. (2015). Cognitive Mobility: Labor Market Responses to Supply Shocks in the Space of Ideas. *Journal of Labor Economics*, 33(S1), S109–S145.  
<https://doi.org/10.1086/676659>
- Boschma, R. (2017). Relatedness as driver of regional diversification: A research agenda. *Regional Studies*, 51(3), 351–364. <https://doi.org/10.1080/00343404.2016.1254767>
- Boschma, R. A. (2005). Does geographical proximity favour innovation? *Économie et Institutions*, 6–7, 111–128. <https://doi.org/10.4000/ei.926>
- Boschma, R. A., & Frenken, K. (2006). Why is economic geography not an evolutionary science? Towards an evolutionary economic geography. *Journal of Economic Geography*, 6(3), 273–302. <https://doi.org/10.1093/jeg/lbi022>
- Boschma, R. A., & Lambooy, J. G. (1999). Evolutionary economics and economic geography. *Journal of Evolutionary Economics*, 9(4), 411–429. <https://doi.org/10.1007/s001910050089>
- Boschma, R. A., & Martin, R. (2010). *The handbook of evolutionary economic geography*. E. Elgar.
- Breiman, L. (2001). [No title found]. *Machine Learning*, 45(1), 5–32.  
<https://doi.org/10.1023/A:1010933404324>

- Breschi, S., & Lenzi, C. (2015). The Role of External Linkages and Gatekeepers for the Renewal and Expansion of US Cities' Knowledge Base, 1990–2004. *Regional Studies*, 49(5), 782–797. <https://doi.org/10.1080/00343404.2014.954534>
- Breschi, S., & Lissoni, F. (2009). Mobility of skilled workers and co-invention networks: An anatomy of localized knowledge flows. *Journal of Economic Geography*, 9(4), 439–468. <https://doi.org/10.1093/jeg/lbp008>
- Breschi, S., Lissoni, F., & Miguelez, E. (2017). Foreign-origin inventors in the USA: Testing for diaspora and brain gain effects. *Journal of Economic Geography*, lbw044. <https://doi.org/10.1093/jeg/lbw044>
- Campbell, D. T. (1965). *Variation and Selective retention in Socio-Cultural Evolution*. <https://api.semanticscholar.org/CorpusID:140836454>
- Campo, F., Mendola, M., Morrison, A., & Ottaviano, G. I. P. (2022). Talents and Cultures: Immigrant Inventors and Ethnic Diversity in the Age of Mass Migration. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.4244790>
- Capello, R., & Lenzi, C. (2019). Structural dynamics of regional innovation patterns in Europe: The role of inventors' mobility. *Regional Studies*, 53(1), 30–42. <https://doi.org/10.1080/00343404.2017.1379600>
- Cappelli, R., Czarnitzki, D., Doherr, T., & Montobbio, F. (2019). Inventor mobility and productivity in Italian regions. *Regional Studies*, 53(1), 43–54. <https://doi.org/10.1080/00343404.2018.1445847>
- Castellani, D., Perri, A., & Scalera, V. G. (2022). Knowledge integration in multinational enterprises: The role of inventors crossing national and organizational boundaries. *Journal of World Business*, 57(3), 101290. <https://doi.org/10.1016/j.jwb.2021.101290>
- Caviggioli, F., Jensen, P., & Scellato, G. (2020). Highly skilled migrants and technological diversification in the US and Europe. *Technological Forecasting and Social Change*, 154, 119951. <https://doi.org/10.1016/j.techfore.2020.119951>

- Champion, T., & Gordon, I. (2021). Linking spatial and social mobility: Is London's "escalator" as strong as it was? *Population, Space and Place*, 27(7), e2306.  
<https://doi.org/10.1002/psp.2306>
- Chang, S.-H. (2024). International Technology Market Hotspots and Development Trends from the Perspective of Inventor Mobility. *Journal of the Knowledge Economy*, 15(1), 2361–2382.  
<https://doi.org/10.1007/s13132-023-01229-5>
- Chang, S.-J., & Matsumoto, Y. (2025). Internal redeployment versus external recruitment of inventors. *Research Policy*, 54(6), 105238. <https://doi.org/10.1016/j.respol.2025.105238>
- Choudhury, P. (2016). Return migration and geography of innovation in MNEs: A natural experiment of knowledge production by local workers reporting to return migrants. *Journal of Economic Geography*, 16(3), 585–610. <https://doi.org/10.1093/jeg/lbv025>
- Choudhury, P., & Kim, D. Y. (2019). The ethnic migrant inventor effect: Codification and recombination of knowledge across borders. *Strategic Management Journal*, 40(2), 203–229. <https://doi.org/10.1002/smj.2977>
- Cobb, M. (2015). Who discovered messenger RNA? *Current Biology*, 25(13), R526–R532.  
<https://doi.org/10.1016/j.cub.2015.05.032>
- Cobb, M. (2017). 60 years ago, Francis Crick changed the logic of biology. *PLOS Biology*, 15(9), e2003243. <https://doi.org/10.1371/journal.pbio.2003243>
- Cover, T., & Hart, P. (1967). Nearest neighbor pattern classification. *IEEE Transactions on Information Theory*, 13(1), 21–27. <https://doi.org/10.1109/TIT.1967.1053964>
- Cowan, R. (2000). The explicit economics of knowledge codification and tacitness. *Industrial and Corporate Change*, 9(2), 211–253. <https://doi.org/10.1093/icc/9.2.211>
- Crespi, G. A., Geuna, A., & Nesta, L. (2007). The mobility of university inventors in Europe. *The Journal of Technology Transfer*, 32(3), 195–215. <https://doi.org/10.1007/s10961-006-9012-0>

- De Rassenfosse, G., & Pellegrino, G. (2024). International mobility of inventors and innovation: Empirical evidence from the collapse of the Soviet Union. *Economics Letters*, 234, 111450. <https://doi.org/10.1016/j.econlet.2023.111450>
- Di Iasio, V., & Miguelez, E. (2022). The ties that bind and transform: Knowledge remittances, relatedness and the direction of technical change. *Journal of Economic Geography*, 22(2), 423–448. <https://doi.org/10.1093/jeg/lbab044>
- Di Lorenzo, F., & Almeida, P. (2012). A Behavioral Perspective on Inventors' Mobility: The Case of Pharmaceutical Industry. *Academy of Management Proceedings*, 2012(1), 18017. <https://doi.org/10.5465/AMBPP.2012.281>
- Diemer, A., & Regan, T. (2022). No inventor is an island: Social connectedness and the geography of knowledge flows in the US. *Research Policy*, 51(2), 104416. <https://doi.org/10.1016/j.respol.2021.104416>
- Dimitriadis, G. J. (1978). Translation of rabbit globin mRNA introduced by liposomes into mouse lymphocytes. *Nature*, 274(5674), 923–924. <https://doi.org/10.1038/274923a0>
- Diodato, D., Hausmann, R., & Neffke, F. (2023). The impact of return migration on employment and wages in Mexican cities. *Journal of Urban Economics*, 135, 103557. <https://doi.org/10.1016/j.jue.2023.103557>
- Diodato, D., Morrison, A., & Petralia, S. (2022). Migration and invention in the Age of Mass Migration. *Journal of Economic Geography*, 22(2), 477–498. <https://doi.org/10.1093/jeg/lbab032>
- Doherr, T. (2016). Inventor Mobility Index: A Method to Disambiguate Inventor Careers. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.2941408>
- Dolgin, E. (2021). The tangled history of mRNA vaccines. *Nature*, 597(7876), 318–324. <https://doi.org/10.1038/d41586-021-02483-w>
- Döring, T., & Schnellenbach, J. (2006). What do we know about geographical knowledge spillovers and regional growth?: A survey of the literature. *Regional Studies*, 40(03), 375–395.



- Dorner, M., Harhoff, D., Hinz, T., Hoisl, K., & Bender, S. (2016). *Social ties for labor market access: Lessons from the migration of East German inventors*. DP11601.
- Dosi, G. (1982a). Technological Paradigms and Technological Trajectories. *Research Policy*, 11(3), 147–162.
- Dosi, G. (1982b). Technological paradigms and technological trajectories. *Research Policy*, 11(3), 147–162. [https://doi.org/10.1016/0048-7333\(82\)90016-6](https://doi.org/10.1016/0048-7333(82)90016-6)
- Dosi, G. (1997). Opportunities, Incentives and the Collective Patterns of Technological Change. *Economic Journal*, 107(444), 1530–1547.
- Fackler, T. A., Giesing, Y., & Laurentsyeveva, N. (2020). Knowledge remittances: Does emigration foster innovation? *Research Policy*, 49(9), 103863. <https://doi.org/10.1016/j.respol.2019.103863>
- Faini, R. (2003). The Brain Drain: An Unmitigated Blessing? *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.463021>
- Fang, F. C., & Casadevall, A. (2016). Research Funding: The Case for a Modified Lottery. *mBio*, 7(2), e00422-16. <https://doi.org/10.1128/mBio.00422-16>
- Feldman, M. P. (1999). The new economics of innovation, spillovers and agglomeration: A review of empirical studies. *Economics of innovation and new technology*, 8(1–2), 5–25.
- Ferrucci, E., & Lissoni, F. (2019). Foreign inventors in Europe and the United States: Diversity and Patent Quality. *Research Policy*, 48(9), 103774. <https://doi.org/10.1016/j.respol.2019.03.019>
- Fielding, A. J. (1992). Migration and Social Mobility: South East England as an Escalator Region. *Regional Studies*, 26(1), 1–15. <https://doi.org/10.1080/00343409212331346741>
- Filippetti, A., & Zinilli, A. (2023). The innovation networks of city-regions in Europe: Exclusive clubs or inclusive hubs? *Papers in Regional Science*, 102(6), 1169–1193. <https://doi.org/10.1111/pirs.12763>

- Findlay, A. M., & Li, F. L. N. (1997). An auto-biographical approach to understanding migration: The case of Hong Kong emigrants. *Area*, 29(1), 34–44. <https://doi.org/10.1111/j.1475-4762.1997.tb00005.x>
- Florida, R. (2002). *The Rise of the Creative Class*. Basic Books.
- Florida, R. L. (2014). *The rise of the creative class: Revisited* (Paperback of the rev. ed). Basic Books.
- Foley, C. F., & Kerr, W. R. (2013). Ethnic Innovation and U.S. Multinational Firm Activity. *Management Science*, 59(7), 1529–1544. <https://doi.org/10.1287/mnsc.1120.1684>
- Freeman, C., & Soete, L. (1997). *The Economics of Industrial Innovation*. The MIT Press.
- Freeman, R. B., & Huang, W. (2015). Collaborating with People Like Me: Ethnic Coauthorship within the United States. *Journal of Labor Economics*, 33(S1), S289–S318. <https://doi.org/10.1086/678973>
- Friedman, J. H. (2001). Greedy function approximation: A gradient boosting machine. *The Annals of Statistics*, 29(5). <https://doi.org/10.1214/aos/1013203451>
- Galambos, L., & Sturchio, J. L. (1998). Pharmaceutical firms and the transition to biotechnology: A study in strategic innovation. *Business History Review*, 72(2), 250–278.
- Gambardella, A. (1992). Competitive advantages from in-house scientific research: The US pharmaceutical industry in the 1980s. *Research policy*, 21(5), 391–407.
- Gambardella, A. (1995). *Science and innovation: The US pharmaceutical industry during the 1980s*. Cambridge University Press. <https://books.google.it/books?hl=it&lr=&id=HQhe83DIX8EC&oi=fnd&pg=PR10&dq=gambardella+science+and+innovation&ots=C5ApLOEFmy&sig=rideddeAMESHRy0pp5pCnj27F0s>
- Ganguli, I. (2015). Immigration and Ideas: What Did Russian Scientists “Bring” to the United States? *Journal of Labor Economics*, 33(S1), S257–S288. <https://doi.org/10.1086/679741>

- Gaviria, M., & Kilic, B. (2021). A network analysis of COVID-19 mRNA vaccine patents. *Nature Biotechnology*, 39(5), 546–548. <https://doi.org/10.1038/s41587-021-00912-9>
- Ge, C., Huang, K., & Png, I. P. L. (2016). Engineer/scientist careers: Patents, online profiles, and misclassification bias. *Strategic Management Journal*, 37(1), 232–253. <https://doi.org/10.1002/smj.2460>
- Gorin, C. (2016). Patterns and Determinants of Inventorss Mobility Across European Urban Areas. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.2778492>
- Grabowski, H. (2002). Patents, Innovation and Access to New Pharmaceuticals. *Journal of International Economic Law*, 5(4), 849–860. <https://doi.org/10.1093/jiel/5.4.849>
- Hald Albertsen, C., Kulkarni, J. A., Witzigmann, D., Lind, M., Petersson, K., & Simonsen, J. B. (2022). The role of lipid components in lipid nanoparticles for vaccines and gene therapy. *Advanced Drug Delivery Reviews*, 188, 114416. <https://doi.org/10.1016/j.addr.2022.114416>
- Halfacree, K. H., & Boyle, P. J. (1993). The challenge facing migration research: The case for a biographical approach. *Progress in Human Geography*, 17(3), 333–348. <https://doi.org/10.1177/030913259301700303>
- Hall, B. (2004). Exploring the Patent Explosion. *Journal of Economic Transfer*, 30(1–2), 35–48.
- Haller, M. (2022). Firm decline and the mobility of US inventors, 1976–2015. *Environment and Planning A: Economy and Space*, 54(7), 1341–1367. <https://doi.org/10.1177/0308518X221103266>
- Hanneke, S., Fu, W., & Xing, E. P. (2010). Discrete temporal models of social networks. *Electronic Journal of Statistics*, 4(none). <https://doi.org/10.1214/09-EJS548>
- Henderson, R., Orsenigo, L., & Pisano, G. P. (1999). The Pharmaceutical Industry and the Revolution in Molecular Biology: Interactions Among Scientific, Institutional, and Organizational Change. In D. C. Mowey & R. R. Nelson (A c. Di), *Sources of Industrial Leadership*. Cambridge University Press.

- Hidalgo, C. A., Balland, P.-A., Boschma, R., Delgado, M., Feldman, M., Frenken, K., Glaeser, E., He, C., Kogler, D. F., Morrison, A., Neffke, F., Rigby, D., Stern, S., Zheng, S., & Zhu, S. (2018). The Principle of Relatedness. In A. J. Morales, C. Gershenson, D. Braha, A. A. Minai, & Y. Bar-Yam (A c. Di), *Unifying Themes in Complex Systems IX* (pp. 451–457). Springer International Publishing. [https://doi.org/10.1007/978-3-319-96661-8\\_46](https://doi.org/10.1007/978-3-319-96661-8_46)
- Hilaire-Perez, L., & Verna, C. (2006). Dissemination of Technical Knowledge in the Middle Ages and the Early Modern Era: New Approaches and Methodological Issues. *Technology and Culture*, 47(3), 536–565. <https://doi.org/10.1353/tech.2006.0179>
- Hodgson, G. M., & Knudsen, T. (2010). *Darwin's Conjecture: The Search for General Principles of Social and Economic Evolution*. University of Chicago Press. <https://doi.org/10.7208/chicago/9780226346922.001.0001>
- Hoisl, K. (2007). Tracing mobile inventors—The causality between inventor mobility and inventor productivity. *Research Policy*, 36(5), 619–636. <https://doi.org/10.1016/j.respol.2007.01.009>
- Hornung, E. (2014). Immigration and the Diffusion of Technology: The Huguenot Diaspora in Prussia. *American Economic Review*, 104(1), 84–122. <https://doi.org/10.1257/aer.104.1.84>
- Hunt, J., & Gauthier-Loiselle, M. (2010). How Much Does Immigration Boost Innovation? *American Economic Journal: Macroeconomics*, 2(2), 31–56. <https://doi.org/10.1257/mac.2.2.31>
- Hunter, D. R. (2007). Curved exponential family models for social networks. *Social Networks*, 29(2), 216–230. <https://doi.org/10.1016/j.socnet.2006.08.005>
- Iammarino, S. (2005). An evolutionary integrated view of Regional Systems of Innovation: Concepts, measures and historical perspectives. *European Planning Studies*, 13(4), 497–519.
- Iammarino, S., & McCann, P. (2006). The structure and evolution of industrial clusters: Transactions, technology and knowledge spillovers. *Research policy*, 35(7), 1018–1036.

- Jacob, F., & Monod, J. (1961). Genetic regulatory mechanisms in the synthesis of proteins. *Journal of Molecular Biology*, 3(3), 318–356. [https://doi.org/10.1016/s0022-2836\(61\)80072-7](https://doi.org/10.1016/s0022-2836(61)80072-7)
- Jaffe, A. B., Trajtenberg, M., & Henderson, R. (1993). Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations. *The Quarterly Journal of Economics*, 108(3), 577–598. <https://doi.org/10.2307/2118401>
- Jonkers, K., & Tijssen, R. (2008). Chinese researchers returning home: Impacts of international mobility on research collaboration and scientific productivity. *Scientometrics*, 77(2), 309–333. <https://doi.org/10.1007/s11192-007-1971-x>
- Karikó, K., Buckstein, M., Ni, H., & Weissman, D. (2005). Suppression of RNA Recognition by Toll-like Receptors: The Impact of Nucleoside Modification and the Evolutionary Origin of RNA. *Immunity*, 23(2), 165–175. <https://doi.org/10.1016/j.immuni.2005.06.008>
- Kerr, S. P., Kerr, W., Özden, Ç., & Parsons, C. (2016). Global Talent Flows. *Journal of Economic Perspectives*, 30(4), 83–106. <https://doi.org/10.1257/jep.30.4.83>
- Kerr, W. R., & Lincoln, W. F. (2010). The Supply Side of Innovation: H-1B Visa Reforms and U.S. Ethnic Invention. *Journal of Labor Economics*, 28(3), 473–508. <https://doi.org/10.1086/651934>
- Kiss, I. M., & Buzás, N. (2016). Communities and central nodes in the mobility network of US inventors. *Journal of Innovation Management*, 3(4), 96–118. [https://doi.org/10.24840/2183-0606\\_003.004\\_0007](https://doi.org/10.24840/2183-0606_003.004_0007)
- Kline, S. J., & Rosenberg, N. (1986). An Overview of Innovation. In R. Landau & N. Rosenberg (A c. Di), *The Positive Sum Strategy*. National Academy Press.
- Koch, P., Stojkoski, V., & Hidalgo, C. A. (2023). The role of immigrants, emigrants and locals in the historical formation of European knowledge agglomerations. *Regional Studies*, 1–15. <https://doi.org/10.1080/00343404.2023.2275571>

- Kōu, A., & Bailey, A. (2014). 'Movement is a constant feature in my life': Contextualising migration processes of highly skilled Indians. *Geoforum*, 52, 113–122.  
<https://doi.org/10.1016/j.geoforum.2014.01.002>
- Kōu, A., Van Wissen, L., Van Dijk, J., & Bailey, A. (2015). A Life Course Approach to High-skilled Migration: Lived Experiences of Indians in the Netherlands. *Journal of Ethnic and Migration Studies*, 41(10), 1644–1663. <https://doi.org/10.1080/1369183X.2015.1019843>
- Lee, C., & Wilkinson, D. J. (2019). A review of stochastic block models and extensions for graph clustering. *Applied Network Science*, 4(1), 122. <https://doi.org/10.1007/s41109-019-0232-2>
- Leifeld, P., Cranmer, S. J., & Desmarais, B. A. (2018). Temporal Exponential Random Graph Models with **btergm**: Estimation and Bootstrap Confidence Intervals. *Journal of Statistical Software*, 83(6). <https://doi.org/10.18637/jss.v083.i06>
- Leong, K. Y., Tham, S. K., & Poh, C. L. (2025). Revolutionizing immunization: A comprehensive review of mRNA vaccine technology and applications. *Virology Journal*, 22(1).  
<https://doi.org/10.1186/s12985-025-02645-6>
- Lissoni, F. (2018). International migration and innovation diffusion: An eclectic survey. *Regional Studies*, 52(5), 702–714. <https://doi.org/10.1080/00343404.2017.1346370>
- Lissoni, F., & Miguelez, E. (2024). Migration and Innovation: Learning from Patent and Inventor Data. *Journal of Economic Perspectives*, 38(1), 27–54. <https://doi.org/10.1257/jep.38.1.27>
- Liu, L., Dehmamy, N., Chown, J., Giles, C. L., & Wang, D. (2021). Understanding the onset of hot streaks across artistic, cultural, and scientific careers. *Nature Communications*, 12(1), 5392. <https://doi.org/10.1038/s41467-021-25477-8>
- Liu, T., Pei, T., Fang, Z., Wu, M., Liu, X., Yan, X., Song, C., Jiang, J., Jiang, L., & Chen, J. (2024). Spatiotemporal mobility network of global scientists, 1970–2020. *International Journal of Geographical Information Science*, 38(10), 1991–2018.  
<https://doi.org/10.1080/13658816.2024.2369540>

- Liversage, A. (2009). Vital conjunctures, shifting horizons: High-skilled female immigrants looking for work. *Work, Employment and Society*, 23(1), 120–141.  
<https://doi.org/10.1177/0950017008099781>
- Losick, R. (2025). Chapter 14: Crick Enunciates the Central Dogma and Two Research Teams Discover Messenger RNA. In *The River Divides into Thousands of Branches*. Harvard University—Faculty of Arts and Sciences. <https://scalar.fas.harvard.edu/the-river-divides-into-thousands-of-branches/chapter-14-crick-enunciates-the-central-dogma-and-two-research-teams-discover-messenger-rna>
- Ma, L., Tan, Y., & Li, W. (2023). Identity (re)construction, return destination selection and place attachment among Chinese academic returnees: A case study of Guangzhou, China. *Cities*, 143, 104563. <https://doi.org/10.1016/j.cities.2023.104563>
- Malerba, F. (2002). Sectoral systems of innovation and production. *Research Policy*, 31, 247–264.
- Manning, P., & Trimmer, T. (2020). *Migration in world history* (Third edition). Routledge.
- Marino, A., Mudambi, R., Perri, A., & Scalera, V. G. (2020). Ties that bind: Ethnic inventors in multinational enterprises' knowledge integration and exploitation. *Research Policy*, 49(9), 103956. <https://doi.org/10.1016/j.respol.2020.103956>
- Martin, R., & Sunley, P. (2006). Path dependence and regional economic evolution. *Journal of Economic Geography*, 6(4), 395–437. <https://doi.org/10.1093/jeg/lbl012>
- Mazzucato M. (2013), The Entrepreneurial State. Debunking Public vs. Private Sector Myths. *Economia politica*, 1, 103–110. <https://doi.org/10.1428/76495>
- Melero, E., Palomeras, N., & Wehrheim, D. (2017). The Effect of Patent Protection on Inventor Mobility. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.2961312>
- Michaels, E., Handfield-Jones, H., & Axelrod, B. (2009). *The war for talent* (5. print). Harvard Business School Press.
- Miguélez, E., & Fink, C. (2023). Measuring the International Mobility of Inventors: A New Database. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.4437246>

- Miguélez, E., & Moreno, R. (2013). Research Networks and Inventors' Mobility as Drivers of Innovation: Evidence from Europe. *Regional Studies*, 47(10), 1668–1685.  
<https://doi.org/10.1080/00343404.2011.618803>
- Miguélez, E., & Morrison, A. (2023). Migrant inventors as agents of technological change. *The Journal of Technology Transfer*, 48(2), 669–692. <https://doi.org/10.1007/s10961-022-09927-z>
- Miguélez, E., & Noumedem Temgoua, C. (2020). Inventor migration and knowledge flows: A two-way communication channel? *Research Policy*, 49(9), 103914.  
<https://doi.org/10.1016/j.respol.2019.103914>
- Morais, P., Adachi, H., & Yu, Y.-T. (2021). The Critical Contribution of Pseudouridine to mRNA COVID-19 Vaccines. *Frontiers in Cell and Developmental Biology*, 9.  
<https://doi.org/10.3389/fcell.2021.789427>
- Morescalchi, A., Pammolli, F., Penner, O., Petersen, A. M., & Riccaboni, M. (2015). The evolution of networks of innovators within and across borders: Evidence from patent data. *Research Policy*, 44(3), 651–668. <https://doi.org/10.1016/j.respol.2014.10.015>
- Moretti, E. (2021). The Effect of -High-Tech Clusters on the Productivity of Top Inventors. *American Economic Review*, 111(10), 3328–3375. <https://doi.org/10.1257/aer.20191277>
- Morrison, A. (2023). Towards an evolutionary economic geography research agenda to study migration and innovation. *Cambridge Journal of Regions, Economy and Society*, 16(3), 529–542. <https://doi.org/10.1093/cjres/rsad013>
- Morrison, A., Rabellotti, R., & Zirulia, L. (2013). When Do Global Pipelines Enhance the Diffusion of Knowledge in Clusters? *Economic Geography*, 89(1), 77–96.  
<https://doi.org/10.1111/j.1944-8287.2012.01167.x>
- Moser, P., Voena, A., & Waldinger, F. (2014). German Jewish Émigrés and US Invention. *American Economic Review*, 104(10), 3222–3255. <https://doi.org/10.1257/aer.104.10.3222>



- Murmann, J. P. (2003). *Knowledge and Competitive Advantage: The Coevolution of Firms, Technology, and National Institutions* (1<sup>a</sup> ed.). Cambridge University Press.  
<https://doi.org/10.1017/CBO9780511510953>
- Nelson, G. D. (2021). Communities, Complexity, and the ‘Conchoration’: Network Analysis and the Ontology of Geographic Units. *Tijdschrift Voor Economische En Sociale Geografie*, 112(4), 351–369. <https://doi.org/10.1111/tesg.12400>
- Nelson, R. R., & Winter, S. G. (1982). *An Evolutionary Theory of Economic Change*. Harvard University Press.
- Nelson, R., & Winter, S. (1982). *An Evolutionary Theory of Economic Change*. Harvard University Press.
- Orsenigo, L., Pammolli, F., & Riccaboni, M. (2001). Technological change and network dynamics: Lessons from the pharmaceutical industry. *Research policy*, 30(3), 485–508.
- Ostro, M. J., Giacomoni, D., Lavelle, D., Paxton, W., & Dray, S. (1978). Evidence for translation of rabbit globin mRNA after liposomemediated insertion into a human cell line. *Nature*, 274(5674), 921–923. <https://doi.org/10.1038/274921a0>
- Palomeras, N., & Melero, E. (2010). Markets for Inventors: Learning-by-Hiring as a Driver of Mobility. *Management Science*, 56(5), 881–895. <https://doi.org/10.1287/mnsc.1090.1135>
- Pardi, N., Hogan, M. J., Porter, F. W., & Weissman, D. (2018). mRNA vaccines—A new era in vaccinology. *Nature Reviews Drug Discovery*, 17(4), 261–279.  
<https://doi.org/10.1038/nrd.2017.243>
- Pavitt, K. (1984). Sectoral patterns of technological change: Towards a taxonomy and a theory. *Research Policy*, 13(6), 343–373.
- Pellegrino, G., Penner, O., Piguet, E., & De Rassenfosse, G. (2023). Productivity gains from migration: Evidence from inventors. *Research Policy*, 52(1), 104631.  
<https://doi.org/10.1016/j.respol.2022.104631>

- Pinheiro, F. L., Alshamsi, A., Hartmann, D., Boschma, R., & Hidalgo, C. A. (2018). *Shooting High or Low: Do Countries Benefit from Entering Unrelated Activities?* (arXiv:1801.05352). arXiv. <http://arxiv.org/abs/1801.05352>
- Pinto, P. E., Honores, G., & Vallone, A. (2021). Exploring the topology and dynamic growth properties of co-invention networks and technology fields. *PLOS ONE*, *16*(9), e0256956. <https://doi.org/10.1371/journal.pone.0256956>
- Polack, F. P., Thomas, S. J., Kitchin, N., Absalon, J., Gurtman, A., Lockhart, S., Perez, J. L., Pérez Marc, G., Moreira, E. D., Zerbini, C., Bailey, R., Swanson, K. A., Roychoudhury, S., Koury, K., Li, P., Kalina, W. V., Cooper, D., Frenck, R. W., Hammitt, L. L., ... Gruber, W. C. (2020). Safety and Efficacy of the BNT162b2 mRNA COVID-19 Vaccine. *New England Journal of Medicine*, *383*(27), 2603–2615. <https://doi.org/10.1056/nejmoa2034577>
- Prato, M. (2022). The Global Race for Talent: Brain Drain, Knowledge Transfer, and Growth. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.4287268>
- Qiao, Y., Ascani, A., Breschi, S., & Morrison, A. (2024). Returnees and innovation: Evidence from Chinese publicly listed firms. *Science and Public Policy*, *51*(5), 861–878. <https://doi.org/10.1093/scipol/scae031>
- Rao, Y., & Dai, D. (2017). Creative Class Concentrations in Shanghai, China: What is the Role of Neighborhood Social Tolerance and Life Quality Supportive Conditions? *Social Indicators Research*, *132*(3), 1237–1246. <https://doi.org/10.1007/s11205-016-1347-9>
- Resce, G., Zinilli, A., & Cerulli, G. (2022). Machine learning prediction of academic collaboration networks. *Scientific Reports*, *12*(1), 21993. <https://doi.org/10.1038/s41598-022-26531-1>
- Robins, G., Pattison, P., Kalish, Y., & Lusher, D. (2007). An introduction to exponential random graph ( $p^*$ ) models for social networks. *Social Networks*, *29*(2), 173–191. <https://doi.org/10.1016/j.socnet.2006.08.002>

- Rosvall, M., & Bergstrom, C. T. (2008). Maps of random walks on complex networks reveal community structure. *Proceedings of the National Academy of Sciences*, 105(4), 1118–1123. <https://doi.org/10.1073/pnas.07068511105>
- Sauermann, H., & Cohen, W. M. (2010). What Makes Them Tick? Employee Motives and Firm Innovation. *Management Science*, 56(12), 2134–2153. <https://doi.org/10.1287/mnsc.1100.1241>
- Saviotti, P. P., & Frenken, K. (2008). Export variety and the economic performance of countries. *Journal of Evolutionary Economics*, 18(2), 201–218. <https://doi.org/10.1007/s00191-007-0081-5>
- Saxenian, A. (2005). From Brain Drain to Brain Circulation: Transnational Communities and Regional Upgrading in India and China. *Studies in Comparative International Development*, 40(2), 35–61. <https://doi.org/10.1007/BF02686293>
- Scellato, G., Franzoni, C., & Stephan, P. (2015). Migrant scientists and international networks. *Research Policy*, 44(1), 108–120. <https://doi.org/10.1016/j.respol.2014.07.014>
- Scoville, W. C. (1952). The Huguenots and the Diffusion of Technology. I. *Journal of Political Economy*, 60(4), 294–311. <https://doi.org/10.1086/257238>
- Scudellari, M. (2020). The sprint to solve coronavirus protein structures—And disarm them with drugs. *Nature*, 581(7808), 252–255. <https://doi.org/10.1038/d41586-020-01444-z>
- Skoglund, P., Malmström, H., Raghavan, M., Storå, J., Hall, P., Willerslev, E., Gilbert, M. T. P., Götherström, A., & Jakobsson, M. (2012). Origins and Genetic Legacy of Neolithic Farmers and Hunter-Gatherers in Europe. *Science*, 336(6080), 466–469. <https://doi.org/10.1126/science.1216304>
- Song, J., Almeida, P., & Wu, G. (2003). Learning-by-Hiring: When Is Mobility More Likely to Facilitate Interfirm Knowledge Transfer? *Management Science*, 49(4), 351–365. <https://doi.org/10.1287/mnsc.49.4.351.14429>

- Storper, M. (2018). Separate Worlds? Explaining the current wave of regional economic polarization. *Journal of Economic Geography*, 18(2), 247–270.  
<https://doi.org/10.1093/jeg/lby011>
- Toma, S., & Villares-Varela, M. (2019). The Role of Migration Policies in the Attraction and Retention of International Talent: The Case of Indian Researchers. *Sociology*, 53(1), 52–68.  
<https://doi.org/10.1177/0038038517750540>
- Tóth, G., & Lengyel, B. (2021). Inter-firm inventor mobility and the role of co-inventor networks in producing high-impact innovation. *The Journal of Technology Transfer*, 46(1), 117–137.  
<https://doi.org/10.1007/s10961-019-09758-5>
- Traag, V. A., Waltman, L., & Van Eck, N. J. (2019). From Louvain to Leiden: Guaranteeing well-connected communities. *Scientific Reports*, 9(1), 5233. <https://doi.org/10.1038/s41598-019-41695-z>
- Trajtenberg, M., Shiff, G., & Melamed, R. (2006). *The «Names Game»: Harnessing Inventors' Patent Data for Economic Research* (NBER Working Papers 12479). National Bureau of Economic Research, Inc. <https://doi.org/None>
- Trucillo, P., Campardelli, R., & Reverchon, E. (2020). Liposomes: From Bangham to Supercritical Fluids. *Processes*, 8(9), 1022. <https://doi.org/10.3390/pr8091022>
- Tunali, I. (2000). Rationality of Migration. *International Economic Review*, 41(4), 893–920.  
<https://doi.org/10.1111/1468-2354.00089>
- Useche, D., Miguelez, E., & Lissoni, F. (2020). Highly skilled and well connected: Migrant inventors in cross-border M&As. *Journal of International Business Studies*, 51(5), 737–763.  
<https://doi.org/10.1057/s41267-018-0203-3>
- Vaccario, G., Verginer, L., & Schweitzer, F. (2020). The mobility network of scientists: Analyzing temporal correlations in scientific careers. *Applied Network Science*, 5(1), 36.  
<https://doi.org/10.1007/s41109-020-00279-x>

- Van Der Wouden, F., & Rigby, D. L. (2021). Inventor mobility and productivity: A long-run perspective. *Industry and Innovation*, 28(6), 677–703.  
<https://doi.org/10.1080/13662716.2020.1789451>
- Verbeke, R., Hogan, M. J., Loré, K., & Pardi, N. (2022). Innate immune mechanisms of mRNA vaccines. *Immunity*, 55(11), 1993–2005. <https://doi.org/10.1016/j.immuni.2022.10.014>
- Verginer, L., & Riccaboni, M. (2021). Talent goes to global cities: The world network of scientists' mobility. *Research Policy*, 50(1), 104127. <https://doi.org/10.1016/j.respol.2020.104127>
- Wachowska, M. (2018). Consequences of the Post-Accession Migration of Polish Inventors for the Innovative Potential of Poland: 2004-2012. *Economics & Sociology*, 11(1), 311–324.  
<https://doi.org/10.14254/2071-789X.2018/11-1/20>
- Wang, Z., Fellows, I. E., & Handcock, M. S. (2024). Understanding networks with exponential-family random network models. *Social Networks*, 78, 81–91.  
<https://doi.org/10.1016/j.socnet.2023.07.003>
- Zacchia, P. (2018). Benefiting colleagues but not the city: Localized effects from the relocation of superstar inventors. *Research Policy*, 47(5), 992–1005.  
<https://doi.org/10.1016/j.respol.2018.03.004>
- Zhang, G., Tang, T., Chen, Y., Huang, X., & Liang, T. (2023). mRNA vaccines in disease prevention and treatment. *Signal Transduction and Targeted Therapy*, 8(1).  
<https://doi.org/10.1038/s41392-023-01579-1>
- Zheng, J., Sun, D., Dai, W., & Shi, L. (2025). Multi-Polar Evolution of Global Inventive Talent Flow Network—An Endogenous Migration Model and Empirical Analysis. *China Economist*, 20(4), 80–100. <https://doi.org/10.19602/j.chinaeconomist.2025.07.04>
- Zinilli, A. (2016). Competitive project funding and dynamic complex networks: Evidence from Projects of National Interest (PRIN). *Scientometrics*, 108(2), 633–652.  
<https://doi.org/10.1007/s11192-016-1976-4>

Zinilli, A., & Cerulli, G. (2023). Link prediction and feature relevance in knowledge networks: A machine learning approach. *PLOS ONE*, 18(11), e0290018.

<https://doi.org/10.1371/journal.pone.0290018>

Zucker, L. G., & Darby, M. R. (1995). *Present at the revolution: Transformation of technical identity for a large incumbent pharmaceutical firm after the biotechnological breakthrough*. National Bureau of Economic Research Cambridge, Mass., USA.

<https://www.nber.org/papers/w5243>