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Emergence of Innovation Ecosystem and the Orchestration of the Science, Technology and Innovation Continuum in a Globally Complex Technopolitical Environment: The case of 5G Technology

ANAS RAMDANI

Département de mathématiques et de génie industriel

Thèse présentée en vue de l'obtention du diplôme de *Philosophiæ Doctor*

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Cette thèse intitulée :

Emergence of Innovation Ecosystem and the Orchestration of the Science, Technology and Innovation Continuum in a Globally Complex Technopolitical Environment: The case of 5G Technology.

présenté par **Anas RAMDANI**

en vue de l'obtention du diplôme de *Philosophiæ Doctor*

a été dûment accepté par le jury d'examen constitué de :

Marcelin JOANIS, président

Catherine BEAUDRY, membre et directrice de recherche

Mario BOURGAULT, membre et codirecteur de recherche

Majlinda ZHEGU, membre

Philippe MONGEON, membre externe

DEDICATION

À mes parents et à mon petit frère,

Pour votre amour et soutien sans faille. Ce travail vous est dédié, en témoignage de mon éternelle gratitude.

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RÉSUMÉ

Dans le contexte mondial actuel, les organisations telles que les entreprises, les universités et les instituts de recherche sont amenées à collaborer, tant au niveau national qu'international, pour rester compétitives. Ces collaborations sont de plus en plus influencées par l'interaction entre la technologie et la géopolitique (techno-politique). Cela se manifeste particulièrement dans le développement de technologies de pointe telles que la blockchain, l'informatique quantique, l'intelligence artificielle et la 5G, où la collaboration est essentielle pour concrétiser les avantages économiques et obtenir un avantage concurrentiel. Parallèlement, ces technologies exacerbent la concurrence géopolitique, alors que les nations et les organisations se disputent la domination stratégique tout en cherchant à éviter une dépendance critique envers certains pays. Dans cet environnement complexe, les écosystèmes d'innovation se révèlent être un cadre pertinent pour analyser ces défis interconnectés.

Les orchestrateurs d'écosystèmes d'innovation doivent naviguer au sein de ces complexités, particulièrement durant la phase critique d'émergence de ces écosystèmes. Cependant, une grande partie de la littérature existante se concentre sur des écosystèmes déjà établis, négligeant souvent les processus de formation dans des contextes internationaux, technologiques et politiques incertains.

Pour combler cette lacune, cette thèse s'articule autour de la question de recherche suivante : Comment les acteurs clés orchestrent-ils l'émergence d'un écosystème d'innovation dans un contexte international, technologique et politique incertain ?

Sur la base d'une revue approfondie de la littérature présentée dans le premier chapitre, trois axes de recherche sont explorés pour répondre à cette question : (1) les mécanismes clés d'orchestration dans la phase d'émergence des écosystèmes d'innovation ; (2) la résilience des écosystèmes d'innovation face aux perturbations externes ; (3) le rôle des politiques publiques dans la phase d'émergence des écosystèmes. Ces trois axes sont abordés sous des angles différents et de manière complémentaire dans quatre articles, chacun contribuant à une meilleure compréhension des processus d'orchestration et des dynamiques au sein des écosystèmes d'innovation émergents.

Tout d'abord, l'écosystème de la 5G est encore dans sa phase d'émergence, car il n'a pas encore été largement adopté, notamment par les entreprises et les industries, laissant ainsi une grande partie de son potentiel inexploité. Ensuite, le fait que la technologie 5G ait déclenché des tensions

géopolitiques en raison de son potentiel économique important et des préoccupations en matière de sécurité en fait un sujet particulièrement pertinent pour nos objectifs de recherche.

L'une des particularités de cette thèse réside dans l'adoption d'une approche multiméthodes qui intègre à la fois des analyses qualitatives et quantitatives pour explorer l'émergence de l'écosystème d'innovation 5G. En combinant des méthodes variées telles que l'analyse des réseaux sociaux, les régressions, la fouille de texte et les entretiens semi-structurés, cette recherche exploite différentes sources de données et méthodologies pour obtenir une compréhension approfondie de plusieurs dimensions de la phase d'émergence d'un écosystème dans des contextes internationaux, technologiques et politiques incertains.

Une étude approfondie identifie ensuite les mécanismes clés impliqués dans l'émergence d'un écosystème d'innovation. Plus précisément, cette analyse met en lumière le rôle d'orchestrateur qu'une structure temporaire collective peut jouer. En réunissant des acteurs clés, cette recherche montre comment, et par quels mécanismes, cette structure temporaire peut orchestrer l'émergence d'un écosystème d'innovation (Article 1).

Une analyse des réseaux sociaux et des structures de type petit monde a mis en évidence des changements dans les modèles de collaboration et les propriétés structurelles du réseau scientifique autour de la 5G durant les périodes de tensions géopolitiques, principalement entre la Chine et les États-Unis (Article 2). De plus, une simulation de l'exclusion de Huawei du réseau académique-industrie 5G canadien examine l'impact de cette exclusion sur la collaboration et les propriétés structurelles du réseau. Cette analyse est complétée par une analyse de texte utilisant des techniques de fouille de texte, qui identifie les thématiques de recherche sur la 5G potentiellement dépendantes de Huawei au Canada (Article 3).

Enfin, une étude quantitative, basée sur un modèle économétrique, permet d'observer l'impact de la collaboration scientifique avec des chercheurs chinois et Huawei sur la performance scientifique des chercheurs canadiens dans le domaine de la 5G (Article 4).

ABSTRACT

In today's global landscape, organizations such as firms, universities, and research institutions are compelled to collaborate both nationally and internationally to stay competitive. These collaborations are increasingly influenced by the interplay between technology and geopolitics (technopolitics). This is particularly evident in the development of frontier technologies like blockchain, quantum computing, AI, and 5G, where collaboration is essential for realizing economic benefits and securing a competitive edge. At the same time, these technologies intensify geopolitical competition, as nations and organizations race to achieve strategic dominance while also striving to avoid dependence on certain countries for critical technologies. In this complex environment, innovation ecosystems emerge as an interesting framework for investigating these interconnected challenges.

Orchestrators of innovation ecosystems must navigate these complexities, particularly during the critical emergence phase of these ecosystems. However, much of the existing literature focuses on established ecosystems, often overlooking how these ecosystems form in uncertain international, technological, and political contexts.

To address this gap, this thesis focuses on the following research question: How do key actors orchestrate an emerging innovation ecosystem in an uncertain international, technological, and political context?

Based on an in-depth review of the literature presented in the first chapter, three research avenues are explored to answer this research question: (1) key orchestration mechanisms in the emergence phase of innovation ecosystems; (2) the resilience of innovation ecosystems to external disturbances; (3) the role of public policy in the emergence phase of ecosystems. These three avenues are approached from different angles and in different ways in four separate articles, each contributing to an understanding of orchestration processes and the dynamics within emerging innovation ecosystems.

First, the 5G ecosystem is still in its emerging phase, as it has not yet been widely adopted, particularly by firms and industries, leaving much of its potential untapped. Second, the fact that 5G technology has triggered geopolitical tensions due to its significant economic potential and associated security concerns makes it especially pertinent to our research objectives.

One of the original features of this thesis lies in its adoption of a multi-method approach that integrates both qualitative and quantitative analyses to explore the emergence of the 5G innovation ecosystem. By combining diversified methods such as social network analysis, regressions, text mining, and semi-structured interviews, this research takes advantage of several types of data and methodologies to obtain a deeper understanding on several dimensions of the emergence phase of an ecosystem in uncertain international, technological, and political contexts.

An in-depth case study then identifies the key mechanisms involved in the emergence of an innovation ecosystem. More specifically, this analysis highlights the orchestrator role that a collective temporary structure can play. By bringing together key players, this research shows how and by what mechanisms this temporary structure could orchestrate the emergence of an innovation ecosystem (Article 1).

An analysis of social networks and small-world structures has showed changes in collaborative patterns and structural properties of the scientific network in 5G during periods of geopolitical tension, mainly between China and the USA (Article 2). In addition, a simulation of Huawei's exclusion from the Canadian 5G academic-industrial network examines the impact of this exclusion on collaboration and structural properties of the network. This analysis is complemented by a text analysis using text mining techniques, which identifies 5G research topics potentially dependent on Huawei in Canada (Article 3).

Finally, a quantitative study based on an econometric model allows us to observe the impact of scientific collaboration with Chinese scientists and Huawei on the scientific performance of 5G Canadian researchers (Article 4).

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LISTE OF SYMBOLS AND ABBREVIATIONS

2SLS	Two-Stage Least Squares
5G	Fifth generation of mobile communications
AI	Artificial Intelligence
CAD	Canadian Dollar
CC_l	Clustering coefficient
CSV	Comma-Separated Values
IH	Innovation Hub
IoT	Internet of Things
IV	Instrumental variable
LCC	Largest Connected Component
LDA	Latent Dirichlet allocation
l_G	Average path lenght
ln	Natural logarithm
MITACS	Mathematics of Information Technology and Complex Systems
MNE	Multinational Enterprise
NPO	Non-Profit Organization
NSERC	Natural Sciences and Engineering Research Council of Canada
OST	Observatoire des Sciences et des Technologies
Ph.D	Doctor of Philosophy
R&D	Research and development
RII	Research and Innovation Intermediaries
ROC	Rest of Canada
SMEs	Small and Medium-sized Enterprises

SNA	Social Network Analysis
STEM	Science, Technology, Engineering and Mathematics
SW	Small-World
TF-IDF	Term Frequency-Inverse Document Frequency
UK	United Kingdom
US	United States
USA	United States of America
WoS	Web of Science

LIST OF APPENDICES

CHAPTER 1 INTRODUCTION

Researchers, practitioners, and policymakers agree that innovation is one of the key drivers of business performance and economic growth (Baldwin et al., 2024). The innovation process has evolved towards a more open model, no longer limited solely to the research and development (R&D) results of large companies. In today's economic context, most innovations require interactions that cross traditional organizational boundaries. The globalization of markets, significant advances in information and communication technologies and intensifying international competition are encouraging companies to collaborate and form alliances to access new knowledge and reduce the risks and costs associated with innovation (Primario et al., 2024).

Considering that the focus of innovation has gradually shifted from individual firms to networks of firms and individuals providing complementary goods and services (Moore, 1996), numerous studies have explored the optimal organizational configuration favoring collaboration between these various entities (Marshall, 1890; Aydalot, 1984; Freeman, 1987; Becattini, 1989; Porter, 1990; Maillat & Perrin, 1992; Lundvall, 1992). Among the most significant contributions in this field is Alfred Marshall's "*Principles of Economics*", published in 1890, which highlights the advantages of an organizational configuration based on territorial agglomeration. These configurations, often referred to as "districts", take advantage of geographical proximity to maximize benefits for stakeholders and stimulate innovation.

Indeed, geographical proximity between various organizations, including SMEs, large corporations, suppliers, and universities, delivers notable economic benefits, such as reduced transaction costs (Scaringella & Radziwon, 2018). This proximity also facilitates coordination and logistics, generating economies of scale and external economies, increasing productivity both at the level of individual companies and the supply chain. Beyond the economic benefits, proximity also offers non-economic benefits, such as the creation of trusting relationships and the sharing of a common culture and social norms, which strengthen collaboration and collective learning within the region (Autio et al., 2018).

Marshall's studies on the benefits of territorial agglomeration have inspired many researchers to explore several other types of configurations, such as Italian industrial districts (Becattini, 1989), innovation milieux (Aydalot, 1984; Maillat & Perrin, 1992), national and regional innovation systems (Freeman, 1987; Lundvall, 1992) and clusters (Porter, 1990). Although these concepts differ in certain respects, they all share the importance of geographical proximity in innovation processes.

In recent years, however, unlike traditional approaches that often emphasize geographical proximity, the concept of ecosystem introduces a novel perspective by focusing on the dynamics of interaction and interdependence, drawing inspiration from biological ecosystems. In a business ecosystem, organizations and consumers are envisioned as living organisms that are interconnected by relationships of mutual dependence. Moore (1993) defines a business ecosystem as an economic community of heterogeneous organizations which, by co-evolving their competencies, create value for customers. Moore (1993) also points out that these organizations will tend to align themselves around a leading firm.

Subsequently, several researchers turned their attention to the concept of business ecosystems from the point of view of innovation. This stream of literature gave rise to the notion of innovation ecosystem. Unlike business ecosystems, which focus on the company and its environment, innovation ecosystems focus on an innovation or new value proposition and the constellation of actors that support it (Jackson, 2011).

Another type of ecosystem that has attracted considerable interest from the scientific community in recent years is the knowledge ecosystem. Whereas the innovation ecosystem incorporates a broader scope, including both exploration and exploitation from invention to commercialization, the knowledge ecosystem focuses primarily on the early stages of knowledge creation (Valkokari, 2015). In this type of ecosystem, universities and research centers play a central role in technological advancement and innovation.

These three types of ecosystems can overlap and are not mutually exclusive. In other words, an organization can be part of, and play a different role in, more than one ecosystem at the same time. For example, an organization may be the leader in one ecosystem but not in another. For Xu et al. (2020), the business ecosystem and the knowledge ecosystem are distinct sub-ecosystems of an innovation ecosystem. The authors stress that knowledge creation in the knowledge ecosystem and value capture in the business ecosystem are two fundamental elements in understanding innovation ecosystems.

Since the contribution of Moore (1993), the concept of ecosystem has been widely debated in literature. Several studies have approached the conceptualization of ecosystems in different ways.

First, some studies focus on their characteristics, structure and dominant roles. For example, Gawer & Cusumano (2002) highlight the importance of platforms in the success of an innovation ecosystem. Iansiti & Levien (2004) examine the different roles within ecosystems and develop performance measures, illustrating the important role of a leader, often referred to as a "keystone" or "hub firm", in managing the ecosystem. In this same perspective, other studies have focused on the role these hub firms can play in orchestrating the ecosystem (Batterink et al., 2010; Dos Santos et al., 2021). Adner & Kapoor (2010) highlight that, without an effective orchestrator to manage challenges between partners, the ecosystem could fail. In this context, the orchestrator must align the needs of the various ecosystem players around a common value proposition, by implementing appropriate coordination mechanisms.

Other articles attempt to propose new definitions of innovation ecosystems. In this context, Adner (2017) highlights the lack of clarity in the conceptualization of innovation ecosystems, resulting from the growing popularity and widespread adoption of this concept in the literature. Reviewing existing work, the author highlights that ecosystems are primarily defined by the alignment of actors, their activities, and relationships, with the aim of creating a common value proposition. Granstrand & Holgersson (2020) have undertaken a systematic review of the literature on innovation ecosystems and propose a new definition:

> An innovation ecosystem is the evolving set of actors, activities, and artifacts, and the institutions and relations, including complementary and substitute relations, that are important for the innovative performance of an actor or a population of actors. (Granstrand & Holgersson, 2020, p. 1)

Finally, some studies contribute to the conceptualization of innovation ecosystems by distinguishing them from other types of ecosystems. The bibliometric analysis carried out by Gomes et al. (2018) on articles about innovation ecosystems highlights the various interpretations of what an innovation ecosystem is in the literature and illustrates how the different types of ecosystems are used interchangeably. The authors differentiate between the concept of a business ecosystem and that of an innovation ecosystem. They show that the former focuses on value capture, while the latter focuses on value creation.

This growing literature on innovation ecosystems underscores the increasing importance of understanding their various dimensions and configurations. Especially as our world becomes increasingly interconnected, the dynamics within these ecosystems have grown more complex. This is particularly relevant today, as ecosystems around frontier technologies such as 5G, Artificial Intelligence (AI), and quantum computing are shaped by the intricate interplay of technology, economics, and geopolitics. This interaction plays an important role in shaping the dynamics of these innovation ecosystems.

Frontier technologies like 5G and artificial intelligence are set to bring substantial economic impacts. By 2035, 5G is expected to generate $13 trillion in global economic value and create 22 million jobs, while artificial intelligence could contribute over $15 trillion to the global economy by 2030 (World Economic Forum, 2021). These projections highlight the importance of economic strategies and public policies in guiding the development and deployment of these technologies. Regulatory actions, such as bans or restrictions on specific companies, play a significant role in this area.

Additionally, the dual-use nature of these technologies, for both commercial and military purposes, fuels global competition and reshapes international alliances, sometimes leading to disputes. The situation with the United States banning Huawei from its 5G projects over security concerns illustrates how economic and security issues intertwined with frontier technologies can influence global geopolitical dynamics and affect strategies within innovation ecosystems.

While research on innovation ecosystems is growing, the specific coordination and management mechanisms, commonly referred to as orchestration (Dos Santos et al., 2021), during their early development phase remain underexplored. Orchestration is generally studied on already established ecosystems and in a retrospective manner, often orchestrated by a single lead entity. This is especially critical for ecosystems centered around frontier technologies, where economic and geopolitical forces introduce additional complexity. Understanding how orchestrators navigate these challenges during the volatile emergence phase is essential for effective ecosystem management.

This thesis seeks to fill this gap in the literature by exploring the following research question: **How do key actors orchestrate an emerging innovation ecosystem in an uncertain international, technological, and political context?** More specifically, this research focuses on three orchestration-related themes that receive little attention in the current literature: orchestration strategies and mechanisms during the emergence phase of the innovation ecosystem, ecosystem resilience to external disturbances, and the role of public policies in the process. These aspects are essential to understanding how innovation ecosystems can not only emerge, but also develop and adapt in complex and uncertain environments.

This thesis aims to contribute to the literature on ecosystems orchestration. First, it distinguishes itself from most existing studies by offering a multi-method empirical analysis, both quantitative and qualitative, of the emergence phase of innovation ecosystems. Furthermore, this thesis focuses on the diversity of actors and their interactions. Specifically, this research considers the actors involved from the earliest phases of an innovation ecosystem, from the creation of knowledge within the knowledge ecosystem to the potential commercialization of products by the principal actors in the business ecosystem. Additionally, this study empirically analyzes the various orchestration activities during the ecosystem emergence phase. Finally, the concepts of resilience and public policies of an emerging ecosystem in relation to the external environment are also empirically studied in this research.

To this end, our study focuses on a technology that has emerged in recent years, enabling us to investigate these different aspects of the genesis of innovation ecosystems: the fifth generation of mobile communications (5G). First, we consider 5G as an emerging innovation ecosystem because, despite its potential, it has not yet been widely adopted, and its full capabilities remain largely untapped. This situation provides a unique opportunity to explore how such ecosystems form and evolve. Second, 5G exemplifies the complex interplay between technological innovation, economic potential, and geopolitical tensions, making it an ideal context for examining the emergence of innovation ecosystems in such conditions. Compared to previous generations, 5G is a frontier technology because it represents a major innovation compared to previous generations, offering significant advancements. It is designed to enhance data throughput, support a high density of connected objects within a territory, and provide unparalleled availability and reliability, while delivering extremely low latency (Andrews et al., 2014). These technological advancements pave the way for creating new use cases (Ullah et al., 2019; Erunkulu et al., 2021; Ranaweera et al., 2021).

From an economic perspective, 5G offers substantial benefits, including significant contributions to GDP growth and job creation (World Economic Forum, 2021). The race to deploy this technology has not only economic implications but also national security concerns, intensifying geopolitical tensions globally. Additionally, 5G has been at the center of these tensions, especially between the United States and China, affecting countries worldwide (Kaska et al., 2019; Parsons, 2020; Cheney, 2019; Jaisal, 2020; Tang, 2020). The conflict stems from U.S. accusations that China uses Huawei, a global leader in 5G, for espionage and sabotage to benefit its government (Jaisal, 2020; Ceci & Rubin, 2022; Creemers, 2020; Wu, 2020). This has impacted both industrial and academic collaborations with Huawei (Silver et al., 2019; Tollefson, 2019).

The technological and economic importance of 5G is driving the formation of a complex and diverse ecosystem, involving a wide range of actors, from industry leaders and policymakers to academic institutions, each playing an important role in its growth. This complexity is heightened by ongoing geopolitical tensions and economic policies that are shaping the 5G ecosystem. The challenge of bringing together these different stakeholders, each with their own interests and goals, makes the 5G ecosystem a perfect setting for studying how innovation ecosystems are orchestrated, especially in uncertain technological, international, and political environments. Also, starting the research for this thesis simultaneously with the emergence of 5G worldwide and in Canada enabled us to investigate the mechanisms of this ecosystem's emergence and to experience its emergence in real time, which allows for deep immersion and promotes a thorough understanding of ecosystem dynamics, rather than studying them a retrospectively.

The thesis is structured into four articles, each focusing on a specific aspect of the overall objective. Collectively, these contributions aim to enhance our understanding of the mechanisms through which innovation ecosystems emerge. The first article investigates the role of temporary structures in orchestrating the emergence of innovation ecosystems. This study focuses on a unique case study involving an innovation ecosystem centered around 5G technology. Through semi-structured interviews, this article explores the specific mechanisms these temporary structures employ, the roles they play, and the challenges they encounter during the orchestration of the emergence phase of an innovation ecosystem. Our observations at various 5G events and interviews with ecosystem members highlighted tensions in collaborations involving Huawei, the global 5G technology leader, and Chinese scientists. The resultant FBI arrests and Huawei's exclusion from the U.S. market cultivated a cautious atmosphere in Canada. This backdrop sets the stage for further exploration in the three subsequent articles of how such geopolitical tensions influence the Canadian 5G innovation ecosystem.

The second article explores the resilience of the 5G ecosystem on an international scale amid geopolitical conflicts. It assesses how these tensions affect the structural properties of co-authorship networks and trends in international collaboration within the 5G domain. The study employs bibliometric data from the Web of Science database to quantify the influence of geopolitical dynamics on scientific collaboration. The results suggest that these geopolitical tensions could have influenced collaboration tendencies between the U.S. and its allies and China.

The third article broadens the analysis to include a wider array of stakeholders such as industry players, universities, and non-profits within the Canadian landscape. Using data from the Natural Sciences and Engineering Research Council (NSERC), this study assesses Huawei’s influence and its impact on network robustness and research themes. The findings indicate that Huawei’s exclusion did not significantly alter the network’s structural properties or the robustness of key research topics. Canada’s contributions to these fields have remained robust, underscoring that Huawei’s role, while significant, is not irreplaceable in the Canadian academic-industry network.

The fourth article expands the scope to include international collaborations between Canadian and Chinese researchers, focusing on their impact on the productivity and utility of Canadian 5G research. Regression analysis indicates that while collaborations with Chinese researchers generally improve research outcomes, partnerships with Huawei slightly reduce productivity yet contribute to broader international benefits. The study also shows that Canadian researchers can achieve high performance through collaborations with scientists from various countries, independent of their interactions with China.

The remainder of this thesis is organized as follows: Chapter 2 introduces the theoretical foundations of innovation ecosystems, highlighting their distinctiveness from other approaches, and provides an overview of 5G technology as a case study. Chapter 3 outlines the thesis objectives, and the methodologies employed to achieve them. Chapters 4 to 7 present the four papers that constitute the core of this research. Chapter 8 discusses the results obtained, and Chapter 9 concludes the thesis.

CHAPTER 2 LITERATURE REVIEW

In this thesis, the literature review aims to provide a broad and general overview of the concepts and theoretical frameworks related to its central topic. Each article already includes a more specific and detailed literature review, focusing on the concepts needed to address its own research questions. The goal here is to go beyond those individual reviews, avoiding redundancies while offering a transversal and integrative perspective. This literature review is structured into four sections. First, an overview of the literature on the territorial configurations that form the conceptual foundation of ecosystems is provided. This includes a description of their characteristics and a comparative analysis of these concepts. The second section of this literature review aims to define the various types of ecosystems and their distinctive characteristics. It addresses the three types of ecosystems examined in this thesis: business ecosystems, knowledge ecosystems, and innovation ecosystems. The third section then focuses on ecosystem orchestration, providing a definition and description of orchestration processes, along with the types of orchestration present in the literature. The fourth section describes 5G technology, highlighting the technological and geopolitical stakes involved.

2.1 Conceptual foundations of ecosystems: from districts to clusters

The notion of an innovation ecosystem originates from a series of earlier concepts that have shaped our understanding of territorial and organizational dynamics. Concepts such as industrial districts, innovative milieus, innovation systems, and clusters laid the theoretical foundations on which the notion of ecosystems is based. This section aims to explore these various concepts by highlighting their similarities and differences.

2.1.1 Industrial districts

The theoretical origins of industrial districts can be traced back to the early 20th century, primarily through the work of Alfred Marshall (Daidj, 2011). In his seminal work, "*Principles of Economics*" published in 1890, Marshall describes the industrial district as a distinct form of industrial organization that contrasts with the structure of large firms (Marshall, 1890; Lévesque et al., 1996; De Marchi & Grandinetti, 2014).This configuration, as detailed by Marshall, is distinctly different from traditional large-scale corporate structures, laying the foundations for a new form of industrial organization (Lévesque et al., 1996; Alberti, 2010). Marshall (1890) describes these industrial districts as concentrations of companies specialized in a particular industrial sector, clustered together in specific localities (Alberti, 2010).

Within industrial districts, companies benefit from several economic advantages mainly due to geographical proximity. These advantages include reduced transaction costs (Daidj, 2011; Scaringella & Radziwon, 2018). However, it was not until the late 1980s that the concept of the industrial district gained popularity, largely due to the contributions of Italian researchers. (Dei Ottati, 1994; Becattini et al., 2003; Dei Ottati, 2003; Sforzi, 2003; Becattini, 2017). Becattini (2017) defines districts as:

> A socio-territorial entity which is characterized by the active presence of both a community of people and a population of firms in one naturally and historically bounded area. (Becattini, 2017, p.15)

Geographic proximity is a fundamental characteristic of industrial districts. This co-location of organizations and individuals brings a series of economic advantages (Sforzi, 2003). For example, proximity reduces the cost of transporting goods, and those associated with sharing resources, such as the expense of training specialized workforce (Marshall; 1890; Asheim, 1996; Breschi & Malerba, 2001). Geographical proximity enables specialized and skilled workers to move from one company to another within the district, thereby reducing recruitment costs (Alberti, 2010).

In addition to geographical proximity, another essential characteristic of industrial districts is their composition of small, specialized companies within a single sector. Each company focuses on producing a specific component of the final product (Lévesque et al., 1996). These characteristics are reinforced by social factors specific to the district (Bellandi, 1996). According to Beccatini (2017), the economic aspect of an industrial district is inseparable from its social dimension (Scaringella & Radziwon, 2018). The shared attitudes and values of the local population play a decisive role in the performance of industrial districts in several ways (McDonald & Belussi, 2002). They facilitate the establishment of common rules within the district, which supports the diffusion and transmission of these values (Lévesque et al., 1996). According to McDonald & Belussi (2002), social proximity between district members promotes the dissemination and sharing of knowledge, and a higher level of mutual understanding. This social cohesion and the sharing of values and rules within the district facilitate informal communications, supported by work ethic and discipline deeply rooted in local customs and culture (Lévesque et al., 1996). Finally, social proximity also helps to mitigate opportunistic tendencies within districts (Staber & Morrison, 2000).

All these social factors within districts enable participants to develop a sense of belonging to the same community (Scaringella & Radziwon, 2018).

Industrial districts are also characterized by the coexistence of cooperation and competition (Alberti, 2010). Competition within these districts encourages companies to optimize costs and improve performance by innovating and rationalizing the use of available resources (Lévesque et al., 1998). At the same time, geographical proximity fosters cooperation between companies, facilitating the sharing of technology and information. This cooperation enhances collective learning, reduces risk, and enables tasks to be divided according to rules established by the members of the industrial district (Scaringella & Radziwon, 2018).

These socio-economic characteristics create what Marshall refers to as an "*industrial atmosphere*" benefiting the entities within the industrial district (Daidj, 2011).

2.1.2 Innovation milieus

The notion of "*innovative milieus*" was introduced by researchers from the Groupe de Recherche Européen sur les Milieux Innovateurs (GREMI), who studied and analyzed the link between innovation and territorial agglomerations. (Aydalot, 1984; Camagni, 1991; Camagni & Maillat, 2006). Aydalot (1984) and Maillat & Perrin (1992) highlight a phenomenon of "reversal of territorial hierarchy" observed in the early 1970s in several European countries, notably in France. These studies indicate that the traditionally attractive northern regions were declining in favor of the southern regions. According to Maillat & Perrin (1992), this transformation is not merely a matter of relocation; rather, it can be explained by the specific spatial characteristics of the territory. These observations led GREMI to update the concept of the industrial district by proposing the notion of "innovative milieus", defined as follows:

> The set or complex network of mainly informal social relations in a limited geographical area, frequently determining a specific external image and a specific internal representation, and also the sense of belonging, which strengthens the local innovative capacity through synergistic processes of collective learning. (Camagni,1991; p. 3)

Innovative milieus share many characteristics with industrial districts. First, geographical proximity provides economic benefits, such as reduced transaction costs for members of the innovation community, similar to what is observed in industrial districts (Uzunidis, 2010). Additionally, the social dimension is a common feature of both concepts. This social dimension facilitates the development of a sense of belonging and trust among actors, which encourages the sharing of resources and information and establishes a balance between cooperation and competition (Fromhold-Eisebith, 2004; Capello & Faggian, 2005; Scaringella & Radziwon, 2018).

However, the literature on innovative milieus differs from that on industrial districts. Greater importance is attached to the social aspect than to the economic aspect, in contrast to what is observed in studies on industrial districts (Scaringella & Radziwon, 2018). This literature suggests that the environment precedes the creation of companies and that innovations emanate from this environment. Consequently, companies are not seen as the sole drivers of innovation but as part of an environment that acts as an innovation incubator. In other words, the environment is viewed not only as a context but also as an active actor playing a significant role in the development of innovation (Tabariés, 2005).

A further distinction between the two concepts lies in the fact that, unlike industrial districts, innovative milieus are not necessarily composed of small companies specializing in a specific industrial sector. Innovative milieus include companies of all sizes (Lévesque et al., 1996). Nor are they limited to a single industry. Unlike industrial districts, companies in innovative milieus are not necessarily involved in the production of a single component of a single product (Scaringella & Radziwon, 2018).

2.1.3 Innovation systems

The notion of an innovation system emerged in the late 1980s, introduced by Freeman (1987) to analyze technological development in Japan. Freeman highlights the importance of interactions between public and private sector organizations in the creation and diffusion of new technologies. Freeman (1987) defines an innovation system as:

> The network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies. (Freeman, 1987; p.1)

More specifically, an innovation system encompasses not only institutions and organizations dedicated to exploration and research, such as R&D departments, technological institutes, and universities, but also those involved in production, marketing, and finance. (Lundvall, 1992, Bassis & Armellini, 2018). These entities are generally located within the borders of a nation-state or are deeply rooted there (Lundval, 1992).

In contrast to previous concepts, the innovation system concept emphasizes the systemic nature of innovation (Carlsson et al., 2002). Indeed, a system is composed of various components and the interdependent relationships between them. In the context of an innovation system, the main components include companies, universities, research centers, governments, and both public and private funding organizations. The relationships between these components manifest in various ways, including the sharing of knowledge and information, the allocation of funding, and the formation of partnerships, among others (Cooke et al., 1997).

In general, literature distinguishes two main types of innovation system, differentiated according to their geographical dimension. On the one hand, the National Innovation System (NIS), which focuses on the country. On the other, the Regional Innovation System (RIS), which targets a specific region. Initially, early studies of innovation systems focused on National Innovation Systems (Lundval, 1992). Gradually, many researchers extended the application of this concept to the regional level, using the term Regional Innovation System (Cooke et al., 1997).

NIS corresponds to systems whose boundaries are aligned with the borders of the country under analysis (Lundvall, 1992, Freeman, 2004). Research on NIS aims to study the interactions between different national organizations and identify the structures that support a country's innovation and economic development (Asheim & Isaksen, 1997). These systems are profoundly influenced by the political-institutional framework and industrial policy of each country:

> Comparative analyses of national innovation systems have shown the specificity of such systems due to different dominating branches of a country. (Asheim & Isaksen, 1997; p. 10)

RISs on the other hand, focus on sub-national levels and aim to simplify and complement the analysis of innovation systems on a national scale. RISs connect knowledge production centers, such as universities and public research laboratories, with innovative companies within a defined region.

These networks facilitate the generation and dissemination of knowledge among diverse organizations, thereby strengthening regional competitiveness (Cooke et al., 1997; Bassis & Armellini, 2018). Although the primary focus in regional innovation systems is on the regional level, it is essential to acknowledge the importance of national and international links. These connections also play a significant role in reinforcing these systems, as demonstrated by Cooke's (2004) definition of RIS:

> Interacting knowledge generation and exploitation subsystems linked to global, national and other regional systems. (Cooke, 2004; p. 4)

Just as in districts and innovative milieus, geographical proximity in innovation systems fosters socio-economic interactions. This proximity facilitates the establishment of common standards and regulations, thus strengthening cooperation in research and development. It also contributes to the creation of a common culture, which in turn supports cooperation among players (Cooke et al., 1997; Suominen et al., 2019).

Although the concept of innovation system is sometimes used interchangeably with the first two territorial configurations, it is important to note that there are significant differences between them. An industrial district, for example, is generally smaller geographically than an innovation system, whether national or regional. Therefore, an innovation system may encompass several industrial districts. According to Tödtling & Trippl (2005), innovation systems should not be seen as homogeneous internal systems. Instead, they often encompass multiple industries, clusters, industrial districts, and innovative milieus.

Additionally, the innovation system concept has attracted greater interest from governments than that of districts and innovative milieus. For government decision-makers, the innovation system concept serves not only as a crucial tool but also as a framework for analyzing innovation policies (Bassis & Armellini, 2018). Indeed, it is used as a means of guiding and developing new, more targeted policies to encourage innovation and improve the performance of local businesses (Balzat & Hanusch, 2004).

2.1.4 Clusters

Over the last few decades, the cluster concept has become the most influential territorial configuration, both among political decision-makers and the scientific community (McDonald et al., 2007). Popularized by the work of Porter (1990, 1998, 2000), this concept is also inspired by the studies of Marshall (1890), who emphasized the advantages and benefits generated by geographical proximity. Porter (2000) defines a cluster as:

> A geographically proximate group of interconnected companies and associated institutions in a particular field, linked by commonalities and complementarities. (Porter 2000; p. 15)

Clusters consist of a population of heterogeneous, complementary, and interdependent players, including product and service companies, consumers, government institutions, as well as research, education, and technical support entities, all supported by a skilled workforce (Porter, 1998; Porter & Ketels, 2009).

Belonging to a cluster offers several advantages to the organizations involved. First, clusters enable efficient knowledge and information sharing among participants (Baptista & Swann, 1998; McDonald et al., 2007). This dynamic strengthens the pool of specialized workers, thereby increasing companies' growth, competitive advantage and capacity for innovation (Baptista & Swann, 1998). The presence of universities within clusters amplifies this trend, increasing the propensity of local firms to innovate and patent. Researchers and students also contribute to this dynamic environment by creating startups and spin-offs (Beaudry & Solar-Pelletier, 2020).

Since its introduction by Porter (1990), interpretations of the cluster concept have diversified and often diverged from the original conceptualization. This evolution can be explained by the variety of cluster types found in the literature, which differ according to several factors such as their stage of development, the territorial environment in which they operate, and the type of industries, goods, or services they encompass (Porter & Ketels, 2009).

According to Beaudry & Schiffauerova (2009), there are two main types of clusters. The first, the specialized cluster, is characterized by a high concentration of companies belonging to a specific industry. The second, the non-specific or diversified cluster, is characterized by the presence of a variety of business sectors.

Torre (2006) categorizes different types of clusters into four groups based on their degree of organization and the location of inter-firm relations within a cluster, as illustrated in Table 2-1. The first type, corresponding to the first box, aligns with Porter's definition of a cluster, characterized by a high degree of localization and organization. The second box illustrates clusters with a low degree of localization but a high level of inter-firm relations, typically observed in national and regional-scale analyses. The third type, described in the third box, features weak local internal links despite a high spatial concentration of companies, with the degree of synergy often stimulated by various national policies. Finally, the fourth box does not represent a cluster in the traditional sense, as it lacks geographical and organizational proximity. Since Porter (1990) popularized the cluster concept, the literature on industrial clusters has evolved considerably. Initially, industrial clusters were thought to correspond only to the first box, which describes a high degree of localization and organization. However, current definitions of clusters now extend to include the configurations described in boxes 2 and 3 (Torre, 2006; Beaudry & Solar-Pelletier, 2020).

Table 2-1. Cluster types

		Organization of Inter-Firm Relationships	
		Strong	Weak
Localization of Inter-Firm Relationships	Strong	1- Porter Cluster	3- Cluster tied to a local resource
	Weak	2- Cluster without proven local base	4- Dispersed Activity

Researchers' enthusiasm for the numerous economic and innovative benefits of clusters, such as improving the economic performance of regions and countries, has prompted several governments to formulate policies to support and develop these clusters. In this context, government policies aim to facilitate access to infrastructure, skilled workforce and financing. They also include investments in the creation of complementary organizations, such as academic institutes and training centers. In addition, the role of governments includes removing obstacles that can hinder the birth and growth of clusters (Lévesque et al., 1996; Porter & Ketels, 2009; Rinkinen, 2016).

However, the lack of clear, unanimous definitions of clusters and their characteristics makes it challenging for public policies to effectively encourage their development. This conceptual ambiguity has led to the creation of a variety of public policies, each significantly different from the others. According to Martin & Sunley (2003), the success of clusters can be attributed to their deliberately vague character, which enables them to be adapted to different local economic development issues.

The concepts of cluster and other local configurations described above are often used interchangeably:

> If clusters are a new way of qualifying local forms of organization of innovation activities, it is not easy to define their exact content, nor to distinguish them radically from concepts already seen before: innovative milieus, technopoles, technological districts. (Torre, 2006; p.4)

The distinction between clusters and earlier concepts lies primarily in their different intellectual traditions (Porter & Ketels, 2009). Research on industrial districts, innovation milieus and systems emphasize social embeddedness within territories and support for local interactions. Some researchers in the field of industrial districts often come from sociology or industrial relations. On the other hand, although it also draws on Marshall's work, industrial cluster theory focuses more on the impact of geographical concentration on corporate competitiveness. Porter strongly emphasizes the role of competition between players within industries. His theory is deeply rooted in the principles of industrial economics and draws on research into value chains, sources of competitive advantage and corporate strategy (Porter & Ketels, 2009). Despite its focus on competition, cluster theory also includes an aspect of cooperation, mainly vertical, between its members (Rinkinen, 2016).

Another distinction concerns the differentiation between clusters and innovation systems. Innovation systems encompass clusters, milieus and industrial districts. They bring together a larger number of players than clusters alone (Tödtling & Trippl, 2005).

In addition, clusters can include various configurations, such as industrial districts and milieus. Suire (2006) suggests that clusters should be seen as an enhanced version of industrial districts. However, in contrast to industrial districts, which are generally limited to small and medium-sized enterprises, clusters can also integrate large companies (Lévesque et al., 1996; Porter, 1998; Porter & Ketels, 2009).

This section concludes with a summary of objectives and characteristics of the territorial configurations that preceded the concept of innovation ecosystems. These concepts, whether industrial districts, innovative milieus, innovation systems or clusters, derive their economic and, in some cases, social benefits primarily from geographical proximity. They all originate from Marshall's work on the benefits of co-locality.

Although these terms are often used interchangeably, we have identified both similarities and differences between these concepts, which are summarized in Table 2-2. This distinction allows us to better understand each of these concepts as an antecedent to the concept of ecosystems, which we will explore in more detail in the next section.

Table 2-2. Similarities and differences between territorial configurations

Features	**Industrial districts**	**Innovative milieus**	**Innovation systems**	**Clusters**
Main references	Marshall (1890) Becattini (2017) Brioschi et al. (2002)	Aydalot (1984) Maillat & Perrin (1992)	Freeman (1987) Lundval (1992)	Porter (1990, 1998, 2000)
Key actors	Small and medium-sized enterprises, each specializing in a component of the final product	Firms of varying sizes	Firms, universities, research centers, governmental bodies	Firms, universities, research centers, governmental bodies
Geographical proximity	High	High	Varies, depending on whether national or regional	High
Social embedding	Strong, common local culture	Strong, the milieu precedes the firms and is also considered an actor in the development of innovation	Strong, innovation systems are characterized by the political context, shared language, culture, and regulation within the innovative environment	Weak, Porter's cluster concept does not emphasize social embedding or the role of local culture and values
Interactions among actors	Coexistence of cooperation and competition	Coexistence of cooperation and competition	Innovation systems emphasize extensive cooperation, treating competition as less central but acknowledging its role in economic dynamism.	This concept highlights competition, although the importance of cooperation is also mentioned
Industrial concentration	Specialized in a specific sector	Diverse sectors, not limited to a specific branch	Multiple industries, clusters, districts	Specialized or diversified
Primary objective	Innovation and competitiveness at the local level	Innovation stemming from the milieu	Promotion of innovation and economic development at the national or regional level	Innovation and economic competitiveness

2.2 Ecosystems: Definitions and characteristics

After reviewing the literature on the antecedents of ecosystems (industrial districts, innovative milieus, innovation systems, and clusters), we now turn to the concept of ecosystems, which represents an evolution of these earlier concepts. This section is dedicated to describing the characteristics of the different types of existing ecosystems -business, innovation and knowledge ecosystems[1], exploring seven key dimensions. For each of these dimensions, we describe the similarities and differences between the three ecosystem types. To conclude this section, we address the criticisms leveled at the notion of ecosystems in the literature.

2.2.1 Definitions and objectives

The term "*ecosystem*" originates from the ecological sciences, where it refers to a complex network of interactions between living organisms and non-living elements within a given environment (Valkokari, 2015). The concept was first formalized by British botanist Arthur Tansley in the 1930s (Robertson, 2020). Biological ecosystems involve the circulation of resources necessary to support species and their habitats, alongside the ongoing coevolution of organisms adapting to environmental changes (Robertson, 2020; Jucevičius et al., 2021).

In the field of economics and innovation management, Michael Rothschild was the first to apply this analogy in 1990 (Beaudry & Solar-Pelletier, 2020). In his book "*Bionomics: The Inevitability of Capitalism*", Rothschild explores how the principles of biological ecosystems can be used to understand market dynamics, suggesting that companies, like biological organisms, evolve in response to their economic environment (Moore, 1993; Bassis & Armellini, 2018).

Continuing this analogy, Moore (1993) further developed the ecosystem concept within the business context. He described companies as part of a business ecosystem that transcends traditional industrial boundaries. The literature on ecosystems generally distinguishes four main types: business ecosystems, innovation ecosystems, knowledge ecosystems, and entrepreneurial

[1] This study does not classify platform-based ecosystems, as described by Gawer & Cusumano (2002), as separate types of ecosystems. Research by Gomez et al. (2018) and Pushpananthan & Elmquist (2022) underscores the significant role of platforms across various ecosystems, including business and innovation, demonstrating that interactions are commonly organized around a technology platform. The role of platforms as tools for orchestration will be further explored in the subsequent section.

ecosystems. In this thesis, we focus solely on the first three types. This section defines each of these types and clarifies their specific objectives.

Moore (1993) was the first to introduce the notion of the business ecosystem. By transposing the concept of a biological ecosystem to the economy, Moore (1993) redefined the economic system as an ecosystem in which organizations and consumers represent living organisms:

> In business, that's because the companies, products, and technologies of a business network are, like the species in a biological ecosystem, increasingly intertwined in mutually dependent relationships outside of which they have a little meaning". (Iansiti & Levien, 2004; p.76)

Moore (1993) defines a business ecosystem as an economic community comprised of heterogeneous organizations. These organizations co-evolve their skills and, through both cooperation and competition, create value for customers. Moore (1993) also states that these organizations tend to align themselves around a leader or keystone company (Iansiti & Levien, 2004; Clarysse et al., 2014). A business ecosystem includes large and small companies, universities, research centers, and public sector organizations (Moore, 1993; Moore, 1996; Peltoniemi et al., 2005). Ecosystems can also include the company's competitors, as well as customers whose behavior is likely to influence the company's performance. The heterogeneity of players implies the convergence of a variety of industries (Moore, 1993; Jucevičius et al., 2021; Cobben et al., 2022). The smartphone exemplifies this convergence of industries, as its manufacture combines the efforts of different sectors such as camera technology, television, and sound systems (Khedher, 2010).

Table 2-3 summarizes various definitions of the business ecosystem concept found in the literature. Generally, the primary objective of business ecosystems is the creation and appropriation of value through a network of companies. These networks aim to commercialize products or services that require combined skills, which individual companies alone may not possess (Clarysse et al., 2014).

Since the 1980s, there has been a profound transformation in innovation processes. The growing complexity of knowledge has forced large companies to open their innovation processes to outside organizations. These processes are evolving towards broader models that include communities where innovation is catalyzed through multiple interactions. In response to these challenges, some researchers have adapted Moore's (1993) business ecosystem concept to an innovation perspective, leading to the conceptualization of innovation ecosystems. Innovation ecosystems are an evolution of business ecosystems and have gained increasing popularity in recent years. This concept is often central to innovation policies in many developed and developing countries (Smorodinskaya et al., 2017).

Table 2-3. Business ecosystem definitions

Authors	**Definitions**
Moore (1993, p. 76)	*"In a business ecosystem, companies co-evolve capabilities around a new innovation: they work cooperatively and competitively to support new products, satisfy customer needs, and eventually incorporate the next round of innovation"*
Iansiti & Levien (2004, p.1)	*"[...] the performance of these [...] firms derives from something that is much larger than the companies themselves the success of their respective business ecosystem. These loose networks - of suppliers, distributors, outsourcing firms, makers of related products or services, technology providers, and a host of other organizations - affect, and are affected by, the creation and delivery of a company's own offerings."*
Peltoniemi & Vuori (2004, p.13)	*"we consider a business ecosystem to be a dynamic structure which consists of an interconnected population of organizations. These organizations can be small firms, large corporations, universities, research centers, public sector organizations, and other parties which influence the system".*
Li (2009, p.379)	*"Business ecosystem is an emerging concept [...] and [...] is now an increasing focus of a firm's business strategy. [...] An ecosystem can also provide an emerging orientation to create novelty in business operations."*
Quaadgras (2005, p.1)	*"A set of complex products and services made by multiple firms in which no firm is dominant".*

The term "*innovation ecosystem*" is often used interchangeably with "*business ecosystem*" (Oh et al., 2016; Gomes et al., 2018). However, a key distinction between the two lies in their respective objectives. Among the most cited articles that clearly distinguish these objectives is the study by Gomes et al. (2018). Through a systematic review of the literature, the authors demonstrate that business ecosystems focus on value capture, while innovation ecosystems primarily aim at value creation. This is supported by Koenig (2012), who argues that business ecosystems have an ambiguous relationship with innovation:

> All types of ecosystems can certainly be drivers of innovation, but according to modalities specific to each type, they can just as easily foster reproduction. (Koenig, 2012; p. 221)

In other words, while innovating and creating value is one of the objectives of innovation ecosystems, it is not necessarily the primary mission of a business ecosystem. In this context, the role of research is central to innovation ecosystems. Jackson (2011) argues that the innovation ecosystem comprises two distinct economies: the research economy, based on fundamental research, and the business economy, which depends on the market. Table 2-4 highlights some of the definitions of the innovation ecosystem concept presented in the literature.

Table 2-4. Innovation ecosystem definitions

Authors	**Definitions**
Adner (2006, p. 2)	"*Innovation ecosystems- the collaborative arrangements through which firms combine their individual offerings into a coherent, customer-facing solution*"
Carayannis & Campbell (2009, p. 202-203)	"*Innovation Ecosystem, where people, culture and technology, [...] meet and interact to catalyze creativity, trigger invention and accelerate innovation across scientific and technological disciplines, public and private sectors [...] and in a top-down, policy-driven as well as bottom-up, entrepreneurship-empowered fashion.*"
Jackson (2011, p. 2)	"*The complex relationships that are formed between actors or entities whose functional goal is to enable technology development and innovation*"
Leten et al. (2013, p. 51)	"*Depending on the innovation needs of the industry, ecosystems can be made up of different sets of partners at different times where companies collaborate and pool their resources on a temporary basis to achieve joint innovation goals while sharing associated costs and risks*."
Autio & Thomas (2014, p. 3)	"*a network of interconnected organizations, organized around a focal firm or a platform, and incorporating both production and use side participants, and focusing on the development of new value through innovation"*
Granstrand & Holgersson (2020, p. 1)	"*An innovation ecosystem is the evolving set of actors, activities, and artifacts, and the institutions and relations, including complementary and substitute relations, that are important for the innovative performance of an actor or a population of actors.*"

Although closely linked to innovation and business ecosystems, knowledge ecosystems exhibit distinct dynamics and objectives. More specifically, their main objective is to create or develop knowledge to address complex technological or societal challenges that transcend the capabilities of isolated actors (Clarysse et al., 2014; Järvi et al., 2018; Abbate et al., 2022).

However, knowledge ecosystems are inherently linked to innovation and business ecosystems. First, they are considered in the literature as a component of the broader innovation ecosystem (Jucevičius et al., 2021). The innovation ecosystem encompasses both exploration and exploitation, including actors from invention to commercialization. In contrast, the knowledge ecosystem focuses solely on early knowledge creation and research, excluding commercialization and exploitation activities (Valkokari, 2015; Almpanopoulou, 2019).

Second, knowledge ecosystems, often situated in pre-competitive environments, can serve as an initial step before evolving into business ecosystems. According to Clarysse et al. (2014), when knowledge created by universities and research organizations within knowledge ecosystems is effectively transferred to businesses, it can fuel economic development and encourage the creation of innovative companies. These companies can eventually become the drivers of a business ecosystem by transforming innovations into commercial solutions. However, the authors also note that the transition from a knowledge ecosystem to a business ecosystem is not systematic or automatic. Companies involved in the knowledge ecosystem do not always actively participate in business ecosystems (Clarysse et al., 2014). Table 2-5 presents some of the definitions of knowledge ecosystems found in the literature.

To sum up, the three types of ecosystems differ in terms of objectives. Firstly, the business ecosystem focuses primarily on appropriating value and gaining competitive advantage. By collaborating with other members of the business ecosystem, companies exploit their interdependencies and gain a competitive advantage over isolated firms (Iansiti & Levien, 2004). The innovation ecosystem aims to create value by developing innovations or collectively realizing a value proposition (Adner, 2006; Jacobides et al., 2018). Knowledge ecosystems aim to create knowledge at a pre-competitive stage. Business ecosystems and knowledge ecosystems are integral parts of innovation ecosystems, which encompass a broader range of activities, including both exploration (knowledge ecosystems) and knowledge exploitation (business ecosystems). (Valkokari, 2015; Almpanopoulou, 2019). In other words, innovation ecosystems leverage the knowledge and ideas generated within knowledge ecosystems to propel them into commercial contexts facilitated by business ecosystems (Clarysse et al., 2014).

Table 2-5. Knowledge ecosystem definitions

Authors	Definitions
Clarysse et al. (2014, p. 1164)	*"where local universities and public research organizations play a central role in advancing technological innovation within the system".*
Van der Borgh et al. (2012, p. 151)	*"heterogeneous set of knowledge-intensive companies and other participants that depend on each other for their effectiveness and efficiency, and as such need to be located in close proximity"*
Järvi et al. (2018, p.1523)	*"emerging collectives in which actors such as universities, public research institutions, and for-profit companies collaborate to create knowledge in a pre-competitive setting"*
Vodă et al. (2023, p. 47)	*"A Knowledge Ecosystem (KE) refers to a system of interconnected components that work together to create, share, and use knowledge. It includes the processes, tools, and platforms that support the creation, dissemination, and application of knowledge."*
Thomson et al. (2007, p. 461)	*"the complex and many-faceted system of people, institutions, organizations, technologies and processes by which knowledge is created, interpreted, distributed, absorbed and utilized"*

2.2.2 The heterogeneity of ecosystem players

In the literature, ecosystem players are often categorized either by organization type or by role (Cobben et al., 2022). Organization type refers to the nature of the entities making up the ecosystem, such as SMEs, large corporations, academic institutions, and government agencies. Roles, however, refer to the specific functions these organizations assume within the ecosystem. In this section, we present the types of organizations and the roles most central to each of the three types of ecosystems.

Types of central organizations

The players in an ecosystem are heterogeneous. According to Moore (1993), a business ecosystem is composed of several layers of actors, each corresponding to different levels of involvement in the company. In business ecosystems, studies primarily focus on companies, suppliers, and distributors, while other participants are often less involved. Large companies play a central role, owning and providing critical resources and infrastructure. Additionally, these ecosystems include SMEs, competitors, and sometimes consumers (Moore, 1996; Peltoniemi & Vuori; 2004).

The innovation ecosystem focuses on a more diverse set of actors than business ecosystems, including universities, research centers, intermediaries, policymakers, entrepreneurs, companies, and venture capitalists, in addition to the types of actors previously mentioned (Autio & Thomas, 2014; Pierrakis & Saridakis, 2019; Cobben et al., 2022). These ecosystems rely on collaboration between these types of organization to create value and stimulate innovation (Adner, 2006; Ritala et al., 2013; Gomes et al., 2018).

Knowledge ecosystems include all actors contributing to the production and dissemination of knowledge: the scientific community, inventors and innovators, entrepreneurs, policymakers, intermediaries, funding agencies, and research organizations (Khademi; 2019). Universities and independent research organizations play a predominant role. These ecosystems are characterized by the presence of a neutral central actor, often a university or public research organization, which does not compete directly with other organizations but facilitates the process of research creation and commercialization (Clarysse et al., 2014; Robertson; 2020; Jucevičius et al., 2021). These institutions produce basic and applied research and act as catalysts for technological innovation by collaborating with local companies, which subsequently use this knowledge for commercial and industrial purposes in a business ecosystem (Clarysse et al., 2014; Attour & Lazaric, 2020).

In summary, although the types of organizations are similar across all three ecosystem types, they differ in terms of which organization type occupies a central position in each ecosystem. This heterogeneity implies that organizations can belong to multiple ecosystem types, allowing them to freely evolve across different ecosystems (Valkokari, 2015).

Central roles

Iansiti & Levien (2004) have used the analogy with biological ecosystems to assign different roles to the members of a business ecosystem. The most central and most studied role is that of the keystone. The keystone strategy focuses on three main points: (1) creating value within the ecosystem, (2) sharing the value created with other members of the community, and (3) managing internal relations and maintaining the health of the business ecosystem (Iansiti & Levien 2004; Barnett, 2006; Cui et al., 2022).

Regarding the first point, value creation within the business ecosystem often requires the creation of a platform by the keystones. This platform may take the form of services, tools, or technologies that offer solutions to other members of the ecosystem. The role of keystones is to enhance the performance of the entire ecosystem by providing a stable set of common assets to its members. This increases ecosystem productivity by fostering connections between participants and encouraging the creation of new businesses within the business ecosystem (Iansiti & Levien 2004; Clarysse et al., 2014).

Keystones then redistribute the value created throughout the ecosystem. They do not seek to control other members; rather, this approach is strategic, not altruistic:

> They are generally part of win-win-win logics in relation to other players and for the ecosystem. (Isckia, 2007; p. 5)

In a business ecosystem, the role of the keystone is important for managing internal relationships and the overall health of the ecosystem. As a central player, the keystone is responsible for creating a strategy to coordinate and align members. This strategic coordination includes managing the health of the business ecosystem through stable and permanent interactions (den Hartigh, Tol & Visscher, 2006).

Iansiti & Levien (2004) mention two other key roles in addition to keystones: dominators and niche players. Dominators are organizations that, unlike keystones, exert a more direct and often exploitative control over the ecosystem. The authors identify two types of dominators: physical dominators and value dominators. Physical dominators seek to control a large part of the ecosystem by vertically and horizontally integrating as many organizations as possible, thereby becoming the main creators and collectors of value. Value dominators, on the other hand, exert less direct control but are adept at extracting maximum value from other network members.

The third role described by Iansiti & Levien (2004) is that of the niche player. These are small, highly specialized entities that maintain close links with keystones. Unlike dominators, who may exploit these small players, keystones often provide resources to support niche players. Niche players focus on developing specialized capabilities that set them apart from other organizations. By collaborating and utilizing complementary resources provided by other niche players or keystones, they can dedicate themselves entirely to enhancing their area of expertise.

In the ecosystem literature, the keystone role, initially introduced in the context of business ecosystems, is also recognized in innovation and knowledge ecosystems, albeit under different designations. In innovation ecosystems, the term "keystone" is frequently used, but other designations include “hub” (Nambisan & Baron, 2013) or “orchestrator” (Pikkarainen et al., 2017). Recently, the role of orchestrator within innovation ecosystems has acquired increasing interest in the literature. Orchestration is described as a set of activities designed to develop, manage, and coordinate actors within an innovation ecosystem (Bittencourt et al., 2019). In an innovation ecosystem, the entity acting as an orchestrator is not necessarily a company; this role can also be assumed by an academic institution such as a university (Thomas et al., 2021). Orchestration is broken down into several sub-roles depending on how orchestrators perform orchestration activities. We will examine this role in detail in the next section of this literature review.

In the literature on knowledge ecosystems, the term equivalent to “keystone” is “anchor tenant” (Clarysse et al., 2014). Knowledge ecosystems are distinguished by the presence of an anchor tenant, often a university or research center, which plays a similar role but is typically a neutral entity that does not compete directly with other organizations. The anchor tenant’s main role is to facilitate the creation and sharing of knowledge, as well as the commercialization of research.

Additionally, this role ensures the stability of relationships among all participants (Clarysse et al., 2014; Scaringella & Radziwon, 2018; Jucevičius et al., 2021; Abbate et al., 2022).

To date, the literature on knowledge ecosystems does not specifically address the notion of roles. Discussions primarily focus on the types of organizations involved in these ecosystems, as described above. In summary, each type of ecosystem is defined by a central role that varies by context: the keystone in business ecosystems, the anchor tenant in knowledge ecosystems, and the orchestrator in innovation ecosystems. Typically, the keystone in business ecosystems is a large company, whereas in knowledge ecosystems, universities or research centers often assume the role of anchor tenants. In innovation ecosystems, the central entity can differ based on the ecosystem’s unique characteristics. This differentiation underscores the diverse nature and adaptability of ecosystems in fostering collaboration and innovation across various domains.

2.2.3 Coevolution and coopetition

Coevolution and coopetition (cooperation and competition) were initially used to describe the dynamics of biological ecosystems (Ehrlich & Raven, 1964; Moore, 1993). The concept of coevolution refers to the continuous adaptation of organisms to changes in their environment. In natural ecosystems, organisms cooperate and compete to survive. This constant interaction leads to the evolution of certain living groups, which in turn influences the evolution of others (Moore, 1993; Robertson, 2020). These notions of coopetition (Nalebuff & Brandenburger , 1996) and coevolution (Moore, 1993; Iansiti & Levien, 2004) have been transposed to business ecosystems to illustrate how companies adapt and react to the dynamics of their economic environment:

> In a business ecosystem, companies coevolve capabilities around a new innovation: they work cooperatively and competitively to support new products, satisfy customer needs, and eventually incorporate the next round of innovations. (Moore 1993; p. 76)

Coevolution represents the interactions through which organizations can have an impact on the potential success of others:

> The success of an innovating firm often depends on the efforts of other innovators in its environment. (Adner & Kapoor, 2010; p. 306)

Thus, coevolution is a key concept for understanding the complex dynamics within the three types of ecosystems and is based on several fundamental principles. First, each organization constitutes an element in the environment of another, and changes in one organization can have a direct impact on others, triggering a chain of modifications that can influence the entire ecosystem (Peltoniemi, 2006). Coevolution is also characterized by a dynamic feedback process (Peltoniemi et al., 2005). Adjustments made by one organization in response to its environment often provoke reactions from other actors, who then adapt their strategies. These reciprocal interactions create a cycle in which changes initiated by one organization lead to responses that, in turn, prompt the original organization to refine its initial changes (Peltoniemi et al., 2005; Khedher, 2010).

Finally, coevolution also occurs between different types of ecosystems. For example, according to Robertson (2020), knowledge ecosystems play a central role in the coevolution of other ecosystem types by facilitating the exchange and enhancement of knowledge across various domains and industries. This enables business and innovation ecosystems to adapt to change, fostering innovation and commercialization in response to new challenges and opportunities. The principle of coopetition applies mainly to business and innovation ecosystems. In both types of ecosystems, interconnected and interdependent organizations form a complex network where their survival depends on a delicate balance between competition and cooperation (Moore; 1993; Iansiti & Levien, 2004; Adner, 2006; Adner & Kapoor, 2010; Valkokari, 2015). For Basole et al. (2015):

> Coopetition refers to the cooperation between competing firms leading to possible win-win conditions. (Basole et al., 2015; p. 537)

According to the authors, there is a cooperative dimension where participants jointly use shared resources to achieve mutual goals. Simultaneously, a competitive dimension emerges when these same resources are employed to gain individual advantages with the aim of outperforming partners. Organizations must adopt competitive postures to adapt to a hyper-competitive world, while also cooperating to counter other competitors and exchange knowledge. One example of this dynamic: Philips and Sony have cooperated on DVD production, while remaining competitors in other market segments (Luo, 2007).

As mentioned above, coopetition is not addressed in the literature on knowledge ecosystems. The main players in this ecosystem, typically including universities and public research organizations, do not find themselves in direct competition with each other within the ecosystem.

2.2.4 Converging industries

Moore's (1993) introduction of the business ecosystem concept aimed to challenge Porter's (1990) traditional analysis of industries. Moore argued that companies should not be viewed as belonging to a single sector, but rather as integral parts of an ecosystem that transcends traditional industrial boundaries:

> I suggest that a company be viewed not as a member of a single industry but as part of a business ecosystem that crosses a variety of industries. (Moore, 1993; p. 76)

This idea, as he explains, allows a company to be seen as part of a larger network that encompasses various industries (Jacobides et al., 2018, Cobben et al., 2022). This evolution is largely due to the emergence of the Internet and information and communication technologies, which have dismantled previous silos and enabled the creation of new value propositions (Gueguen & Torrès, 2004).

The literature on innovation ecosystems illustrates how these ecosystems facilitate collaboration among various stakeholders from different backgrounds and industries. These players combine their efforts and resources, transcending traditional industrial boundaries, to co-create value. This cross-industry dynamic is essential for stimulating innovation (Pushpananthan & Elmquist, 2022).

However, the literature on knowledge ecosystems does not explicitly address industry convergence. This may be because these ecosystems are primarily focused on the exploration, creation, and transfer of knowledge, involving mainly universities, research centres, and certain specialized companies. Nevertheless, it can be argued that knowledge ecosystems indirectly influence industry convergence. They enrich business and innovation ecosystems with new knowledge, which is essential for nurturing innovation processes and fostering sectoral integration on a broader scale (Robertson, 2020).

2.2.5 Modularity and complementarity

The literature on business and innovation ecosystems highlights modularity as an important feature that enables the efficient distribution of innovation activities among different actors (Pushpananthan & Elmquist, 2022). However, although modularity and complementarities are frequently addressed in the literature on innovation and business ecosystems, they are less prevalent in studies on knowledge ecosystems.

Modularity views products, services, and processes as modules embedded in a larger technical architecture, facilitating the delegation of design and production to various organizations. These entities, although independent, collaborate to form a coherent system (Baldwin et al., 2024). Although the overall architecture is often defined by the ecosystem leader, the leader grants companies considerable autonomy to develop their modules, provided they comply with established standards and align with the overall goals (Jacobides et al., 2018; Pushpananthan & Elmquist; 2022).

While modularity emphasizes the independence and interchangeability of components, complementarity examines how these modules interact to create value. Jacobides et al. (2018) identify three main types of complementarities in ecosystems:

- **Unique complementarities**: This type of complementarity manifests itself in two ways. The first is when a component A cannot function without a specific component B, illustrating a direct dependency. The second form of unique complementarity occurs when the value of component A is maximized in the presence of component B. These complementarities can be unilateral, where only A depends on B, or bilateral, where the two components are mutually indispensable.

- **Generic complementarities**: In this case, the elements required to create a value proposition are sufficiently standard to be used in a variety of contexts. For example, the components needed to prepare a cup of tea (cup, boiling water, tea bag) are generic and can be bought and used separately as required, without any specificity exclusive to this preparation.
- **Super-modular complementarities**: This type describes a relationship where increasing the quantity or quality of component A increases the value of component B, thus reinforcing the positive interdependence between them in increasing the overall value of the ecosystem.

These different types of complementarities can also coexist. However, the ecosystem concept only includes non-generic complementarities, i.e. unique and super-modular complementarities:

> We exclude generic complementarities because they do not give the parties any vested interest to align and act as a group. While any focal actor would do well to consider all its complementarities, we do not think that generic complementarities can usefully capture what is unique about an ecosystem. (Jacobides et al., 2018; p. 2264)

Modularity is not explicitly addressed in the literature on knowledge ecosystems, which could be due to the difficulty of segmenting knowledge from multiple actors into distinct modules. Indeed, an ecosystem also includes tacit knowledge that is intrinsically linked to the context and does not lend itself easily to modularization.

2.2.6 The role of geographical proximity

The notion of a business ecosystem, as described by Moore (1993), differs from earlier approaches such as clusters, industrial districts, innovation milieus and innovation systems, in that it does not emphasize geographical proximity. Furthermore, the literature on innovation ecosystems emphasizes the importance of the local environment in the innovation process (Scaringella & Radziwon, 2018). Valkokari (2015) points out that although empirical studies on innovation ecosystems recognize the geographical concentration of key players, they have often neglected the global dimension by focusing on regional and geographically close players.

The importance of geographical proximity in innovation ecosystems extends beyond access to resources; it also encompasses the institutional and regulatory framework established by regional and national authorities, which encourages the emergence of innovation (Pilinkienė & Mačiulis, 2014).

However, the relevance of geographical proximity is much more widely recognized in the literature on knowledge ecosystems. Indeed, the geographical proximity of partners in a knowledge ecosystem plays a significant role, often materialized by their co-location in spaces such as technology parks, universities, or technopoles (Van der Borgh et al., 2012; Cobben et al., 2022). This proximity facilitates interactions between companies and local research institutions, such as universities and research centres. For example, geographical concentration in the same area facilitates the sharing of knowledge and new technologies, which tends to be more effective over shorter distances (Fiandrino et al., 2023).

However, although geographical proximity facilitates certain interactions, it is not always essential. Valkokari (2015) points out, for example, that recent research shows that co-location can also mean virtual proximity between actors, developed using information and communication technologies.

2.2.7 Ecosystem life cycle phases

The ecosystem life cycle has been widely discussed in the literature on business and innovation ecosystems, where the stages of development are similar and well-defined.

Most studies are based on the life-cycle phases described by Moore in 1993: birth, expansion, leadership, and self-renewal. In the initial stage, the birth phase involves combining various competencies to develop a value proposition that will serve as the foundation upon which the ecosystem can be built. During the expansion phase, the hub firm relies on an initial network of enriching collaborations to strengthen and extend its influence. In the leadership phase, the leader must ensure a central and indispensable presence, consolidating its dominant position within the business ecosystem. The renewal or obsolescence phase aims to preserve competitiveness by integrating new ideas, thereby avoiding the ecosystem’s decline (Moore, 1993).

Subsequent studies by Moore (1993) have renamed or slightly modified the phases he originally described. For instance, Tolstykh et al. (2020) propose alternative terms for the life-cycle phases of innovation ecosystems: “conceptual design”, “ecosystem building”, “operation and maintenance”, and “succession”. According to these authors, after the “succession” phase, the ecosystem can respond to challenges in one of two ways: through self-sustaining growth or by scaling back. The aim during the first stage is to select the most appropriate concept for a new product or service, define its functionalities, and prepare a detailed plan for subsequent phases, ensuring the feasibility and sustainability of the envisioned ecosystem. The main aim of the ecosystem construction stage is to build a prototype that meets criteria of efficiency, reliability, and safety. At the same time, this stage helps to structure the ecosystem, clearly define its boundaries, and develop specific strategies for the evolution of each player involved. After the construction phase, the ecosystem enters the operation and maintenance phase. This stage is essential for ensuring the long-term viability of the ecosystem by continually adapting its configuration to respond to internal and external changes.

According to Thomas & Autio (2013), although the emergence process is unique for each ecosystem, three common phases stand out: initiation, momentum, and optimization. The initiation phase encompasses the formulation of the original idea, and the assembly of the resources needed to get the ecosystem off the ground. This period is characterized by limited access to the ecosystem, the establishment of initial norms and rules, low promotion and media visibility, and little activity on the part of competitors. n the momentum phase, the ecosystem undergoes rapid expansion, fueled by an influx of investment, an increase in the number of participants, and frequent interactions among them. The third phase, optimization, is characterized by a shift in priorities from expansion to control and capitalization of the value created. During this phase, the ecosystem moves towards stricter regulation of participants' actions and increased appropriation of the value created. In a similar vein, Pique et al. (2019) divides the cycle into three phases: inception, growth, and maturity. The process of developing an innovation ecosystem begins with an inception phase in which the initially scattered players and resources require a defined strategy to catalyze the formation of the ecosystem. Once this strategy has been set in motion, it marks the start of the ecosystem construction phase, during which resources and players begin to mobilize actively. During this phase, there is an acceleration of collaborative processes and increased joint participation in ecosystem development. Finally, the ecosystem reaches a phase of maturity when it extends its influence internationally and consolidates its leadership position.

However, unlike these two types of ecosystems, the literature on knowledge ecosystems does not really address the issue of knowledge ecosystem development over time. Table 2-6 highlights the main characteristics, similarities, and differences between the three ecosystem types.

Table 2-6. Ecosystem types

Characteristics	Business Ecosystems	Innovation Ecosystems	Knowledge Ecosystems
Main Objectives	Value appropriation and achieving a competitive advantage.	Value creation through the development of innovations and realization of value propositions.	Creation of knowledge at a precompetitive stage.
Central Organization Types	Large firms, suppliers, distributors.	Firms, universities, research centers, companies, venture capitalists.	Universities, research organizations.
Central Roles	Keystone: creates and shares value, manages ecosystem health.	Orchestrator: coordinates and manages actors to stimulate innovation.	Anchor Tenant facilitates the creation and sharing of knowledge
Industry Convergence	Transcends traditional industry boundaries	Collaboration among diverse stakeholders from different backgrounds and industries.	Not explicitly linked to industry convergence but influences industry convergence in business and innovation ecosystems.
Modularity and Complementarity	Modularity and complementarity among modules.		Less present: difficulty in segmenting knowledge from multiple actors into distinct modules.
Geographical Proximity	Less emphasis on geographical proximity compared to previous approaches such as clusters.	Importance of the local environment in the innovation process	Preeminent role of geographical proximity.
Coevolution	Present: Companies coevolve their capabilities around innovations.		
Coopetition	Present: Companies cooperate and compete to survive and evolve.		Absent: Mainly focused on academic and research cooperation, without direct competition among actors.
Life-cycle phases	Present: birth, expansion, leadership, and self-renewal		Absent

2.2.8 Criticism of the ecosystem concept

The ecosystem concept, which extends the biological analogy to the dynamics of technological and organizational innovation, has faced criticism in the literature. In particular, the use of the prefix "eco" in the traditional framework of innovation systems has been questioned regarding its real added value. In the debate on the use of the biological analogy for innovation ecosystems, the articles by Oh et al. (2016) and Ritala & Almpanopoulou (2017) offer contrasting perspectives, with the former criticizing the analogy while the latter defending its relevance.

Oh et al. (2016) express reservations about adding the term "eco" to the well-established concept of innovation system, arguing that it might obscure rather than illuminate the understanding of the mechanisms of innovation emergence. According to these authors, the use of this ecological metaphor risks leading to erroneous interpretations. They illustrate this difference by comparing interactions in the two types of ecosystems: In a biological ecosystem, a leopard that consumes a gazelle remains a leopard, whereas in a business or innovation ecosystem, a company that acquires another may transform itself into a fundamentally new entity. Furthermore, according to Oh et al. (2016), the comparison between biological ecosystems and innovation systems lacks rigor. They point out that natural ecosystems operate without deliberate policy, whereas innovation ecosystems are intrinsically linked to strategies and policies. Also, Oh et al. (2016) point out that current literature frequently uses the term "innovation ecosystem" interchangeably with antecedent concepts such as innovation systems. For the authors, there is a lack of convincing evidence that ecosystems represent special cases of more complex systems, which raises questions about the theoretical value-added of the term "ecosystem" compared with earlier notions.

While acknowledging that the concept of an innovation ecosystem is often used loosely, Ritala & Almpanopoulou (2017) see potential in its application, particularly given the growing interest it is attracting in innovation research. They mention that the analogy offers useful insights for the design of innovation policies and strategies.

However, some authors add value to the term "ecosystem" by highlighting the distinctions between the systems approach and the ecosystem approach to innovation. According to this perspective, the systems approach to innovation is characterized by a static structure. In contrast, the ecosystem approach emphasizes open interactivity, where decisions made by one participant can influence and be influenced by the actions of other participants within the same ecosystem. Thus, the particularity of an ecosystem lies in its ability to describe a dynamic structure (Smorodinskaya et al., 2017).

Another notable distinction between innovation ecosystems and the earlier concepts discussed in this thesis lies in the unique coexistence of complementarities and interdependencies within these systems. Unlike the preceding concepts, where relationships are often hierarchically structured or limited to complementarities without strong interdependencies, innovation ecosystems integrate these two dimensions simultaneously (Jacobides et al., 2018, Cobben et al., 2022).

In summary, there are several types of ecosystems. For the purposes of this thesis, three types have been selected: the business ecosystem, the innovation ecosystem, and the knowledge ecosystem. Although these ecosystems share similarities, they also differ in certain respects. Despite the growing popularity of ecosystems in the literature, the concept is still used in various ways by researchers, which can sometimes dilute its clarity and weaken its definition.

2.3 Orchestrating innovation ecosystems

How do you manage and coordinate an innovation ecosystem? The term used in the literature to describe these processes is “orchestration”. This section defines what orchestration means in the context of innovation ecosystems and describes the role of platforms in this process. The discussion continues with a description of orchestration processes and the different approaches that orchestrators can adopt to implement these processes. Finally, this section looks at the various roles that orchestrators can play in orchestrating ecosystems.

2.3.1 What is orchestration?

Innovation ecosystems can emerge and develop organically; however, this process can also be shaped by deliberate intervention (Dos Santos et al., 2021). In the literature, this proactive intervention is frequently referred to as “orchestration” (Dhanaraj & Parkhe, 2006; Leten et al., 2013; Pikkarainen et al., 2017; Valkokari et al., 2017; Linde et al., 2021; Reypens et al., 2021; Lingens et al., 2022). The term “orchestration” is frequently used to refer to the management and coordination of ecosystems (Dos Santos et al., 2021). Some authors also use the term “ecosystem governance”, often interchangeably with “ecosystem orchestration” (Yaghmaie & Vanhaverbeke, 2020). The concept of orchestration, with its roots in the literature on network governance, has gradually been adapted to the context of ecosystems (Dhanaraj & Parkhe, 2006; Garin et al., 2022).

Indeed, while network governance is more broadly concerned with the coordination and management of inter-organizational relationships, orchestration is specifically associated with the structuring of ecosystems (Dos Santos et al., 2021). The term “choreography” is also used in some studies (Ferraro & Iovanella, 2015).

In the literature, the work of Dhanaraj & Parkhe (2006) is frequently cited as a key reference on orchestration (Still et al., 2014; Ritala et al., 2009; Azzam et al., 2017; Hurmelinna-Laukkanen & Nätti, 2018). Although their original research focused on network orchestration, several researchers have since extended this conceptual framework to ecosystems (Garin et al., 2022). For Dhanaraj & Parkhe (2006), the concept of orchestration is intended to replace traditional command-and-control management methods with collaborative and participatory processes (Mignoni et al., 2021). Thus, orchestration does not rely on a hierarchical authority system; instead, each member pursues its own interests and is not compelled to participate in the central firm’s initiatives (Giudici et al., 2018). In this context, Dhanaraj & Parkhe (2006) define network orchestration as:

> The set of deliberate, purposeful actions undertaken by the hub firm as it seeks to create value (expand the pie) and extract value (gain a larger slice of the pie). (Dhanaraj & Parkhe, 2006; p. 659)

As mentioned earlier, innovation ecosystems consist of a diversity of players. This heterogeneity makes interactions aimed at creating and capturing value particularly complex (Yaghmaie & Vanhaverbeke, 2020). In this context, the role of a central actor, or orchestrator, becomes essential to navigate the challenges inherent in the ecosystem. The orchestrator deploys strategic governance mechanisms to align partners, prevent opportunistic behavior, and realize the collective value proposition (Cobben et al., 2022).

In the context of innovation ecosystems, it is commonly accepted that orchestration generally falls to a hub firm (Iansiti & Levien, 2004; Dhanaraj & Parkhe, 2006; Nambisan & Sawhney, 2011; Azzam et al., 2017; Hurmelinna-Laukkanen & Nätti, 2018). However, orchestration can also be exercised by various actors such as a group of companies, a consortium, a research group, or a non-profit organization (Papadonikolaki et al., 2022).

2.3.2 Platforms as a method of orchestration

Having defined orchestration and identified the various actors likely to assume its responsibility, it is pertinent to consider the modalities of this orchestration. Regarding orchestration methods, the literature primarily focuses on the role of platforms (Gawer & Cusumano, 2002; Azzam et al., 2017; Gomes et al., 2018; Gu et al., 2021). A platform represents the services, tools or technologies that offer solutions to all members of an ecosystem, as shown in the definition by Eisenmann, (2006):

> A platform embodies an architecture-a design for products, services, and infrastructure facilitating network users' interactions- plus a set of rules; that is, the protocols, rights, and pricing terms that govern transactions. (Eisenmann, 2006; p. 5)

Platforms play a central role in innovation ecosystems by facilitating value creation and enhancing coordination among players (Azzam et al., 2017). They foster collaboration and provide a space for expression, exchange, and the accumulation of perceptions concerning ecosystem issues. The creation of platforms helps attract new members to the ecosystem. In this context, platforms become more attractive when they offer a wide range of complementary services or products (Baldwin et al., 2024). This encourages the formation and expansion of the ecosystem.

Companies capable of managing their ecosystem's innovation process via platforms are referred to as "leading platforms" (Gawer & Cusumano, 2008). For example, a leading platform such as Apple produces the iPhone through a platform that also includes users and complementors. Add-ons include software and hardware that enrich the iPhone ecosystem (Baldwin et al., 2024).

The literature also mentions ecosystems that operate without a platform. Unlike ecosystems with a platform, where the rules of governance and access are defined by the platform owners, ecosystems without a platform rely on collaborative arrangements among their members to establish these rules (Jacobides et al., 2024). Members share certain assets to achieve their common goals. Orchestration can also occur through market prices, bilateral contracts, multilateral negotiations, or system integration (Baldwin et al., 2024).

2.3.3 Orchestration process

The orchestration of an ecosystem, as mentioned above, involves managing and coordinating the participating members and their interactions. This orchestration encompasses various processes and activities carried out by one or more orchestrators. The processes described by Dhanaraj & Parkhe (2006) are among the most widely cited in the literature. Subsequently, other studies have built on this work to break these activities into several sub-activities or to propose different ways of presenting them (Batterink et al., 2010; Nambisan & Sawhney, 2011; Klerkx & Aarts, 2013; Reypens et al., 2021). Nevertheless, all orchestration activities can be grouped within the theoretical framework proposed by Dhanaraj & Parkhe (2006) for understanding the orchestration of innovation networks. The authors identify three key processes that the hub firm, or a set of firms, must perform: knowledge mobility, innovation appropriability and network stability. This section reviews these three processes and presents other similar processes identified in subsequent studies. Although named differently, these processes are similar to those described by Dhanaraj & Parkhe (2006).

Knowledge mobility

First, knowledge mobility is defined as:

> The ease with which knowledge is shared, acquired, and deployed within the network. (Dhanaraj & Parkhe, 2006; p.660)

Dhanaraj & Parkhe (2006) point out that, to improve knowledge mobility within an ecosystem, the pivotal firm needs to focus on three main processes: knowledge absorption, network identification, and inter-organizational socialization.

The process of knowledge absorption involves the hub firm identifying, assimilating, and exploiting the knowledge available in the ecosystem environment. This includes the transfer of relevant knowledge between network members, preventing this specialized knowledge from remaining confined within individual organizations. Second, network identification aims to create a common identity among members to encourage active participation and open knowledge sharing. This process relies on the establishment of a climate of trust and good faith between network players. Finally, inter-organizational socialization strengthens formal and informal links between network members. This is achieved through exchange forums and various communication channels, both formal and informal, facilitating interaction and cohesion within the ecosystem.

Similarly, Nambisan & Sawhney (2011) use the term “managing innovation leverage” instead of knowledge mobility. Although the terms differ, their first process aligns with that described by

Dhanaraj & Parkhe (2006). Managing innovation leverage implies that network members can reuse or redeploy innovation assets, such as technologies and processes, belonging to other members, to foster their own innovation. The same applies to the "demand articulation" activity proposed by Klerkx & Aarts (2013). This activity involves continually elaborating and refining objectives in terms of the technologies needed, and the knowledge and other resources required. Similar to the process of "knowledge mobility", the concepts of "managing innovation leverage" and "demand articulation" emphasize the optimization and exploitation of knowledge within the ecosystem.

The appropriability of innovation

The second orchestration process proposed by Dhanaraj & Parkhe (2006) is "innovation appropriability". Orchestration requires the hub firm to ensure the equitable distribution of the value generated across the network. Effective management of appropriability ensures that profits from innovations are fairly captured by network members. This is achieved by implementing structures to prevent opportunistic behavior and reinforcing the perception of a fair distribution of value. From a similar perspective, Nambisan & Sawhney (2011) also address this theme, which they refer to as "managing innovation appropriability". According to Nambisan & Sawhney (2011), the diversity of participants and their contributions requires the hub firm to ensure a fair distribution of the value created. Klerkx & Aarts (2013) also emphasizes the importance for the orchestrator of ensuring equitable value sharing, which is one of the elements included in the activity they term "innovation process management".

Network stability

The third and final orchestration activity mentioned by Dhanaraj & Parkhe (2006) is network stability. Network stability is enhanced by improving the reputation of the hub firm, extending the future perspective, and developing multiplex relationships.

First, a good reputation for the hub firm acts as a guarantor of reliability and attracts new companies seeking to gain legitimacy. This aspect is also highlighted in one of the orchestration activities proposed by Klerkx & Aarts (2013), named "innovation network composition". This activity focuses on the identification and strategic integration of new partners, an approach that aims to enrich the network with essential resources and complementary skills. The reputation of the hub firm also helps to secure collaboration within the network.

Second, the hub firm can encourage reciprocity strategies to promote cooperation. In this way, cooperation and reciprocity within the network enable members to perceive expected future gains from their participation, thus influencing their current behavior and contributing to network stability. Finally, the hub firm reinforces stability by developing the multiplicity of interactions, or multiplexity, within the network. By multiplying interactions, whether through joint projects or by encouraging other members to do the same, the hub firm broadens and deepens existing ties, leading to enhanced network stability (Dhanaraj & Parkhe, 2006).

Network stability is addressed by Nambisan & Sawhney (2011) under the concept of “managing innovation coherence”. The hub firm must therefore consider and promote changes within the network, considering both the internal and external environment. First, internal coherence refers to the harmonization of processes and results between network members. Second, external coherence concerns the alignment of network objectives and results with the external environment. The hub company must therefore consider and promote changes within the network, considering both the internal and external environments.

2.3.4 Orchestration types

Orchestration type refers to the approach by which orchestrators implement orchestration processes and activities. As mentioned earlier, although the literature on orchestration has grown considerably in recent years, it primarily focuses on the need for one or more orchestrators and details specific orchestration activities to be carried out. However, although some studies mention the existence of different types of orchestrators or orchestration approaches, this topic remains largely unexplored. In this section, the types of orchestration discussed in the literature are divided into three categories: directive orchestration, collaborative orchestration, and hybrid orchestration.

Directive orchestration

Directive orchestration is characterized by centralized, directive management within the network, led by central firms. These entities strictly control innovation efforts by exploiting members’ dispersed resources and capabilities, with the aim of maximizing the benefits derived from collective innovation. Admission to the network is selective and based solely on members’ potential contribution. Participation is through formal contracts. Directive orchestration is designed to ensure that the distribution of profits is strongly tilted in favor of the central firms. In this context, orchestrators define objectives and strategic vision and coordinate the flow of information, and resources required for successful projects. They also create incentives to encourage collaboration and establish rules to follow, along with sanctions for members who fail to meet expectations (Giudici et al., 2018; Reypens et al., 2021).

This type of orchestration is similar to that practiced by what Hurmelinna-Laukkanen & Nätti (2018) refer to as player orchestrators. Player orchestrators are actors whose coordination position is based on their resources. They aim to achieve individually meaningful goals using the network. Their goals may include market survival, improving competitiveness, or exploiting emerging opportunities. Although their actions may indirectly benefit other network members, their priority remains the optimization of their own financial advantage.

Collaborative orchestration

Collaborative orchestration is characterized by a decentralized approach that values non-hierarchical interactions among network members. This method favors inclusion based on specific criteria for member admission and encourages voluntary participation in activities. In this context, orchestrators play a central role in forging a shared vision and facilitating access to and sharing of resources without exercising rigid control, thereby enabling the establishment of a flexible network structure. To achieve this, orchestrators organize workshops that develop a common understanding and a shared language (Giudici et al., 2018; Reypens et al., 2021).

Facilitator orchestrators, as described by Hurmelinna-Laukkanen & Nätti (2018), adopt collaborative orchestration. This type of orchestrator is characterized by its intermediary role, lowering barriers to collaboration and innovation. Their position in the network is based on high visibility and connectivity. Distinguished by their neutrality and integrity, facilitator orchestrators focus on collective objectives rather than personal financial gain. They seek to ensure the widespread dissemination of innovative ideas and promote cooperation between network members.

Hybrid orchestration

Hybrid orchestration represents an intermediate form that combines the characteristics of directive and collaborative orchestration. This orchestration modality reflects a flexible approach, adapted to the changing dynamics of innovation ecosystems. According to Reypens et al. (2021), hybrid orchestration manifests itself in two main ways.

First, an orchestrator may alternate between a directive and a collaborative approach during the innovation trajectory. For example, in a hybrid orchestration, orchestrators begin by using a directive approach, assigning specific tasks to participants, and organizing the first face-to-face meetings. This initial phase creates essential connections and engages participants in the project. Later, orchestrators switch to a collaborative approach, working with participants to discuss and allocate tasks in a participatory manner.

Second, the orchestrator may choose to apply the principles of both types of orchestration simultaneously throughout the innovation trajectory. An example of this is when orchestrators employ collaborative orchestration to encourage collaboration between partners, while simultaneously applying directive orchestration to actively connect stakeholders around new collaborative opportunities (Reypens et al., 2021).

The hybrid type of orchestration is similar to sponsor orchestration discussed by Hurmelinna-Laukkanen & Nätti (2018). These orchestrators simultaneously aim to extract value from other network members while promoting mutual benefits. Sponsor orchestrators are commercially oriented actors who seek to improve their financial position by enhancing the competitiveness of network participants. They offer resources and connections to members, with the expectation that their efforts and investments will be rewarded in the future. Their position is based on a combination of relational and financial resources, and they seek to promote mutual benefits and cooperation within the network.

2.3.5 Orchestration roles

We have previously established that orchestration consists of one or more organizations coordinating and managing the ecosystem through orchestration processes. These processes comprise various activities and the way actors perform these activities defines their roles.

Ensuring effective knowledge transfer, coordinating actions, and mobilizing stakeholders are examples of activities performed by orchestrators (Hurmelinna-Laukkanen & Nätti, 2018). When carried out in particular ways, these activities define the specific roles of orchestrators (Pikkarainen et al., 2017; Hurmelinna-Laukkanen & Nätti, 2018). The different emphases on specific activities and the type of orchestration employed by orchestrators result in distinct orchestration roles. Indeed, orchestrators may emphasize different activities depending on the situation. For example, knowledge mobility may sometimes be favored over innovation appropriability or network stability. Indeed, orchestrators may emphasize different activities depending on the situation. For example, knowledge mobility may sometimes be prioritized over innovation appropriability or network stability. Additionally, orchestrators may adopt different orchestration types to perform these activities. For instance, network stability can be maintained through binding contractual arrangements (directive orchestration) or by frequently bringing core actors together for joint meetings to facilitate the construction of a shared identity (collaborative orchestration). (Pikkarainen et al., 2017; Hurmelinna-Laukkanen & Nätti, 2018). Thus, the role of the orchestrator is determined by the emphasis they place on certain activities and the type of orchestration employed to perform these activities. The existing literature provides specific examples, as shown in Table 2-7.

Table 2-7. Orchestration roles

Role	Key activities
Architect	Sets agendas and coordinates activities. Selects network participants
Gatekeeper	Facilitates knowledge extraction and dissemination.
Conductor	Manages information acquisition, transmission, and sharing.
Developer	Creates tangible and intangible assets for the network based on knowledge mobility.
Auctioneer	Sets the agenda and joint vision for the innovation network.
Leader	Motivates and fosters voluntary collaboration. Identifies roles of network members. Manages and instructs members engaged in the network for a common purpose. Specifies contributions and benefits of participation.
Promoter	Supports ecosystem members to work towards a common goal. Engages actors in an innovation development process.
Facilitator	Brings together diverse, even competing, parties to work together
Judge	Defines and initiates the network
Representative	Shares knowledge about the network with outsiders. Filters information.
Link	Acts as an external intermediary between network members.
Coordinator	Manages interactions between network members to strengthen ties.

Source(s): Pikkarainen et al (2017); Hurmelinna-Laukkanen and Nätti (2018); Mignoni et al. (2021)

Although some of these roles (e.g., architect, leader, facilitator) may appear to overlap, each highlights a distinct aspect or emphasis. For instance, an architect might prioritize setting the agenda and selecting participants, whereas a leader focuses on motivating and uniting actors around common goals. In this way, seemingly similar roles in the literature reflect subtle but important differences in how orchestrators approach coordination, knowledge sharing, or stakeholder engagement. Such distinctions underscore the diversity of conceptualizations authors bring to the study of orchestration and enrich our overall understanding of how ecosystems can be orchestrated.

To sum up, the orchestration of innovation ecosystems is an increasingly prevalent theme in innovation management literature. It involves the management and coordination of actors and their interactions within an ecosystem. Orchestration is implemented by one or more orchestrators applying specific processes. In this context, the theoretical framework established by Dhanaraj & Parkhe (2006) remains a major reference for research into the orchestration of innovation ecosystems. Moreover, orchestration can take directive, collaborative, or hybrid forms, depending on the motivations of the orchestrators. Finally, the way orchestrators carry out orchestration activities defines their specific role within the ecosystem.

2.4 5G: Definition, challenges, benefits, and geopolitical tensions

Over the past few decades, the evolution of wireless technologies has led to the emergence of five successive generations. From the introduction of the first generation (1G) to the present day, this technological progression has fostered the transformation toward a networked society in which people and objects are interconnected (Eluwole et al., 2018). Today, information and communication technologies are important in socio-economic progress (Yu et al., 2017).

This section presents 5G technology, its key features and enabling technologies. It also discusses the potential impact on various economic sectors, the situation in Canada, and the geopolitical tensions associated with this technology.

2.4.1 The five generations of mobile telecommunication

Launched in the 1980s, the first generation of wireless technologies (1G) laid the foundations for mobile telephony (Eluwole et al., 2018). It introduced the possibility of making voice calls (del Peral-Rosado et al., 2017). Based on an analog transmission system, 1G presented several constraints: susceptibility to interference and reduced quality, lack of security due to the absence of advanced encryption methods, limited capacity for the number of users, the imposing size of phones, and poor voice quality during calls (Andrews et al., 2014; Kachhavay & Thakare, 2014; Eluwole et al., 2018).

The transition to 2G in the 1990s overcame some of these limitations. 2G introduced text messaging services and enabled the transition from an analog system to the digitization of communications (Shukla et al., 2013). This advance played a key role in the democratization of cell phone use (Eluwole et al., 2018). Then, in 2000, 3G distinguished itself from previous generations by significantly improving data transmission speed and providing access to multimedia services (Pereira & Sousa, 2004; Shukla et al., 2013).

These benefits were significantly enhanced with the advent of 4G in the 2010s. 4G enabled high-speed Internet access and supported more advanced applications such as high-definition television (Mehta et al., 2014). It also facilitated certain Internet of Things applications by improving the user experience (Yu et al., 2017). The advent of 4G, coupled with the widespread adoption of smartphones, has led to a significant increase in data exchange volumes and the number of connected devices. This increase poses a major connectivity challenge for 4G technology (Andrews et al., 2014). The situation is further complicated by the growing popularity of social networking, virtual reality, and augmented reality. Consequently, the primary objective of the fifth generation of mobile telephony is to address this challenge effectively. From its inception, 5G has considered the issue of increasing data volumes and the diversity of connected devices, as will be elaborated in the following section on 5G features.

2.4.2 5G features

The 3rd Generation Partnership Project (3GPP) groups 5G features into three broad categories:

- **Enhanced Mobile Broadband (eMBB)**: This feature highlights the significant increase in throughput provided, essentially aimed at increasing data throughput. In an ideal scenario, the introduction of 5G could deliver download speeds up to 20 times faster than 4G. The minimum speed of 5G, meanwhile, would be 10 times faster than 4G (Pirinen, 2014). As a result, 5G enables users to enjoy ultra-high-definition video or download virtual or augmented reality content with unprecedented efficiency (Yu et al., 2017). For example, with 5G, the download time for a file that would take 7 minutes in 4G would be reduced to just 6 seconds (Tekir, 2020).

- **Ultra-reliable and Low Latency Communications (URLLC)**: This category represents a key feature of 5G, designed specifically for applications requiring high availability and reliability with very low or no latency (Eluwole et al., 2018). The transition to 5G will significantly reduce latency, potentially reaching less than 1 millisecond, compared to 50 milliseconds for 4G (Andrews et al., 2014). Such a reduction in latency is crucial for several 5G usage scenarios. For example, reduced latency is essential for the development and deployment of autonomous cars (Tekir, 2020). Additionally, 5G enables highly reliable communications with data transmissions occurring in 1 millisecond or less, with a probability of success close to 100% (Popovski et al., 2014; Eluwole et al., 2018).
- **Massive machine communications (mMTC)**: This feature facilitates the connection of a high density of objects distributed across a territory, enabling coverage for several thousand devices per square kilometer (Rühlig & Björk, 2020). This coverage is achieved using low-cost software and equipment that consume minimal energy and benefit from extended battery life (Eluwole et al., 2018). This aspect of 5G is particularly conducive to the development of the Internet of Things (IoT) (Rühlig & Björk, 2020).

2.4.3 Enabling technologies and techniques for 5G

5G embodies the integration of multiple technologies and techniques to achieve its full potential. This section presents some of the technologies most frequently discussed in the literature.

Network Function Virtualization (NFV) and Software Defined Network (SDN)

NFV and SDN are two key technologies that play distinct but complementary roles in 5G network architecture (Yousaf et al., 2017). Both technologies are essential for the virtualization and automation of 5G networks (Zaidi et al., 2018). First, NFV aims to virtualize network functions that are traditionally performed by physical equipment, such as routers and firewalls (Bouras et al., 2017). This approach reduces hardware investment costs and ensures greater flexibility of the 5G network (Abdelwahab et al., 2016).

Second, SDN introduces a separation between the control plane and the data plane (Hakiri & Berthou, 2015; Eluwole et al., 2018). This separation enables the establishment of a centralized, programmable network via a virtual controller, thus relieving physical equipment of control tasks (Zaidi et al., 2018).

Millimeter waves and network ultra-densification

5G is characterized by its diversified use of the spectrum, encompassing low frequencies (less than 1 GHz), medium frequencies (1 GHz to 6 GHz), and very high frequencies, or millimeter waves (more than 6 GHz, extending up to 100 GHz) (Alexandru et al., 2020). Millimeter waves enable a significant increase in bandwidth (Niu et al., 2015).

However, the adoption of millimeter waves for mobile communication is not without its challenges. These frequencies, due to their inverse correlation with wavelength, tend to weaken over long distances and are sensitive to various environmental factors (Boccardi et al., 2014). For example, disturbances can arise from atmospheric absorption and rain (Banday et al., 2019). To overcome these obstacles and ensure effective coverage, it is essential to establish a dense network of small cells arranged in close proximity to each other (Feng et al., 2017). This process, known as network ultra-densification, relies on deploying a vast network of small, low-cost smart antennas in areas with high data transmission activity. These micro-antennas support the connectivity of numerous devices by mitigating the transmission difficulties inherent in millimeter frequencies, primarily by reducing the transmission distance (Ge et al., 2016).

Massive Multiple-Input Multiple-Output (Massive MIMO) and Beamforming

Massive MIMO, which represents an evolution of traditional MIMO, is a fundamental technology for 5G deployment. This technology relies on the installation of numerous small antennas on the base station to handle more connected devices (Adnan et al., 2016; Lopez-Perez et al., 2021). Beamforming, a technique that exploits the potential of massive MIMO, uses these small antennas to focus the signal precisely on a specific area (Ali et al., 2017). In other words, beamforming optimizes the use of the radio signal by directing it to users only when needed, rather than broadcasting it indiscriminately in all directions. This approach improves both network coverage and energy efficiency (Razavizadeh et al., 2014).

Network slicing

5G technology is being developed to meet a wide range of service requirements, which vary considerably in terms of latency, throughput, and capacity. The aim of 5G networks is to ensure that the intensive use of data by users does not adversely affect the overall quality of service. To meet this challenge, 5G networks rely on a key technique known as Network Slicing. This involves dividing a single physical network into several distinct virtual segments, with each segment specifically tailored and optimized to meet the requirements of a particular application or service (Zhang, 2019; Rühlig & Björk, 2020). Each network segment operates as an independent network with its own virtual resources and regulations (Rost et al., 2017).

2.4.4 5G applications in key economic sectors

Many experts agree that 5G will have a significant impact on various important economic sectors. Among the sectors most frequently discussed in the literature, five main ones are identified: smart industries, smart mobility, smart healthcare, smart home, and smart grid. We will explore these five sectors, providing a brief description of each.

Smart industries

5G technology is having a significant impact on the industrial sector. According to Rao & Prasad (2018), 5G enables the full automation and virtualization of industrial processes. Sensors and robots, connected in real time, enhance productivity for companies through low latency, improved production control, and more effective collaboration between humans and robots (Mourtzis et al., 2021). Rao & Prasad (2018) also mention that 5G improves connectivity between a company's different sites, regardless of their geographical location. A company with several globally distributed sites can benefit from enhanced connectivity between these locations, enabling centralized control of operations and optimized production management.

Smart mobility

Smart mobility represents a major advance aimed at improving travel productivity, efficiency, and safety through the integration of 5G networks. According to Yu et al. (2017), 5G will enable vehicles to make real-time decisions to avoid accidents caused by human error. With 5G, it is possible to know the position and speed of vehicles in real time with minimal latency, thereby maintaining suitable safety distances between vehicles that communicate with each other (Yu et al., 2017). Additionally, smart mobility leverages the Internet of Things (IoT) to enhance safety and optimize traffic management by utilizing large volumes of real-time data on current traffic conditions (Hakak et al., 2023; Zoghlami et al., 2023).

Smart health

5G is opening new horizons in healthcare, offering revolutionary benefits such as remote diagnosis and real-time surgery (Ahad et al., 2020; Rühlig & Björk, 2020). This breakthrough is made possible by key features of 5G, including its low latency and superior reliability compared to previous generations of mobile networks. Beyond surgical interventions, 5G can play a crucial role in the management of infectious diseases. Its ability to provide fast and continuous services enables better prevention, more effective epidemic control, and reduced hospital overload (Devi et al., 2023). Additionally, 5G-enabled wearable devices can alert healthcare professionals in real time to issues such as abnormal blood pressure or missed medications (Uddin et al., 2019; Devi et al., 2023).

Smart home

5G enriches the smart home experience by increasing performance, reliability, and security. Automating the home to make it smart requires the integration of multiple devices, enabled by 5G, such as air conditioning systems, thermostats, security cameras, televisions, lighting, and other home appliances (Uddin et al., 2019). With 5G, these devices will become more energy-efficient and enhance occupant comfort and safety (Skouby & Lynggaard, 2014).

Smart grid

According to Ho et al. (2019), the integration of 5G technology into electricity distribution networks, or smart grids, allows for much more efficient, sustainable, reliable, and secure management of the generation, transmission, and distribution of electricity. The authors also mention that 5G significantly improves the remote control of smart grid infrastructures. This new generation of connectivity enhances the prediction of energy consumption and enables a more appropriate response in the event of disruptions. By leveraging data collected in real time by sensors and smart meters, operators can accurately anticipate variations in demand and adjust supply accordingly (Ho et al., 2019).

2.4.5 5G in Canada

Economic, environmental, and social impact

The adoption of 5G technology in Canada is expected to bring significant economic, environmental, and social benefits.

Economically, the rollout of 5G is associated with optimistic forecasts, with incremental growth estimated at $40 billion by 2026 (Accenture, 2018), and an annual contribution to the Canadian economy of up to $94 billion by 2035 (PwC, 2021). The impact of 5G on the labor market is also notable, with the expected creation of 250,000 permanent jobs by 2026 (Accenture, 2019). Additionally, telecom companies are projected to invest $26 billion in 5G network deployment and infrastructure, an effort anticipated to generate 154,000 temporary direct and indirect jobs from 2020 to 2026 (Accenture, 2018). Business productivity is another area that will benefit considerably from the introduction of 5G. In the intelligent transportation sector, for example, the adoption of 5G could result in a significant increase in annual productivity, estimated at $535 million for Montreal and $270 million for Vancouver (Accenture, 2019). The implementation of 5G in Canada offers promising prospects for the environment by optimizing industrial operations to minimize ecological impact, reducing greenhouse gas emissions, and improving water consumption management (PwC, 2021). These advances align with Canada's international environmental commitments, such as the Paris Agreement and the United Nations Sustainable Development Goals (PwC, 2021). For example, in the smart grids sector, the integration of 5G is expected to reduce household energy consumption by up to 12% (Accenture, 2019). For a city like Calgary, this could represent annual savings of $87 million in household energy consumption (Accenture, 2019). On a societal level, the impact of 5G in Canada will significantly improve the quality of life of Canadians through a major evolution of several services such as education, transportation, and healthcare (PwC, 2021). In addition, the expansion of 5G has the potential to radically transform Internet access in rural Canada, regions that have historically suffered from limited connectivity (Accenture, 2019). By improving Internet access in these areas, 5G promises to significantly reduce the disparity between urban and rural areas.

Delay in the rollout of 5G in Canada

According to PwC (2021), compared to other nations such as South Korea and G7 members, Canada is notably behind in the deployment of 5G technology. This is mainly due to the country's slowness in allocating spectrum and organizing auctions for the medium and high frequency bands. Among the G7 countries, Canada is among the last to have launched auctions for these bands. To fully exploit the benefits and potential of 5G, it is crucial to deploy these three frequency bands. Another factor contributing to Canada's delay concerns telecom operators' uncertainties about return on investment. Indeed, the cost of deploying 5G is estimated to be 71% higher than that of 4G.

5G initiatives in Canada

Several projects and initiatives aim to bring the ecosystem together around 5G technology. One of the most important projects, bringing together key players in the ecosystem, is the ENCQOR[2] project (Evolution of Cloud Services in the Quebec-Ontario Corridor for Research and Innovation). This project is a public-private collaboration involving both the Canadian federal government and the provincial governments of Quebec and Ontario, as well as five major multinationals: Ericsson, Ciena, Thales, CGI and IBM Bromont. The ENCQOR project represents a total investment of $400 million. Half of this amount is being provided by the governments of Quebec, Ottawa and Ontario, with each contributing an equivalent $66.7 million. The rest of the funding comes from the five multinationals involved. The initiative is designed to stimulate research and innovation in 5G technology.

In addition to the ENCQOR project, the City of Montreal's 5G initiative, notably through the 5G Urban Laboratory[3], represents a concerted effort to bring together operators and innovation players within the metropolis. This experimental space, located in the heart of Montreal, aims to assess the challenges associated with the deployment of 5G infrastructure and to test and develop the applications enabled by this technology.

Interest in 5G within the Canadian ecosystem is also reflected in LabVI[4], a unique open-air laboratory created in collaboration between Videotron and Montreal's Innovation District. This initiative offers small and medium-sized enterprises (SMEs) a valuable opportunity to develop and test their solutions in synergy with Videotron.

Another 5G initiative is the result of a collaboration between CENTECH, Bell, and Verizon. Entitled "5G Development Hub"[5] this project aims to create a link between Canadian SMEs and Verizon, a major US telecommunications player. Although Verizon does not operate directly in Canada, this initiative demonstrates the company's keen interest in Canadian startups. The goal is to explore business cases and 5G applications that could be of interest to their customers in the USA.

[2] https://www.encqor.ca
[3] https://montreal.ca/articles/projet-pilote-urbain-5g-9155
[4] https://labvi.ca
[5] https://centech.co/en/5g-development-hub/

2.4.6 Geopolitical implications of 5G

The crucial importance of the security of 5G infrastructures and equipment, as well as their considerable economic and social impacts, are fueling competition between nations and provoking the emergence of geopolitical tensions (Tekir, 2020). This growing dependence on networks for critical services, ranging from smart mobility to the healthcare sector, such as remote surgery, to emergency services, increases the risk of attacks or malfunctions that could compromise the security of nations and societies (Eluwole et al., 2018). Against this backdrop, Huawei's leading role in 5G has placed China at the center of international geopolitical concerns (Rühlig & Björk, 2020).

The rise of China and Huawei, and mistrust of the United States

Huawei, a Chinese company specializing in telecommunications, was founded in 1987 by Ren Zhengfei in Shenzhen (Tang, 2020). "Huawei", meaning "China with achievements" in Mandarin, offers a diversified range of activities, positioning itself in several markets. It acts as a supplier of telecom equipment, handling the supply and maintenance of such equipment. Additionally, Huawei produces a variety of devices, including computers, tablets, and smartphones (Tang, 2020).

The rise of Huawei and China in the development of 5G technology is perceived by the US government as a national and international security issue (Tang, 2020; Friis & Lysne, 2021). Several arguments are put forward by the American authorities to support their position.

First, the United States accuses the company of acting as an extension of the Chinese government, partly because of the background of Huawei's founder. The latter, a former member of the Communist Party, held an engineering post in the People's Liberation Army (PLA) (Jaisal, 2020). US critics also draw on recent Chinese legislation, such as the 2017 National Intelligence Law and the 2014 Counterintelligence Law, which oblige Chinese companies to cooperate with the Chinese government, including its secret services, by providing information on request (Chikermane, 2019; Kaska et al., 2019; Rühlig & Björk, 2020; Friis & Lysne, 2021). Huawei has refuted these accusations (Zhang, 2021).

Second, the USA justifies its accusations of espionage against China and Huawei by China's stated desire to export its 5G technology. In their view, the establishment of Huawei and its infrastructures in various countries represents a significant risk to global cybersecurity (Tekir, 2020). This assertion is often supported by references to two major strategic initiatives, seen as illustrations of China's ambition to spread its 5G technology internationally.

The first, the "Belt and Road" initiative launched in 2013, aims to strengthen China's connections with many countries in Asia, Europe and parts of Africa that were previously neglected by the West (Tekir, 2020; Kliman, 2022). This ambitious project seeks to export Chinese technologies by building infrastructure such as railroads, roads, and ports to link these countries to China (Kaska et al., 2019). A notable aspect of the "Belt and Road" initiative is its focus on digital connectivity, including the construction of digital infrastructure such as fiber-optic networks, essential for the deployment of 5G networks (Tekir, 2020).

The second initiative, the "Made in China 2025" strategy launched in 2015, demonstrates China's commitment to the production and export of cutting-edge technologies (Tekir, 2020). As part of this strategy, 5G is presented as the telecoms network of the future, underlining the importance China places on developing and mastering the key technologies of the future. Using these two strategies, Huawei has succeeded in expanding its presence in 170 countries (Tang, 2020).

Another dimension that puts China at the heart of geopolitical conflicts lies in the fact that Huawei, beyond its extensive presence, clearly dominates the competition in the 5G field. For example, Huawei's investment in 5G R&D exceeds that of Nokia and Ericsson. Additionally, Huawei holds 30% of the 5G market, ahead of Ericsson with 26% and Nokia with 22%. Also, Huawei holds 35% of 5G patents, which is a larger share than all patents held by the USA (Tekir, 2020).

In 2019, Sino-American tensions reached a peak. Huawei and ZTE were banned from the US market, prohibiting them from contributing to the construction of 5G infrastructure (Rühlig & Björk, 2020). In addition, the Department of Commerce prevented American companies from trading with Huawei (The Globe & Mail, 2018; U.S. Department of Commerce, 2020). This measure has led multinationals such as Google and Qualcomm to cut their ties with Huawei (Tekir, 2020).

The expansion of the conflict into Canada and across the world

Tensions between China and the United States are reverberating beyond their borders, impacting other countries. The United States has issued an ultimatum, threatening to restrict security cooperation and the exchange of security information if these countries do not toe its line (Tekir, 2020).

Many countries, including Australia, Japan, and the UK, have followed the US lead in excluding Huawei from their 5G networks. Canada, however, has found itself more directly involved in the dispute. The arrest of Meng Wanzhou, Huawei's CFO and daughter of the founder, by Canadian authorities in Vancouver in December 2018 significantly intensified tensions between Canada and China (Jaisal, 2020; The Globe & Mail, 2018; Friis & Lysne, 2021; Azad, 2022). Faced with prolonged deliberation and pressure from allies, particularly the United States, which expressed significant security concerns, Canada ultimately decided in May 2022 to ban Huawei's 5G technology. This decision followed Canada's 2018 announcement that it would review the risks associated with using Huawei equipment (Hertzberg & Platt, 2022).

For Rühlig & Björk (2020), despite the validity of security concerns associated with Huawei, an outright ban on the company might not be the most effective solution. They advocate for alternative technological measures, such as enhanced cryptography and diversification of suppliers to reduce reliance on a single source, which could be more beneficial. They also argue that absolute network security is unattainable and propose a more nuanced and technical approach to managing risks, rather than resorting to complete bans.

Importing conflict into the academic world

The geopolitical tensions surrounding 5G have extended their impact beyond governmental and commercial domains, significantly affecting the academic sphere. These tensions have disrupted international scientific collaboration, particularly between China and other nations (Owens, 2022). In the United States, this impact is evident through specific actions. In 2018, the Trump administration launched the "China Initiative" program, aimed at countering intellectual property theft and espionage, with a particular focus on Chinese researchers and individuals in the U.S. with connections to China (Silver, 2020). This initiative resulted in several arrests by the FBI of scientists suspected of engaging in espionage on behalf of Chinese interests (Silver et al., 2019; Subbaraman, 2020).

Faced with the fear of being targeted by the government, some researchers in the USA have decided to abandon dual affiliations. For several years, researchers had been participating in the "Thousand Talents Program" (TTP), which facilitated their simultaneous affiliation with one research institution in China and another abroad (Jia, 2018). However, following the arrest of scientists involved in the TTP, many researchers chose to sever their ties with Chinese universities and publish only under their American affiliation (Van Noorden, 2022).

Concern has also focused on collaborations between Huawei and Western universities due to fears of espionage and intellectual property theft. In 2019, prestigious institutions such as MIT and Oxford University made significant decisions regarding Huawei. For example, MIT has decided not to establish new partnerships or renew existing ones with Huawei and ZTE, citing federal investigations into possible sanctions violations (Perper, 2019).

These tensions have led the European Union and several European countries to establish guidelines for scientific collaboration with China. The Finnish government, in collaboration with its universities, has issued “Recommendations for academic cooperation with China” (Ministry of Education and Culture, 2021), and Sweden has published its “Approach to China-related issues”, highlighting the challenges posed by such collaboration (Government of Sweden, 2019). For its part, Canada, faced with the changing geopolitical context, saw its main national research agencies announce on February 14, 2021, restrictions on funding projects involving foreign collaborators considered a security risk. Although these measures do not specifically mention China, they are in line with the precautions adopted by other nations (Mervis, 2023).

CHAPTER 3 RESEARCH DESIGN

3.1 Research question and objectives

As we discussed in the previous chapter, research on orchestration typically focuses on well-established and mature ecosystems. This focus tends to overlook the unique challenges and dynamics that arise in the early, more unpredictable stages of an innovation ecosystem. This gap in research, particularly the limited empirical studies on orchestration during these formative phases, represents a significant opportunity for further exploration. Dedehayir et al. (2018) offered insights into the roles and activities of key players at this stage, yet their study mainly identifies these roles without exploring the actual mechanisms orchestrators use or how these players interact with one another. Additionally, the literature often simplifies orchestration by focusing on scenarios where a single organization takes the lead. This overlooks the complex realities of ecosystems where orchestrators can take other forms, such as multiple organizations. Exploring these other forms of orchestration could uncover critical mechanisms essential for the early stages of ecosystem development.

As we discussed in the previous chapter, research on orchestration typically focuses on well-established and mature ecosystems. This focus tends to overlook the unique challenges and dynamics that arise in the early, more unpredictable stages of an innovation ecosystem. This gap in research, particularly the limited empirical studies on orchestration during these formative phases, represents a significant opportunity for further exploration. Dedehayir et al. (2018) offered insights into the roles and activities of key players at this stage, yet their study mainly identifies these roles without exploring the actual mechanisms orchestrators use or how these players interact with one another. Additionally, the literature often simplifies orchestration by focusing on scenarios where a single organization takes the lead. This overlooks the complex realities of ecosystems where orchestrators can take other forms, such as multiple organizations. Exploring these other forms of orchestration could uncover critical mechanisms essential for the early stages of ecosystem development.

Additionally, a layer of complexity is introduced in the orchestration process when dealing with ecosystems around frontier technologies. These ecosystems are influenced by geopolitical tensions and economic policies. As we explored in the preceding chapter, geopolitical concerns involving 5G technology, have extensive implications for various organizations including firms, universities, and governmental bodies. These geopolitical dynamics can drastically alter operational landscapes, affecting everything from collaboration networks to policy frameworks. While resilience in mature ecosystems has recently garnered some attention (Floetgen et al., 2021; Liu et al., 2022; Chen & Cai, 2023; Wang et al., 2023; Abdi et al., 2024; Zhang et al., 2024), resilience in the context of geopolitical tensions in nascent ecosystems remains underexplored.

Studies like those by Neto et al. (2024) highlight how crucial public policies are, especially in high-risk contexts undergoing technological change. Similarly, Rinkinen & Harmaakorpi (2019), through a multiple-case study in Europe, emphasize the importance of government support, particularly in fostering a culture of experimentation and providing funding. Additionally, in geopolitically tense environments, governments often play a direct role in the orchestration process, making decisions that shape the strategic direction of the ecosystem. Therefore, understanding the role of public policies is essential to see how these ecosystems are supported during their most vulnerable stages.

Thus, this thesis proposes to address the following general research question:

How do key actors orchestrate the strategic interactions within an emerging innovation ecosystem to navigate uncertainties in international, technological, and political contexts?

In this thesis, we explored three main themes: mechanisms of emergence ecosystem adaptation to external environment, and the role of public policy, as illustrated by our three research sub-questions:

What strategic and operational mechanisms do ecosystem orchestrators use to facilitate the emergence of an innovation ecosystem, and how are these mechanisms implemented? How does the emerging innovation ecosystem exhibit resilience in response to external environmental factors, such as geopolitical fluctuations and uncertainties? What roles do public policies and government interventions play in influencing the development of emerging innovation ecosystems? The objectives of this research are:

Objective 1: Analyze the strategic and operational mechanisms involved in the emergence of an innovation ecosystem:

- Identify and describe the main strategic and operational mechanisms used by ecosystem leaders to initiate the development of an innovation ecosystem.

- Examine how these mechanisms are planned and implemented and assess their impact on the emergence of an innovation ecosystem.

Objective 2: Assess how geopolitical changes may influence and test the robustness of the innovation ecosystem:

- Examine how geopolitical tensions may influence the innovation ecosystem.
- Understand how the innovation ecosystem evolves in response to geopolitical changes and instabilities.

Objective 3: Explore how public policies and government interventions may influence the innovation ecosystem emergence:

- Study the role and effect of public policies and government actions on the activities and orientations of emerging innovation ecosystems.

3.2 The strategic choice of 5G technology

Delineating the boundaries of innovation ecosystems remains a complex task, making the analysis of their various dimensions, characteristics, mechanisms, and dynamics particularly challenging. Thus, the judicious selection of the field of study is crucial for an in-depth exploration of this concept. In our research, we have chosen to focus on the 5G technology innovation ecosystem. We believe that this sector provides a pertinent context for addressing our research questions and analyzing the various aspects related to the emergence of an innovation ecosystem.

Several arguments justify our choice to study the 5G innovation ecosystem. First, the start of my PhD coincided with the emergence of this ecosystem, marked by the launch of activities, projects and other initiatives by various organizations. This simultaneity provided a unique opportunity to observe and analyze the development of this ecosystem in real time. Additionally, as mentioned earlier, 5G is expected to have a significant impact on society and the economy, further reinforcing its relevance as a subject of study.

Second, 5G is characterized by a wide diversity of players involved, transcending several industrial sectors. Participants in this ecosystem include large companies, SMEs, universities, research centers, NPOs, government bodies and intermediaries, from diverse sectors such as healthcare, transport, telecommunications, and agriculture. This heterogeneity is key to gaining an in-depth understanding of the orchestration activities carried out by all these players during the emergence phase of this ecosystem. It also enables us to examine the activities undertaken by these stakeholders and thus determine their roles during the emergence of the 5G ecosystem.

Last, the geopolitical context surrounding 5G reinforces the interest of our study on this ecosystem, not least because our research question focuses on the emergence of an ecosystem in an uncertain technological and geopolitical environment. The security of 5G infrastructures and equipment, combined with their significant economic and social impacts, has generated geopolitical tensions.

Together, these elements justify the choice of this ecosystem in answering the proposed research questions.

3.3 Organization of the thesis

While the thesis as a whole addresses the broader dynamics of innovation ecosystems, individual articles emphasize different dimensions. Article 2 focuses on knowledge ecosystems, exploring research collaboration networks and the structure of scientific activities. Article 1 examines the intersection between innovation ecosystems and business ecosystems, focusing on how value is created through collaborative innovation and subsequently captured through commercialization and scaling. Articles 3 and 4 investigate the intersection between knowledge ecosystems and innovation ecosystems, analyzing how knowledge is generated and integrated to support innovation. By framing the research within the concept of innovation ecosystems, this thesis investigates how orchestrators can leverage knowledge from knowledge ecosystems to enable value creation in innovation ecosystems and facilitate value capture within business ecosystems.

This approach provides a comprehensive understanding of the interconnected processes that shape innovation in complex and dynamic environments (see Figure 3-1).

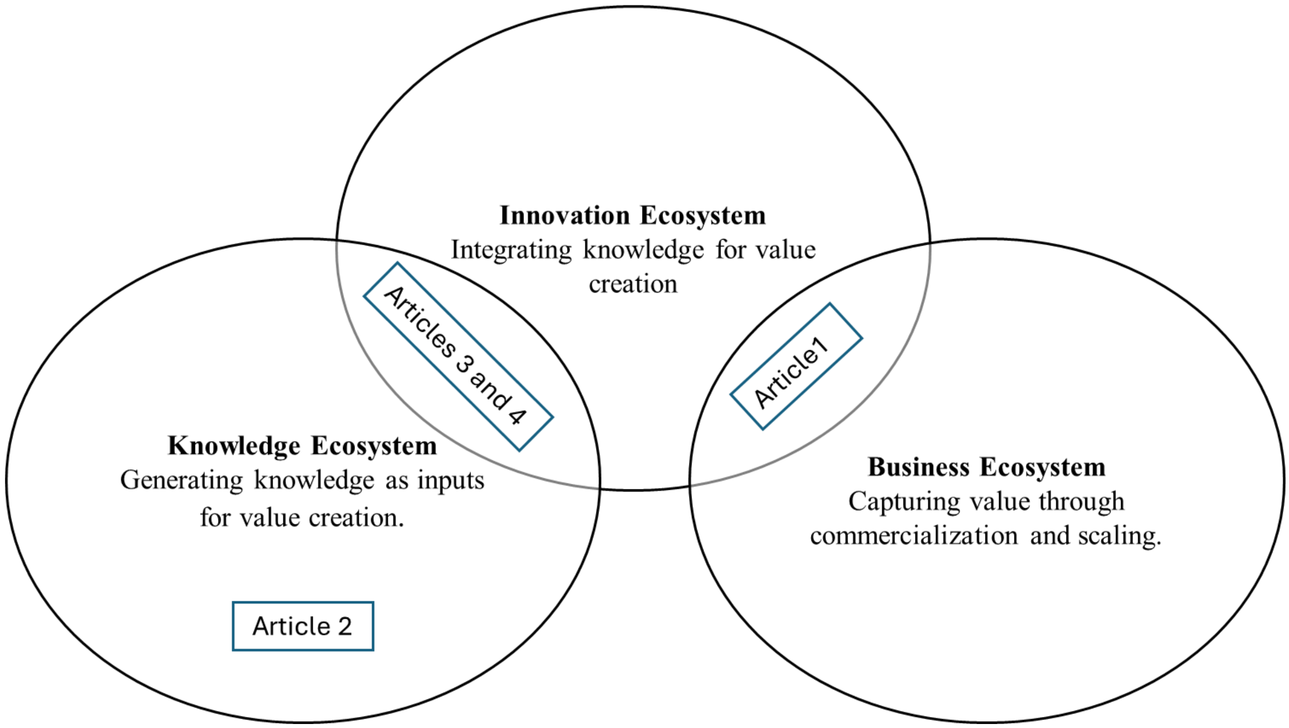

Figure 3-1: Organization of the thesis: Intersections of Knowledge, Innovation, and Business Ecosystems

Table 3-1 below summarizes the research questions and objectives of the four articles presented in this thesis.

Table 3-1. Articles main objectives

	Article 1	***Article 2***	***Article 3***	***Article 4***
Title	From transient to transformative: The influence of temporary structures on orchestrating innovation ecosystems.	Politicizing science: How the turbulent waters of international politics influence 5G research network	*Navigating Geopolitical Storms: Assessing the Robustness of Canada's 5G Research Network in the Wake of the Huawei Conflict*	In the shadow of geopolitical conflict: is collaboration with China key to Canadian 5G research success?
Research question	How can a temporary structure orchestrate the emergence of an innovation ecosystem?	How might ongoing geopolitical tensions involving China potentially influence the patterns of international scientific collaboration in the field of 5G technology?	How might the presence of Huawei and the associated geopolitical conflicts shape the network's structural robustness and the landscape of 5G research topics in Canada?	What is the impact of scientific collaboration with China on the scientific performance of Canadian researchers in the field of 5G?
Main objectives	Analyze strategic and operational mechanisms in the emergence of an innovation ecosystem.	Assess the adaptation and transformation of the innovation ecosystem.	Assess the adaptation and transformation of the innovation ecosystem.	Explore the impact of public policies and government interventions.
Journal	Technovation	Science and public policy	Scientometrics	Science and public policy
Publication status	Submitted	Submitted	Accepted	Submitted

3.4 Methodology

To address our research questions, we employed a multi-method approach[6]. We began with a qualitative approach involving in-depth interviews. This was followed by quantitative methods, including statistical regressions, social network analysis, and text mining. Each methodology employed allows us to explore different facets of an innovation ecosystem. Below, we describe each method used, the data mobilized, and the specific aspects they help us understand. This section does not aim to detail the methodologies outlined in each article. Instead, it explains our reasoning, the challenges encountered, and how each methodology relates to the research question and corresponding articles. For more detailed information, readers are referred to the four articles presented in the subsequent chapters. The aim of this section is to answer the following questions: Why did we opt for these methodologies? How do these methodologies enable us to answer our research questions? What challenges did we encounter? What choices did we make as researchers, and why?

3.4.1 Qualitative approach

A qualitative methodology is employed to examine various aspects of the ecosystem emergence phenomenon. Specifically, the research question addressed in Article 1 involves studying how a temporary structure can orchestrate the emergence of an innovation ecosystem. To address this, a single case study with integrated units of analysis was employed, following the approach recommended by Yin (2014). According to Yin, a single case study is an empirical investigation that explores a contemporary phenomenon in depth and within its real-world context, particularly when the boundaries between phenomenon and context are not clearly evident. The case study method is particularly relevant for studying emerging phenomena (Eisenhardt, 1989; Yin, 2014), even though it does not necessarily aim to generalize the results.

We selected the unique case of INNOV5G[7] [8] for our study due to several factors that align closely with our research questions. First, INNOV5G was designed to catalyze the formation of an

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[6] It is important to clarify that this approach does not qualify as a mixed method in the sense defined by Creswell (1999), where qualitative and quantitative methods are integrated in the same study to jointly address a research question. To avoid any ambiguity, I have chosen not to label this approach as a “mixed method” because the quantitative and qualitative analyses are conducted in separate articles.

[7] The name “INNOV5G” is used throughout this thesis to maintain confidentiality and privacy

[8] INNOV5G represents a five-year partnership involving international and local multinationals, along with federal and provincial governments and research innovation intermediaries in Canada. The primary goal of this partnership is to

innovation ecosystem, which is directly relevant to our interest in exploring how such ecosystems emerge. Moreover, INNOV5G is the largest initiative of its type in Canada, involving a diverse array of stakeholders including multinationals, SMEs, intermediaries, universities, and government entities. This selection of INNOV5G demonstrates a partnership aimed at uniting these varied participants, pushing their collaborative efforts beyond the conventional limits of the telecommunications industry to prepare for new technological advances.

Another compelling reason for choosing this case is that unlike typical orchestrators in the literature, which are often permanent hub firms or keystones, the orchestrator here is a temporary collaborative organization. This aspect provides a unique perspective on the orchestration of innovation ecosystems.

This initiative excludes Huawei due to the deteriorating geopolitical context but includes its direct competitor in Canada and one of the main contributors to the INNOV5G project. Analyzing the activities and challenges of INNOV5G provides a robust foundation for examining the critical attributes and roles of a catalyst within innovation ecosystems. We conducted several semi-structured interviews during two distinct periods: in 2019-2020 and in 2023[9]. Our original plan also included immersive observations within INNOV5G and regular field visits. Unfortunately, these activities were rendered impossible due to government restrictions imposed during the COVID-19 pandemic. This restriction significantly complicated our research, limiting our access to stakeholders who were prioritizing other urgent issues arising from the pandemic. Furthermore, the heightened geopolitical sensitivity surrounding 5G technologies, coupled with various anti-5G incidents and demonstrations during the pandemic, made access to government representatives particularly challenging.

Additionally, there was a notable reluctance among interviewees to discuss the Huawei issue, and our attempts to secure an interview with Huawei were unsuccessful. In our study, we conducted interviews with three distinct types of organizations: 1) The founding organizations of INNOV5G, which include multinationals, governments, and research innovation intermediaries; 2) Organizations that subsequently joined INNOV5G and participated in its various programs; 3)

prepare and mobilize the ecosystem for the adoption and advancement of 5G technologies. For more detailed information about this initiative, see Article 1 of this thesis.

[9] This study was conducted with ethical approval from the Polytechnique Montréal Research Ethics Committee (certificate number CER-2223-66-D)

Other 5G initiatives within the ecosystem that collaborated with INNOV5G. This comprehensive approach allowed us to capture a broad spectrum of insights and experiences related to the development and impact of INNOV5G (see Table 3-2).

All interview transcripts were systematically coded and analyzed using NVivo software.

Table 3-2. Data sources

Type of data	Data sources	Data usage objectives
Primary data: Interviews	Interviews with founding multinationals of INNOV5G	To familiarize ourselves with the context that led to the creation of INNOV5G, deepen our understanding of INNOV5G's operations, its objectives, governance structure, and overall program coordination. Investigate collaboration among partners and challenges encountered during the project development. Understand the general role of engagement and coordination partners within the program, learn more about their strategies for outreach and SME attraction, and the challenges associated with these efforts. Understand the processes of SME acceptance and support by the program, and the challenges faced by these companies.
	Interviews with SMEs that participated in INNOV5G	Understand the interest of businesses in 5G technology, identifying why it is considered important (or not) for their operations. Capture the motivations that led these companies to join INNOV5G, as well as the challenges they faced during the project.
	Interviews with organizations or initiatives that collaborated with INNOV5G	Understand the objectives pursued by these initiatives as well as the nature of their collaboration with INNOV5G and identify the challenges encountered during this collaboration.
Primary data: Observations	Participation in meetings of INNOV5G founding partners and engagement partners.	Observe the collaboration process among partners and the decision-making mechanisms within the project. Focus on the challenges encountered and the solutions provided by partners to address them.
	Participation in events organized by INNOV5G, as well as demonstration sessions showcasing 5G solutions developed by participating SMEs	Maintain an active presence in the field and engage in informal discussions with SMEs and ecosystem actors. Observe the proposed activities and participate in discussions and exchanges among ecosystem members.

Table 3-3. Data sources (continued and end)

Type of data	Data sources	Data usage objectives
Secondary data	Review of INNOV5G's websites and those of participating organizations. Exploration of their social networks, annual reports, press documents, and videos related to INNOV5G.	Familiarize ourselves with INNOV5G programs and the specifics of 5G technology. Closely monitor the activities organized by INNOV5G, documenting them chronologically to accurately capture the dynamics of the initiative. Pay special attention to INNOV5G announcements, particularly those related to new partnerships.

3.4.2 Quantitative approach

Social network analysis

Social network analysis is an interdisciplinary methodology developed primarily by sociologists and social psychology researchers. This approach allows for the examination of social systems' behavior at various levels, including individual actors, groups, and sub-groups (Wasserman & Faust, 1994). Networks are composed of nodes and the links that connect these node pairs (Freeman, 2002). There are multiple network configurations, each distinguished by different types of nodes and links. Nodes can represent entities such as individuals or organizations, while links can correspond to relationships such as co-publication, collaboration on a project, or joint funding applications. Social network analysis provides various metrics related to nodes and links (local measures) as well as metrics that capture the overall structure of the network (global measures). These metrics facilitate the analysis of the importance of nodes, the dynamics of interactions, and the diffusion of knowledge within the network. Social network analysis is particularly relevant to our research questions, as it allows us to examine and visualize the interactions between different players in the innovation ecosystem. Additionally, it helps identify key players who play a central role in the transfer of information and knowledge[10]. Social network analysis also allows us to observe the collaborative structure of the network, enhancing our understanding of how knowledge flows circulate. This approach also enables the examination of the temporal dynamics of networks.

[10] Co-publication networks are interpreted here as knowledge diffusion networks, as they capture the collaborative interactions through which knowledge is shared and developed

For instance, by identifying collaborative trends and structural changes in networks over time, we can gain deeper insights into the dynamics of ecosystem emergence.

In this thesis, social network analysis was employed in two articles (Articles 2 and 3). Article 2 examines the researchers' collaboration network, which was constructed using bibliometric data from the Web of Science. Local measures, such as node centrality, allowed us to analyze the evolving importance of researchers' countries of affiliation within the network, both before and after the onset of 5G-related geopolitical tensions. By applying global network measures, we examined how these tensions may have influenced the structural properties of the researchers' network. Similarly, Article 3 draws on funding data from NSERC to observe the robustness of researcher-industry and researcher-industry-thematic collaboration networks in the face of geopolitical conflicts, and more specifically their resistance to the ban on collaboration with Huawei.

Numerous software packages are available for social network analysis, with R, Pajek, and Gephi being among the most well-known. We opted for R due to its flexibility, which allows for adaptation to customized needs and direct programming of the desired analyses—an advantage not offered by the other two software packages, which are not designed for programming. Additionally, R provides a variety of packages tailored to social network analysis, offering robust functions for calculating metrics. We mainly used functions from the igraph package (Csardi, 2013) to calculate local and global network metrics. However, for network visualization, we chose Gephi for its ease of use and superior aesthetic capabilities compared to R.

Text mining

In Article 3, we employed text mining techniques to investigate the robustness of the collaboration network against targeted attacks. Specifically, this article examines the potential impact on 5G-related research topics in Canada if collaboration with Huawei were to be prohibited. The first step involved extracting the various research topics on which scientists and industry are working in Canada. This approach was essential for identifying and analyzing the key areas of focus within the 5G field in Canada. To carry out this study, we used the NSERC database which contains abstracts of all funded projects. These abstracts served as our source of textual data. We then applied traditional text mining methods to extract the most relevant themes related to 5G.

In the literature, various text mining techniques are employed to extract the most relevant themes from a text corpus, including LDA, K-means, and hierarchical clustering. The choice of a particular technique depends largely on the nature of the corpus, the theme under study, and the research objective. In our case, we opted for hierarchical clustering for several reasons. Unlike other approaches, hierarchical clustering allows us to visualize the similarities between documents through the use of a dendrogram. Similar documents, which appear close to each other on the branches of the dendrogram, can be grouped within the same cluster, helping to identify and understand the main theme they address and share. By manually exploring the dendrogram branch by branch, we maintain greater control over the assignment of documents to specific clusters and themes. This manual process, which does not require a predetermined number of clusters and is iterative—meaning it involves revisiting the original summaries whenever two documents appear close in the dendrogram—is made feasible by the brevity of the summaries, allowing for quick analysis. We used R software for hierarchical clustering, as it provides practical packages and functions for constructing and exploring the dendrogram.

It is important to highlight some of the challenges encountered during the text mining process. Two primary difficulties were identified: the first related to data pre-processing, and the second to the assignment of thematic names to each cluster.

First, during text data processing, a significant challenge involved cleaning the abstracts, which occurred on two levels. At the pre-processing stage, it was necessary to remove certain unwanted symbols and characters. Additionally, during hierarchical clustering, certain words, considered as noise, did not accurately reflect terms relevant to identifying 5G themes. Their presence in the corpus led to the formation of incomprehensible clusters, making it difficult to assign precise labels. Data cleaning was performed manually and iteratively, as the lack of recurring patterns in some cases made it impossible to automate the process using R.

Secondly, assigning thematic names to each group of words representing the clusters proved to be challenging. To address this, we first read the abstracts associated with each cluster to gain a deeper understanding of the context. Following this, we consulted the scientific publications of the authors of these abstracts and conducted additional internet searches to accurately determine the appropriate thematic names.

Econometrics

An innovation ecosystem encompasses numerous dimensions, involving a diverse array of players and industries, all of which are interconnected. The challenge of gathering and accessing the necessary data significantly complicates the task of identifying relevant indicators for the emergence of an innovation ecosystem and determining the factors that contribute to it. Indeed, several indicators can partially reflect the development of an ecosystem, such as the increase in the number of startups created, venture capital investments, the number of products or services launched on the market, employment rates, company survival rates, collaboration between universities and companies, as well as the number of publications, citations, and patents. However, access to data for some of these variables is challenging, as it is often not publicly available. Additionally, these variables are frequently interdependent, further complicating the measurement of the emergence process. Given these limitations and the time constraints associated with my PhD and considering that the understanding of the emergence process is further explored in the other articles, Article 4 focuses on a specific aspect of the innovation ecosystem: the knowledge ecosystem, utilizing publicly available indicators.

The number of scientific publications and citations serves as a measure of the emergence of an innovation ecosystem, reflecting not only active R&D activity but also the integration and impact of this research within the scientific community. We then reviewed the literature to identify factors that could explain the increase in the number of articles and citations. Among the variables selected, we focused primarily on public funding and collaboration, particularly with Chinese scientists and Huawei, to assess the emergence of the innovation ecosystem in a context of geopolitical tensions. These two characteristics—public funding and international collaboration—are frequently highlighted in the literature as crucial for the development of an innovation ecosystem. The bibliometric data utilized in this study was sourced from the Observatoire des Sciences et des Technologies (OST)[11] database, to which we had access. Information on funding was obtained from the NSERC database.

Our econometric approach is designed to assess the impact of collaboration with Chinese scientists and Huawei on scientific publications. Specifically, this method examines how such collaborations affect the volume of publications and the number of citations these publications subsequently

[11] https://www.ost.uqam.ca/

attract. Several software packages are commonly used for statistical analysis, including Stata, SPSS, and R. We chose to use Stata due to our familiarity with the software. The methodologies employed for each article are summarized in Table 3-3:

Table 3-4. Articles methodologies

	Article 1	Article 2	Article 3	Article 4
Methodology	Case study	Social Network Analysis	Social network Analysis, Text mining	Econometrics (regressions)
Data Source	Semi-structured interviews	Web of Science	Web of Science MITACS NSERC	Web of Science MITACS OST database NSERC

CHAPTER 4 ARTICLE 1: FROM TRANSIENT TO TRANSFORMATIVE: THE ROLE OF TEMPORARY STRUCTURES IN ORCHESTRATING EMERGING INNOVATION ECOSYSTEMS

Anas Ramdani, Catherine Beaudry and Mario Bourgault

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4.1 Abstract

Existing literature on innovation ecosystems predominantly focuses on the analysis of established ecosystems, leaving a significant gap in empirical studies examining the emergence phase and the mechanisms that underpin their creation. To address this gap, this research mobilizes the concepts of orchestration and temporary structures, exploring their role in the development of the ecosystem surrounding fifth generation (5G) mobile telecommunication technology. This study specifically investigates the conditions necessary for the formation of a temporary structure and the orchestration mechanisms that facilitate the emergence of an innovation ecosystem. The results of this research reveal three critical aspects: (1) the establishment of a temporary structure for orchestrating the pre-emergence phase of the innovation ecosystem, (2) the orchestration mechanisms essential for a temporary structure during the ecosystem's emergence, and (3) the resilience dynamics associated with collective temporary orchestrators. We conclude our paper by discussing the theoretical and managerial implications to shed light on the process of innovation ecosystem emergence with temporary structures acting as orchestrators.

Keywords: Innovation Ecosystems; Ecosystems Orchestration; Temporary Structures; Case study; 5G.

4.2 Introduction

Since Moore's (1993) seminal contribution on business ecosystems, academic interest has gradually extended to their innovation and value-creation-focused counterpart, namely innovation ecosystems (Jackson, 2011, Clarysse et al., 2014; Adner and Kapoor, 2016; Ritala and Almpanopoulou, 2017; Gomes et al., 2018; Jacobides et al., 2018). According to Granstrand & Holgersson (2020), an innovation ecosystem is composed of a set of actors and activities, as well as complementary relationships that play a role in the innovative performance of one or more actors. These ecosystems follow a life cycle that can be broken down into several key stages: birth, expansion, leadership, regeneration or dissolution (Moore, 1993; Rabelo & Bernus, 2015; Pique et al., 2019; Cantner et al., 2021).

Most existing research on innovation ecosystems focuses on retrospective analysis of already established ecosystems, studying their distinctive features without exploring their genesis (Leten et al., 2013; Still et al., 2014; Adner, 2017; Valkokari et al., 2017; Gomes et al., 2018; Jacobides et al., 2018). Many researchers have called for research into the emergence processes of innovation ecosystems, a particularly volatile and uncertain phase (Dedehayir et al., 2018; Jacobides et al., 2018; Pushpananthan & Elmquist, 2022).

One of the key elements to study in the emergence phase of innovation ecosystems is the way key actors are orchestrated by means of a variety of mechanisms and resources. Existing literature on the orchestration of innovation ecosystems (Dhanaraj & Parkhe, 2006; Ritala et al., 2009; Still et al., 2014; Hurmelinna-Laukkanen & Nätti, 2018) mainly focuses on orchestrators that are key firms, referred to as central or hub firms (Iansiti & Levien, 2004; Nambisan & Sawhney, 2011; Adner, 2012; Clarysse et al., 2014; Leten et al., 2013). For Dhanaraj & Parkhe (2006), ecosystem orchestration is a deliberate action or practice on the part of these hub firms in exerting a significant influence on the strategies, development and overall success not only of individual ecosystem members, but of the ecosystem as a whole.

As this emergence phase is relatively short-lived, the literature on temporary structures could help fill this gap. Studying the emergence of an ecosystem from a grouping of key ecosystem players within a temporary organization could provide additional insights into the orchestration of this volatile phase in the life cycle of an innovation ecosystem. To our knowledge, only one study, conducted by Poblete et al. (2022), addresses the concept of temporary structure in the literature dedicated to innovation ecosystems.

Temporary structures are defined as groupings of organizations that come together for a set period of time to achieve a specific goal (Grabher, 2002; Burke & Morley, 2016; Pushpananthan & Elmquist, 2022). They are often formed to generate momentum or create a sense of urgency (Poblete et al., 2022). Once the desired objectives have been achieved, the temporary structure is dissolved (Grabher, 2002).

In this article, we argue that temporary structures, bringing together the key players in an ecosystem, represent a specific form of orchestration during the emergence of innovation ecosystems. The main objective of this article is to contribute to a better understanding of the underlying dynamics, including mechanisms, activities and critical roles, of a temporary structure as an orchestrator of the early stages of development of an innovation ecosystem. This is achieved by scrutinizing the complete life cycle of a temporary structure, from its conception to its dissolution. To achieve this objective, we have structured our investigation around the following research question and sub-questions:

- How do temporary structures orchestrate the emergence of an innovation ecosystem?
    - How and under what circumstances does a temporary structure designed to orchestrate the emergence of an innovation ecosystem take shape, and what specific mechanisms are involved in this process?
    - What are the mechanisms and activities performed by a temporary structure, the roles it undertakes and the specific challenges it encounters during the orchestration of the emergence phase of an innovation ecosystem?

Through these two questions, our aim is also to examine the value and relevance of a temporary structure, compared with permanent ones. To deepen our understanding of these dynamics, our analysis will be based on a specific case study: Canada's INNOV5G[12]. This 5G partnership comprises stakeholders from both the public and private sectors, collaborating to expedite the transition towards a digital economy and to bolster Canada's competitiveness on the global stage. Operating for a period of 5 years, INNOV5G aims to initiate and support the emergence of a 5G ecosystem in Canada. The selection of the INNOV5G case study was driven by its innovative approach to ecosystem orchestration. Unlike the traditional orchestrators typically documented in academic literature, often permanent entities like hub firms or keystones, INNOV5G functions as a temporary collaborative organization. This distinctive structure offers a valuable context for exploring how such a temporary structure can orchestrate an emerging innovation ecosystem. The decision to focus on the 5G ecosystem was guided by several key factors that make it an ideal subject for our study. First, the 5G ecosystem remains in its emergent phase, with its full potential yet to be realized and adopted across industries. Furthermore, the 5G ecosystem is characterized

[12] The name INNOV5G is employed fictitiously in this study. To preserve the confidentiality of all participating organizations, all names mentioned in this document are fictitious.

by a diverse array of stakeholders from multiple industrial sectors, including large corporations, SMEs, academic institutions, research centers, non-profit organizations, governmental entities, and intermediaries. These participants come from varied sectors such as healthcare, transport, telecommunications, and agriculture. The heterogeneity of these stakeholders is essential for gaining a comprehensive understanding of the orchestration activities undertaken by these diverse players during the emergent phase of the ecosystem.

This article is structured as follows: a review of the literature on innovation ecosystems, their emergence and orchestration are presented first. Next, the methodology is detailed, describing the methods used for data collection and analysis. The results of the study are then presented, followed by a discussion of the implications and conclusions drawn from this research.

4.3 Literature review

4.3.1 Emerging innovation ecosystems

The notion of innovation ecosystem attracted the attention of the scientific community following Moore’s (1993, 1996) pioneering work on business ecosystems, sparking a strong interest in adapting this concept from a value creation perspective (Gomes et al., 2018). Over the course of the contributions, the literature has progressively enriched our understanding of innovation ecosystems, with each definition bringing an additional nuance (Jackson, 2011; Adner, 2017; Jacobides et al., 2018). Granstrand & Holgersson (2020, p.1) conducted a systematic literature review on innovation ecosystems and proposed a new definition: “*An innovation ecosystem is the evolving set of actors, activities, and artifacts, and the institutions and relations, including complementary and substitute relations*”

These ecosystems are characterized by a diversity of heterogeneous actors such as companies, universities and research centers, suppliers, distributors, financial institutions, and governmental entities (Moore, 1993; Moore, 1996; Adner & Kapoor, 2010; Autio & Thomas, 2014, Dedehayir et al., 2018). These actors co-evolve, mutually enriching their expertise and capabilities with the aim of co-creating value and innovating (Gomes et al., 2018; Thomas & Autio, 2019; Hou & Shi, 2021). In other words, ecosystem members are interdependent, their products or services complementary to one another. This complementarity of products and services would be unattainable for a company operating independently (Pushpananthan & Elmquist, 2022). Also, an innovation ecosystem is often defined by a coopetition dynamic, in which entities simultaneously collaborate and compete, catalyzing value generation that is later disseminated within the ecosystem (Basole et al., 2015; Bacon et al., 2020). Finally, the innovation ecosystem not only brings together various actors for value creation, but also plays an important role in the commercialization of this created value (Gu et al., 2021; Dedehayir et al., 2018).

Like a biological ecosystem, an innovation ecosystem goes through a life cycle that Moore (1993) describes as comprising four key phases: birth, expansion, leadership, followed by renewal or termination. According to the author, in the initial stage, the hub firm’s approach is to combine various competencies to develop a value proposition that will serve as the foundation on which the ecosystem can be built. During the expansion phase, the hub firm relies on an initial network of enriching collaborations to strengthen and extend its influence. A critical mass of potential partners must be reached before moving on to the next phase. During the leadership phase, the leader must ensure a central and indispensable presence. This period is also devoted to consolidating its dominant position within the business ecosystem. In the renewal phase, the aim is to maintain competitiveness by integrating new ideas to avoid the death of the ecosystem (Moore, 1993). The transformation or renewal of an ecosystem is in fact a form of emergence of a new ecosystem, as it engenders a restructuring and reorganization of the ecosystem (Almpanopoulou et al., 2019).

Since Moore’s seminal work, numerous researchers have examined and described the life cycle of innovation ecosystems. Cantner et al. (2021) articulates this process in five distinct stages: birth, growth, maturity, decline and re-emergence. Pique et al. (2019), analyzing innovation ecosystems within a district, categorize the life cycle into four distinct phases: inception, launching, growth and maturity. Meanwhile, Thomas & Autio (2013, 2014), define a cycle in three phases: initiation, momentum and optimization.

These life-cycle typologies are broadly in line with the phases identified by Moore (1993), illustrating a natural progression through various significant periods. However, the transition of an innovation ecosystem from one phase to another is neither linear nor automatic. An ecosystem may regress to an earlier phase or skip certain stages without necessarily following each phase of the life cycle sequentially (Dos Santos et al., 2021).

This unpredictability highlights the importance of the emergence phase, which remains underexplored in literature, with only a few studies addressing it (e.g., Thomas & Autio, 2014; Dedehayir & Seppänen, 2015; Dedehayir et al., 2018, 2022; Pushpananthan & Elmquist, 2022).

For example, according to Thomas & Autio (2014), the creation of an innovation ecosystem involves the consideration of three types of interconnected architectures. Technology architecture defines access rules and roles within the innovation ecosystem, dictating who can connect and how. Business architecture determines configuration, organization and coordination mechanisms. The aim is to define how players collaborate and contribute to the ecosystem. Value architecture illustrates how value is generated through the interaction between technological architecture and business organization. These three architectures require the coordination of specific strategic activities in the technological, economic, behavioral and institutional domains. The authors provide interesting insights about the emergence phase of innovation ecosystems through the lens of interconnected architectures. However, it offers limited details on the specific mechanisms and dynamics at play, leaving gaps in our understanding of how these elements systematically contribute to the broader emergence of innovation ecosystems. Pushpananthan & Elmquist (2022) demonstrate how alliances can foster the emergence of an innovation ecosystem. Their study of the development of autonomous driving technology at Volvo Car Group reveals that initial resource constraints drove the company to form new alliances. These partnerships transformed their in-house technology platform into a modular one, fostering the emergence of an innovation ecosystem with players co-creating value around this new platform. While this study shed light on platform ecosystems, there remains a significant need for empirical research that explores other types of ecosystem emergence.

4.3.2 Ecosystem emergence orchestration

The coexistence of different objectives and logics among the players in an innovation ecosystem makes managing their interactions particularly complex (Yaghmaie et al., 2020). To navigate this complexity, the literature often refers to the management of ecosystems using terms such as “ecosystem governance” and “ecosystem orchestration”. Adner & Kapoor (2010) highlight that without effective orchestration, the ecosystem could face detrimental outcomes.

While some research suggests that ecosystems are naturally self-organizing, others indicate that their creation can be deliberate and initiated by key players. In the early stages of ecosystem creation, orchestration requires a more centralized and formal strategy to harmonize actors’ motivations and activities (Dos Santos et al., 2021). Dhanaraj & Parkhe (2006) see this coordination issue through the perspective of a central firm or hub, often a large corporation: “*the* *set of deliberate, purposeful actions undertaken by the hub firm as it seeks to create value (expand the pie) and extract value (gain a larger slice of the pie)*" (Dhanaraj & Parkhe, 2006, p.659).

This underlines the need for specific actors to manage and coordinate these efforts. Chesbrough & Appleyard (2007) offer a somewhat different view in their claim that coordination of an innovation ecosystem can be provided by a set of companies, a consortium or a non-profit organization.

Regardless of which organization or group of organizations assumes the role of orchestration, certain specific activities are essential to the process. According to Dhanaraj and Parkhe (2006), orchestration mainly involves three activities that the hub company must carry out: knowledge mobility, innovation appropriability and network stability. Batterink et al. (2010) identify three network orchestration functions: innovation initiation, network composition and innovation process. These functions are then defined in specific actions such as: designing the innovation ecosystem, mobilizing by attracting various types of participants, encouraging cooperation between partners, defining goals and vision, providing the resources necessary for value creation by members, ensuring equitable distribution of the value created between participants, guaranteeing knowledge mobility by ensuring that all necessary information is available to all members, properly coordinating ecosystem activities, and maintaining network stability (Batterink et al., 2010; Leten et al., 2013; Hurmelinna-Laukkanen et al., 2021).

Although orchestration encompasses a multitude of activities, orchestrators do not assign equal importance to all these activities, nor do they perform them in the same manner or simultaneously. In this context, the choice of activities to be undertaken by the orchestrator at any given time, and the way in which these activities are carried out, define a specific orchestrator role. In this context, Hurmelinna-Laukkanen & Nätti (2018) identified specific orchestrator roles and explored the orchestration activities corresponding to each role. The roles described by Hurmelinna-Laukkanen & Nätti (2018) include: Architects, Representatives, Liaisons, Promoters, Judges, Guardians, Conductors, Coordinators, Auctioneers, Developers, and Leaders, among others. For example, the role of Architect encompasses activities such as promoting mobilization, agenda-setting and coordination. The Promoter role also includes agenda-setting, but also extends to promoting network stability. Dedehayir et al. (2018) prefer to use the term "leadership" rather than "orchestration". The authors classify leadership roles in an emerging innovation ecosystem into four categories: ecosystem governance (initiating and developing the ecosystem), partnership creation (attracting relevant partners), platform management (facilitating the efficient functioning of the ecosystem) and value management (ensuring the creation and capture of value for all ecosystem players).

These studies primarily focus on the roles and activities within more established ecosystems, leaving a significant gap in our understanding of how these orchestration mechanisms are initiated, adapted, and executed during the critical early stages of ecosystem development. This lack of detailed exploration into the initial orchestration efforts highlights the need for empirical studies that investigate the nuanced dynamics of orchestrating the formation and early growth of innovation ecosystems.

4.3.3 Temporary structures

Temporary structures, often referred to as "temporary organizations" (Poblete et al., 2022), "project-based organizations" (Hobday, 2000, Almeida & Soares, 2014) or "innovative projects" (Mintzberg, 2023), are increasingly common organizational forms in various industrial sectors. For simplicity's sake, we will refer to them as "temporary structures". Burke & Morley (2016, p.1251) define temporary structures as "a temporally bounded collectives of interdependent actors, in pursuit of some mandate (or mandates), embedded within multiple contexts simultaneously, which set the boundaries and constrain the entity".

These structures are characterized by their ability to create arrangements and systems to achieve goals in a specific timeframe (Prado & Sapsed, 2016). Various entities, such as private companies, governments and universities, can collaborate to initiate projects aimed at innovation (Poblete et al., 2022). These may take the form of consortia of companies brought together to carry out a specific project, only to be dissolved once the objective has been achieved. In other cases, these projects may be managed entirely within a single collective organization (Hobday, 2000; Prado & Sapsed, 2016; Sydow & Braun, 2018).

Such organizations are increasingly highlighted in the literature to address societal challenges and instill a sense of urgency to promote change (Chesbrough, 2020). The concept of temporary structures has been extensively discussed and analyzed by researchers across a variety of disciplines, including construction, healthcare, software development, and telecommunications (Jacobsson et al., 2015; Burke & Morley, 2016; Burke & Morley, 2023).

Temporary organizations differ from permanent ones in several significant ways. Their most notable characteristic is their purpose: the achievement of a specific mission within a defined timeframe, a goal to which all participants are committed (Pushpananthan & Elmquist, 2022). In contrast to permanent organizations, which are characterized by their long-term durability, temporary organizations are designed with a predefined endpoint from their inception, ceasing to exist once their mission is accomplished or a specific deadline is reached (Winch, 2013; Feldbrugge, 2015). These entities are specifically structured to carry out a time-bound project, after which the structure ceases to exist. This approach is proving to be an effective instrument for addressing issues that long-term organizations might not be able to resolve on their own (Feldbrugge, 2015).

Except for Poblete et al. (2022), the role of temporary structures has been largely neglected in studies of innovation ecosystems. Poblete et al. (2022) examine the challenges and opportunities arising from the use of temporary structures in the construction of innovation ecosystems. According to the authors, although temporary structures offer a considerable advantage for fostering innovation, careful preparation is essential to effectively exploit the opportunities offered by such structures.

To date, little is known about the role that temporary structures play in orchestrating an emerging ecosystem. A comprehensive understanding of their role in the initial phase of ecosystem emergence is largely absent from the literature on innovation ecosystems.

4.4 Methodology

4.4.1 Research design

We adopted an inductive methodology based on a single case study with integrated units of analysis, in line with the approach proposed by Yin (2014). We also applied the method proposed by Gioia et al. (2013) for data collection and analysis. Case studies allow for an in-depth examination of contemporary phenomena within their specific contexts, providing insights into the complexity of the frameworks in which they evolve. This method is particularly well suited to analyzing complex processes such as the emergence of complex systems like innovation ecosystems in a particular local context (Eisenhardt, 1989; Yin, 2014). In our case, this approach will enable us to thoroughly investigate the conditions, mechanisms, interactions, and challenges that highlight the complexity of ecosystem genesis by integrating the perspectives of various contributing actors.

INNOV5G was selected due to its explicit objective of catalyzing the emergence of an innovation ecosystem, thereby providing an ideal framework for examining orchestration mechanisms during the initial phase of ecosystem development. By integrating the diverse perspectives of different stakeholders, we were able to gain an in-depth understanding of the role of INNOV5G and the dynamics at work in orchestrating the emergence of the 5G ecosystem. The analysis was structured into two main strands: on the one hand, the examination of INNOV5G initiative itself as a singular case, and on the other, the study of the interactions and impacts resulting from collaboration with the participating organizations, thus representing the integrated units of analysis.

4.4.2 Case description[13]

INNOV5G is a collaborative initiative between the public and private sectors, involving several levels of government (Federal Government, Province A government and Province B government) and five multinational enterprises (MNE) specializing in advanced information and communication technologies: MNE1, MNE2, MNE3, MNE4, MNE5. The INNOV5G project represents a significant investment shared equally between the public and private sectors. The initiative aims to stimulate research and innovation in 5G technology.

As part of this effort, INNOV5G has established a pre-commercial digital infrastructure corridor for 5G telecommunications, covering several strategic sites. Each site, hosted by five innovation hubs (IH)[14] (IHA, IHB, IHC, IHD, and IHE), provides a development and testing platform for cutting-edge technologies.

The INNOV5G program also incorporates several research and innovation intermediaries (RII): RII1, RII2 and RII3. These non-profit organizations are responsible for mobilizing and attracting the ecosystem. The management of INNOV5G is entrusted to a newly established nonprofit organization, referred to here as NPO_GOV, which is specifically created for this mission and is responsible for the coordination and administration of the project.

[13] To preserve the confidentiality of all participating organizations, the names mentioned in this document are fictitious.
[14] In the context of our study, "innovation hubs" refer to well-established accelerators or incubators in both provinces.

Over a five-year period, the principal aim of INNOV5G project is to raise awareness, mobilize and support small and medium-sized enterprises (SMEs) as they prepare for the advent of 5G. This aims to position the country as a leader in the transition to 5G, catalyzing innovation in various key economic sectors, including smart cities, telemedicine, autonomous driving and the Internet of Things. INNOV5G aspires to be the starting point of a dynamic ecosystem, bringing together a diversity of players such as SMEs, manufacturers and academic institutions on a national scale.

To support the participation of SMEs in INNOV5G, each government has dedicated specific funds to finance projects directly targeting SMEs. These projects may include collaborations with academic institutions and researchers focused on the development of 5G technology through the INNOV5G platform. In addition, additional budgets are allocated to encourage co-development with one or more of the multinationals involved.

INNOV5G has set up several key programs. Although the program specifics may vary between Province A and Province B, all share a common goal. Examples of such programs are described below[15]:

- Technology Access Program: This program aims to offer SMEs free access to 5G infrastructures deployed by INNOV5G in five specific hubs, to submit and develop their 5G-related projects.
- Subsidized Technological Initiatives: In addition to the access offered by the Technological Access Program, certain SMEs can benefit from financial support to carry out their 5G projects within INNOV5G hubs.
- Partnership and Innovation Program: oriented towards collaboration, this program encourages SMEs to team up with an end-user to design, test and demonstrate the usefulness of new products, processes or services exploiting 5G. Funding is also available to support these initiatives.
- Collaborative Research Initiative: Dedicated to projects carried out in partnership with one of the multinational partners, this initiative offers collaboration opportunities on specific 5G-related topics, with financial support for selected SMEs.
- Skills Enhancement Program: INNOV5G also offers organizations participating in these programs the opportunity to strengthen their teams by integrating new talent, such as

[15] The actual names of the programs have been anonymized, and different names are used in this study.

students and experts. To achieve this, INNOV5G collaborates with an independent non-profit organization, facilitating companies' access to qualified human resources and funding opportunities.

The financial support offered by INNOV5G for 5G projects takes the form of reimbursement of part of the eligible expenses incurred by organizations participating in the program. In exceptional cases, the reimbursement rate can be significantly increased through an additional financial contribution from a national research non-profit organization, referred to as RII4, which aims to fund partnerships between universities and the private sector.

As part of the INNOV5G project, multinationals also receive funding specifically allocated to their 5G research and development, representing a significant portion of the total budget. This part of the budget is mostly funded by the provincial governments of Province A and Province B to foster technological advancement in their respective territories.

Since its launch, INNOV5G has successfully mobilized hundreds of SMEs from a variety of sectors, including smart cities, media and entertainment, transport and mobility, telecommunications and IoT. INNOV5G collaborated with several higher education institutions in Province A and Province B on various innovative 5G projects. The program has also enabled numerous student internships. The program, initially launched in 2018 for a five-year period, was extended to 2023 due to the pandemic.

This case is relevant to our research question, which aims to identify specific orchestration mechanisms in the context of an emerging innovation ecosystem. The choice of INNOV5G case illustrates the establishment of a temporary structure articulated around a public-private partnership, with the aim of attracting the various players in the ecosystem, and more specifically SMEs, and even extending its influence beyond the traditional boundaries of the telecommunications industry, by preparing them for emerging technologies. Analysis of the activities and challenges faced by INNOV5G provides a solid basis for describing the attributes and orchestration mechanisms of an emerging ecosystem.

4.4.3 Data collection and analysis

Data source

The primary data collection method consisted in semi-structured interviews[16], conducted in two different phases, between 2019 and 2020, and then in 2023. Due to the COVID-19 pandemic and government-imposed containment measures, it was impossible to conduct interviews on an ongoing basis. With companies primarily focused on managing urgent crisis-related priorities, data collection was suspended until the situation stabilized. We identified three types of respondents to interview (see Table 4-1): (1) INNOV5G's core partners, comprising multinationals and innovation intermediaries; (2) ecosystem participants that joined INNOV5G through engagement in its programs; and (3) other ecosystem organizations that independently initiated 5G projects but subsequently collaborated with INNOV5G.

To implement our strategy of identifying and selecting potential candidates to interview, we conducted an in-depth online search for potential candidates, exploring websites and LinkedIn profiles. We then contacted selected candidates via email. We also adopted a snowball sampling strategy, in which interviewees recommended other potential participants. To increase our visibility and generate interest from other potential participants, especially in view of the COVID-19 pandemic, we also actively took part in webinars organized by various 5G players in Canada and attended various 5G events in several Canadian cities. These participations were crucial in identifying new candidates to interview. Data collection and interviewing continued until information saturation was reached.

We conducted 53 interviews based on a semi-structured interview protocol. Our interview protocol was developed from the literature review presented above, as well as online information about INNOV5G and the projects it approved. The first round of interviews began in June 2019 and continued until mid-December. Our objectives were (1) to learn about the context that led to the creation of INNOV5G, to understand its functioning, objectives, governance structure and program coordination; (2) to investigate collaboration between partners and the challenges encountered during project development; (3) to understand the role of mobilization and coordination partners, as well as their strategies for raising awareness and attracting new members, and the associated

[16] This study was conducted with ethical approval from the Polytechnique Montréal Research Ethics Committee (certificate number CER-2223-66-D)

challenges; (4) to study the program's processes for accepting and supporting new members, and the challenges they faced; (5) to understand companies' interest in 5G technology and why it is considered important (or not) for their business; and finally (6) to capture companies' motivations for joining INNOV5G, the challenges encountered during the project, and the nature of their collaboration with INNOV5G.

The second series of interviews, conducted in 2023, mainly highlighted the challenges faced by INNOV5G. It also explored the mechanisms put in place to overcome these obstacles. Secondary data came from a variety of sources, including websites, several reports, as well as articles from the press. We also consulted videos available online concerning INNOV5G project, as well as videos produced by SMEs, illustrating their 5G projects carried out in collaboration with INNOV5G.

Interviews ranged in length from thirty minutes to two hours, and some candidates were interviewed several times. Interviews were conducted both face-to-face and remotely, in French and English. Together, the data transcriptions represent approximately 713 pages of textual data.

Table 4-1. Interview data

	Number of interviews	**Provinces**	**Period**
Interviews with MNE and RII members of INNOV5G.	26 interviews 13 organizations	Province A and Province B	2019-2021 2023
Interviews with SMEs participating in INNOV5G	19 interviews 16 SMEs	Province A	2019-2021 2023
Interviews with organizations or initiatives that have collaborated with INNOV5G	8 interviews 5 organizations	Province A and Province B	2019-2021 2023

Data analysis

We adopted Gioia et al.'s (2013) method for the coding process. We initiated our data review process with open coding (Strauss & Corbin, 1998), conducting a line-by-line analysis of all transcripts. We began with an intra-unit analysis, coding line by line the interviews conducted with each of the organizations involved in INNOV5G programs. This initial step enabled us to identify a variety of first-order codes that directly reflect the terms and experiences expressed by each of the participants. These codes were then synthesized into second-order themes. This step was carried out by comparing the results obtained across the various integrated units. It highlighted common themes, differences, as well as a deeper understanding of INNOV5G's role in the ecosystem and the experience of the participating organizations. Finally, these second-order themes were integrated into broader dimensions.

Data coding was carried out progressively, in parallel with the interview series. This iterative process enabled us to adjust and optimize the quality of subsequent interviews by integrating the learnings from each previous interview series. Additionally, in an iterative manner, we consulted the existing literature concurrently with the development of the dimensions to identify and integrate relevant concepts into our analytical framework. In addition, we reread the transcripts several times, adjusting the codes and themes assigned. The coding process was carried out using NVivo software. The codes, themes and dimensions are illustrated in Figure 4-1.

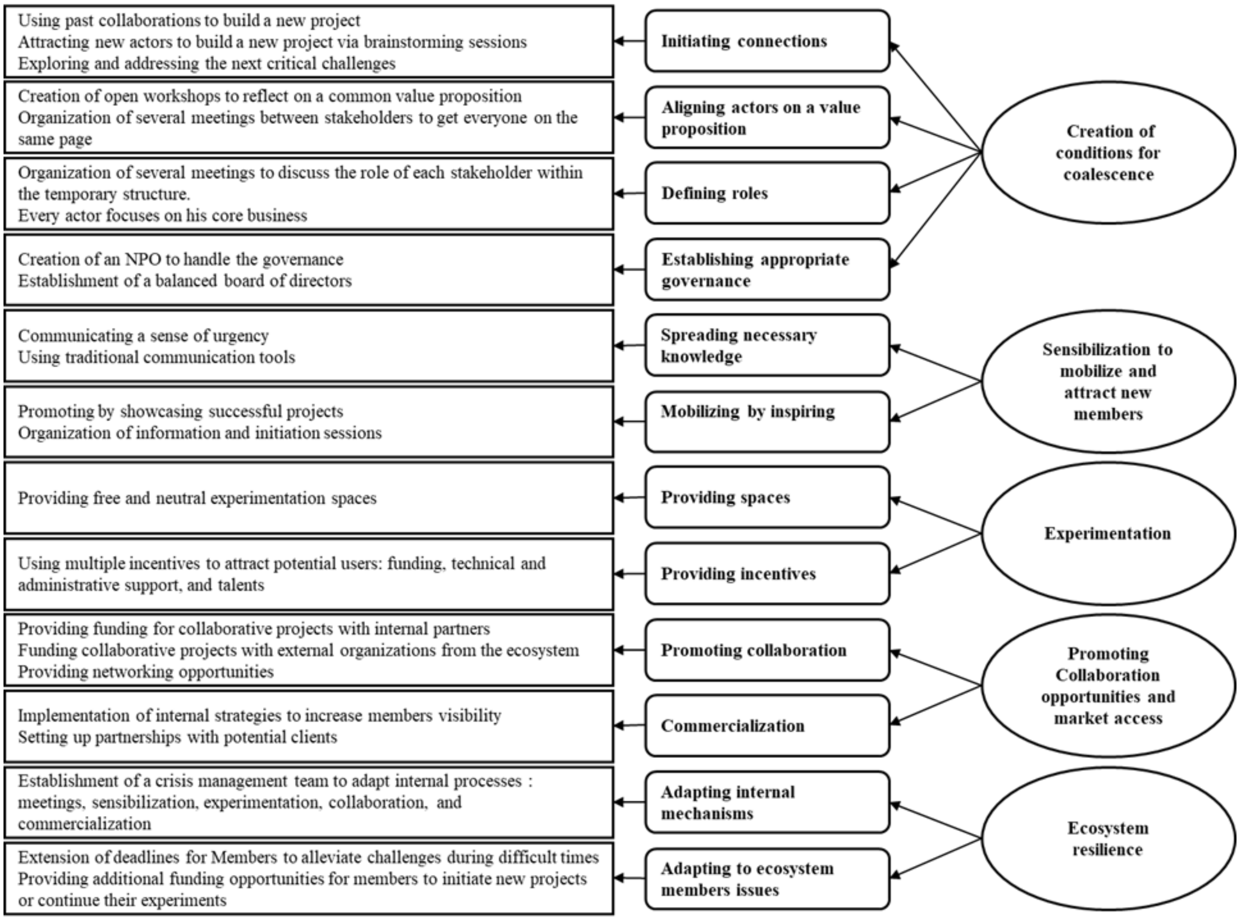

Figure 4-1. Data structure

Several secondary data sources (reports, videos, websites) were used to ensure the validity and reliability of our results (Lincoln & Guba, 1985). We also reinforced this validity by regularly comparing our qualitative data with existing theoretical frameworks. In addition, we selected samples from a variety of SMEs from different economic sectors to ensure diversity in our sample. We also validated our results through numerous informal discussions with the partners of INNOV5G.

4.5 Results

The paragraphs below address each of the dimensions identified by our analysis in turn, detailing each of the related second-order dimensions.

4.5.1 Creating conditions for coalescence

Daymond et al. (2023) have shown that, during the emergence phase, ecosystem architects fall into two categories: those from the public sector, and those from the private sector. Public-sector architects must focus on creating conditions for coalescence, while private-sector architects must foster conditions conducive to cooperation. In our study, the temporary structure manifests itself in the form of a public-private partnership, where both types of conditions have been integrated by INNOV5G. Based on our results, we assert that these conditions are established by various actions: the creation of connections and the search for opportunities, aligning actors around a common value proposition, defining roles and establishing appropriate governance.

Creating connections and opportunity screening

The first stage involved discussions between various players in the ecosystem to jointly define future priorities, existing opportunities and the challenges to be overcome. These exchanges occurred at the conclusion of a prior project coordinated by RII1. This project already brought together some of the multinationals in INNOV5G, such as MNE1, MNE4 and MNE5, as well as several SMEs, research centers and universities in Province A. Taking advantage of this already established momentum, the participants saw the opportunity to continue their collaboration in a broader framework, inviting new members of the ecosystem who had not participated in the initial project to join them.

At the end of the project, brainstorming workshops were organized to discuss future initiatives. MNE3 and MNE2, who had not participated in the previous project, joined the discussions at these workshops, which were open to new participants. During these workshops, 5G technology was highlighted as an urgent opportunity to shape the future direction of the next major collaborative project:

> Specifically, when it came to 5G deployment, Canada lagged behind other regions such as Asia, Europe and the United States, where this technology had already been implemented... It was therefore urgent to strengthen research and development initiatives to ensure that our national companies develop adequate technological capacity in this area. **RII1 Manager**

As a result of these discussions, five multinationals – MNE1, MNE2, MNE3, MNE4, and MNE5 – have committed to build a partnership whose aim is to mobilize and prepare the ecosystem for the transition to 5G technology.

Aligning actors on a common value proposition

Recognizing 5G as a strategic opportunity and the next priority for the ecosystem, the subsequent step for the multinationals was to develop a value proposition that the entire ecosystem could embrace. To enhance the reach and visibility of this proposition, the multinationals decided to involve three levels of government: the federal government and two provincial governments (Province A and Province B).

The multinationals took the initiative to formulate a value proposition, which they then presented to the federal and provincial governments for consideration. This process involved numerous discussions and deliberations between the multinationals and the governments to refine and finalize the proposal. From these exchanges emerged the value proposition that led to the creation of INNOV5G, envisaged as a five-year public-private partnership and characterized by several key points.

First, INNOV5G's value proposition aimed to address Canada's lag compared to other industrialized countries, creating a sense of urgency and positioning Canada as a major 5G player on a global scale. Second, to distinguish itself from the private 5G trials already underway in Canada[17], INNOV5G offered access to state-of-the-art 5G technology platforms in the pre-commercial phase, open to all organizations interested in 5G technology. Its geographic reach, covering two provinces and five key cities, and the interconnection of these locations via various networks, made INNOV5G remarkably unique. Finally, all types of organizations were invited to join the project, focusing particularly on SMEs, considered by INNOV5G to be the main beneficiaries of 5G. This initiative allowed Canadian companies to familiarize themselves with 5G technologies, gain first-hand experience, develop innovative local solutions, and position themselves competitively for the 5G rollout. Our interviews reveal that developing this value proposition was a complex and meticulous process. Shared values among the multinationals facilitated consensus, and their prior collaborations improved coordination. However, extensive discussions with government entities prolonged the process. The complexity of contracts involving multiple levels of government and partner agreements necessitated numerous meetings to overcome these administrative challenges.

Defining roles

INNOV5G's value proposition also clearly defines the roles of each founding participant. Each multinational involved in INNOV5G focuses on its area of expertise, contributing to a synergy of

[17] Mainly private trials carried out by telecom operators in Canada.

technologies essential to the deployment and creation of INNOV5G. Even though they are competitors in certain markets, they have focused on their respective areas of expertise to collaborate effectively on this project. For instance, 5G technology necessitates both radio and wired connections. In constructing INNOV5G's technology platforms and infrastructure, MNE1 is responsible for deploying the radio infrastructure, encompassing both indoor and outdoor installations. Meanwhile, MNE2 handles the wired infrastructure, acting as the private network manager to ensure the network's smooth operation, maintenance, and security. Additionally, MNE2 contributes to the development of advanced technologies such as edge computing, which is essential to fully leverage the potential of 5G. The contribution and combined know-how of each of these companies have enabled the construction of a 5G infrastructure in all five cities.

> To illustrate how they operate the platform and technology infrastructure, consider the analogy of the human body: MNE2 functions as the circulatory system of the Internet, ensuring the movement of all information from one point to another, managing the flow of data, and maintaining internal connectivity. In comparison, MNE1 represents the endpoints of the system, akin to the sensory organs—like fingers and eyes—that capture sensations and information, enabling data transmission through the antennas. **MNE2 Manager**

Similarly, the other three multinationals have provided essential contributions and expertise that complement the infrastructure built by INNOV5G and enrich its global offering. MNE3 has strengthened SME products and solutions in the security, transport, aerospace and cybersecurity sectors. MNE4 improved bandwidth by integrating photonics. MNE5 proposed an innovative mobile solution facilitating video communications between technicians, control centers and mobile resources. Together, these combinations of expertise from each of the multinationals have strengthened INNOV5G 's infrastructure and offering.

However, the multinationals involved in INNOV5G, recognizing their lack of expertise in ecosystem coordination and partnership formation, have delegated this responsibility to specialized intermediary organizations: RII1 and RII2 in Province A, and RII3 in Province B. In addition to this responsibility, each of these organizations is tasked with managing one of the programs proposed by INNOV5G. RII1, with its expertise in business financing, is responsible for the Subsidized Technological Initiatives program. For its part, RII2 is committed to promoting the adoption of 5G technology through the Partnership and Innovation Program. In Province B, RII3 assumes all the roles of RII1 and RII2.

Establishing appropriate governance

The complexity of INNOV5G's structure stems from the large number of multinationals and government bodies that make up this alliance. This organizational heterogeneity complicates decision-making, coordination and ensuring compliance with established standards and regulations. To meet these challenges, our interviews revealed the importance of two established governance mechanisms.

First, the composition of INNOV5G's Board of Directors has been carefully structured to ensure balanced representation. For each province involved in the project, the board includes a representative from a major company and an SME, as well as a member from the academic sector. The majority of voting members are not from the company's partners. This configuration ensures that all partners are fairly represented, promoting diversity and full integration of the various players in the ecosystem. Second, to ensure effective governance of INNOV5G, a non-profit organization, NPO_GOV, was created specifically for this initiative. NPO_GOV acted as a financial intermediary between governments, industrial partners, SMEs and universities. One of its missions was to manage government funds, ensuring a fair and efficient allocation of resources to SMEs and universities. The governments of Province A and federal government entrusted NPO_GOV with the task of redistributing these funds, ensuring fair distribution in line with project agreements. In Province B, the management of funds allocated by the provincial government was entrusted to RII3 because of their extensive experience in this field. A subsequent agreement between NPO_GOV and RII3 enabled the latter to also act as distributor of central government funds in the province.

NPO_GOV also assumed financial supervision of the contracts between the main partners and the governments. The partners submitted their claims to NPO_GOV, which then distributed the government funds to the partners as appropriate. It also ensured that the value created by SMEs was not captured by large multinationals. In addition, NPO_GOV coordinated a series of activities to ensure smooth collaboration between all the organizations involved in INNOV5G program. These activities included frequent meetings bringing together key players for updates and the sharing of essential information. These meetings, held at least every two weeks, sometimes intensified to weekly frequency, particularly in crucial phases of the project. The aim was to synchronize participants, facilitate the exchange of information and resolve issues encountered during the project.

4.5.2 Sensibilization to mobilize and attract new members

The second dimension revolves around the ability to mobilize and attract potential members.

Spreading necessary knowledge

To attract new players to join INNOV5G and raise awareness of 5G in the ecosystem, several communication mechanisms were put in place. One initiative was the formation of a communication committee by the innovation intermediaries (RII1, RII2 and RII3). This committee was also open to participation by multinationals interested in monitoring progress and understanding the challenges of communicating and raising awareness around 5G technology and INNOV5G's programs. The message from the mobilization partners had to be persuasive to encourage SMEs to take an interest in INNOV5G's offering. The emphasis was on communicating a sense of urgency about adopting this technology, highlighting the opportunities it presents both in the short and long term for businesses. It was also about highlighting the uniqueness of the benefits offered by INNOV5G to pique the curiosity of SMEs, encouraging them to discover how 5G technology could help their development and expansion by joining INNOV5G program.

> It's important for SMEs to understand that the adoption of new technologies like 5G is not a distant future, but an imminent reality. It's not enough to talk to them about these issues; it's important to make sure they truly recognize the urgent need to prepare and adapt. **CEO, Canadian startup specializing in aerospace software development**

Several strategies were implemented to raise awareness among members of the ecosystem. First, classic communication tools were used. These included newsletters, which regularly circulated targeted information on 5G technology and INNOV5G program directly to SME members of the research intermediaries responsible for raising ecosystem awareness.

Specific information sessions and presentations for each vertical sector, such as healthcare, smart cities, video games, etc., were organized. Webinars were set up to detail the potential of 5G and present what the INNOV5G's platforms can offer SMEs. These sessions also offered participants the opportunity to put their questions directly to the experts present. The approach to raising SME awareness of 5G technology and the programs offered by INNOV5G also includes an active presence on social networks and multinational websites, where specific information on 5G and the opportunities and incentives offered by INNOV5G are regularly published.

Mobilizing by inspiring

Another key strategy of INNOV5G to raise awareness among SMEs of the potential of 5G is to highlight those that have developed innovative solutions thanks to INNOV5G. This is achieved by showcasing the best projects at special events, such as the demo days organized by INNOV5G. In addition, video clips of these demonstrations are broadcast on the website, and companies are invited to share their experience and present their projects during webinars.

In addition, INNOV5G organized information sessions to explain the importance of 5G and present its infrastructures and resources. These half- or full-day sessions offered SMEs an introduction to 5G, its applications and benefits, while facilitating exchanges with experts and guiding discussions towards potential projects.

Next, INNOV5G set up an intensive program offering an immersive, hands-on experience. The aim of the program was to enable participants to ask specific questions and motivate companies to develop concrete projects exploiting 5G. The emphasis was on the practical application of 5G through interactive workshops, with a focus on key sectors such as healthcare, smart cities and transportation.

To spread knowledge and interest in 5G more widely, INNOV5G implemented another awareness-raising strategy at formal and informal external events. In partnership with various trade associations, INNOV5G was invited to present the opportunities offered by 5G technology at training days, galas and professional meetings. These collaborations have helped to broaden discussions and exchanges on 5G, reaching a wider audience.

Although raising awareness was primarily the role of intermediaries (RII1, RII2 and RII3), the multinationals in INNOV5G also contributed by taking part in various events and using social media to promote the program. The heads of the innovation hubs hosting the infrastructures also helped to mobilize their members. However, awareness-raising efforts had to overcome a few challenges. A major obstacle was the lack of explicit demand for 5G among SMEs. Many SMEs did not see 5G as an immediate necessity, being faced with more pressing priorities. This limited their perception of 5G's potential benefits and transformative impact.

> Among the SMEs we support, only a minority, operating in niche sectors, spontaneously consider solutions such as 5G. This reality stems from a situation where, despite the considerable potential of 5G, many SMEs are focused on more pressing innovation priorities. **Representative of an IT research center, collaborating with a multinational in INNOV5G**

> We go out with a hammer and look for nails. **Manager of a company specializing in traffic lights**

Furthermore, effectively communicating the significance of 5G was challenging due to the technical nature of the technology and the diverse range of its applications. To achieve this, the outreach teams had to simplify their discourse, using more accessible terms such as the Internet of Things, edge computing, millimeter waves, and bandwidth optimization. This adaptation ensured that the communication was aligned with the needs and level of understanding of different SMEs.

4.5.3 Experimentation

Our results have highlighted the importance of this aspect as a key orchestration mechanism for INNOV5G. To facilitate this process, INNOV5G has provided dedicated experimentation spaces for 5G technologies, as well as incentives to encourage organizations to use 5G infrastructure.

Providing spaces

For many SMEs, investing in testing and experimentation phases in preparation for the adoption of emerging technologies, such as 5G, with no guarantee of tangible results or market launch obligations, represents a major challenge. One way to raise awareness and interest in this technology among SMEs is to make experimentation accessible and secure.

INNOV5G has established a culture of experimentation, setting up state-of-the-art technology platforms for testing at innovation hubs in both provinces to enable pre-commercial 5G experimentation. These platforms, which are accessible free of charge, aim to involve several hundred SMEs in each province. SMEs can experiment and test their solutions and products to solve their technical challenges before the commercial deployment of 5G.

> It helped us not only to test the technology and ensure the quality of our tool. We were able to discover missing functions and test the limits of our solution. **CEO of an immersive technology SME**

To ensure the protection of their intellectual property during experimentation, SMEs retain their rights to their innovations, except in the case of joint projects with multinationals, where intellectual property is negotiated. This policy guarantees the security of their innovations, eliminating the fear of undue appropriation.

Additionally, INNOV5G ‘s technology platforms provide a neutral, open platform. They are independent of telecom operators, enabling all SMEs, regardless of their usual telecom operator, to participate without fear of favoritism or restriction. The admission process is transparent, with an initial technical assessment by infrastructure providers, followed by a final evaluation by a committee of independent experts.

Our interviews indicate that 5G experimentation encountered challenges due to the evolving nature of infrastructures, which did not include all 5G features from the outset. For example, millimeter bands were not immediately available, complicating testing for SMEs.

> The main challenge encountered is technological, linked to the fact that 5G is not yet fully deployed in INNOV5G. This prevents us from maximizing our presence on social networks and asserting that our solution is 5G-compatible. **CEO of an immersive technology SME**

Some have postponed their experiments until 5G is fully available, while others have used an almost 5G (4.5G) environment to advance their projects. This has dampened SMEs’ initial enthusiasm for 5G experimentation.

Providing incentives

A key mechanism for attracting SMEs to test or develop their 5G solutions on INNOV5G platforms is to offer dedicated funding. Various INNOV5G programs, such as “Subsidized Technological Initiatives”, “Partnership and Innovation Program”, “Collaborative Research Initiative”, and “Skills Enhancement Program”, provide financial support, requiring SMEs to contribute at least 50% of project costs.

In addition, some SMEs in need of talent and expertise, such as master’s and PhD students, have also been able to benefit from additional funding. With the participation of RII4, INNOV5G funding can reach 75% of the total project cost, instead of the usual 50%, when SMEs engage students in their 5G projects. Interviews show that funding was the key factor in attracting SMEs to engage in 5G projects within INNOV5G.

In addition to funding, INNOV5G offers SMEs ongoing technical support within the technology platforms. As soon as a project is accepted, an initial meeting is organized to explain how the platform works, and the specific tests involved. The technical expert presents the facilities and test sessions, while the SME representatives outline their project and expectations. A detailed understanding of projects helps to detect compatibility problems and clarify SME expectations.

A technical manager is always on hand to help companies use the platform and answer any questions they may have, allaying concerns about a lack of technical skills and enabling specific problems to be dealt with and other difficulties anticipated.

Another important incentive is administrative support. For SMEs, resource constraints, both in terms of time and personnel, are a major obstacle to engaging in external programs, such as INNOV5G program.

Administrative support begins with the application process. The complexity and administrative demands of applying for admission and claiming reimbursement can deter SMEs from seizing these opportunities. To address this, personalized administrative support is offered to SMEs joining INNOV5G. Innovation intermediaries provide essential assistance to SMEs in preparing their application files, ensuring that all necessary elements are included. They review applications, suggest improvements and strengthen certain aspects of the application to ensure a complete dossier is submitted. In addition, innovation intermediaries organize informative and preparatory workshops to help SMEs submit their applications. These sessions aim to dispel doubts, validate and refine proposals before their final submission, ensuring that applications are meticulously prepared and comply with established criteria and expectations.

Administrative support to facilitate the reimbursement process was also considered from the outset of the project. The creation of NPO_GOV was intended to simplify the refund application process for SMEs.

> The fact that NPO_GOV acts as an intermediary with the government is an advantage, simplifying interactions that would otherwise be too complex if everyone had to communicate directly with the various levels of government. This consolidation makes communication more uniform and efficient. **Head of one of the multinationals in INNOV5G**

As an intermediary between SMEs and government bodies, NPO_GOV aims to speed up the redistribution of government funds. By acting as a single point of contact, NPO_GOV makes it easier for SMEs to navigate the reimbursement process, ensuring that claims are handled more efficiently and quickly than if companies had to deal directly with government agencies.

Despite NPO_GOV's intervention, feedback gathered during our interviews shows that the measures put in place were not sufficient to fully meet the needs of SMEs. One recurring criticism concerns the complexity of the claim's reports, which seem to be designed more for the requirements of large companies than for those of SMEs. The latter, often limited in terms of time, human and financial resources, were faced with major difficulties in completing long and complex claims.

In addition to the complexity of the reports required, another significant problem was the length of reimbursement times. SMEs expressed frustration at the long delays, which impacted on their cash flow and their ability to pursue their projects smoothly.

> Managing the financial claim was extremely difficult. The first claim was so arduous that I almost gave up on the project. At a certain point, it just didn't seem worth it. It became a major burden, to the point where I seriously considered abandoning it, as it was becoming absurd to spend three weeks preparing a claim. We're a startup, so I don't have a 20-strong accounting department at my disposal to deal with these tasks. **CEO of an SME specializing in software development**
>
> It was a real nightmare there, you know? We're supported by other funding organizations where everything happens easily online: you submit your claims on a platform, and a week or two later, the money is in your account. With NPO_GOV, it was a constant struggle. We're talking about several months' waiting before the money arrived. In hindsight, I talked to them about it, underlining the risk for companies: as a start-up, the absence of cashflow is critical. If the expected money doesn't arrive, we turn to the bank. But after two rejections, the bank says no, and that's really the end of it. **CEO of an SME specializing in frequency test automation**

To address this issue, specialized claim report validation teams were set up. Their mission was to accompany SMEs through the submission process, to avoid claim rejections by government authorities and maximize the chances of accelerated reimbursement. In addition, question-and-answer workshops were organized on a monthly basis to provide precise guidance on how to fill in the claim forms, and to offer a platform where SMEs could clarify any queries, they may have about the claims process.

> Thanks to these measures, we have managed to reduce rejection rates to a very low level of 1%. **NPO_GOV Manager**

Another important incentive is access to specialized human resources. SMEs are often faced with a shortage of human resources, which can hamper their ability to prepare for the adoption of new technologies, or to test and experiment with their ideas. To overcome this problem, INNOV5G, in collaboration with RII4, is proposing a solution to bridge this gap in specialized skills. RII4 makes available Masters and PhD students with specific expertise in various fields. This initiative offers SMEs the opportunity to hire these talents to bring their projects to completion, while benefiting from dedicated funding to pay for these talents.

4.5.4 Providing collaboration opportunities and market access

Collaboration accelerates the development of new ideas and technologies, facilitating the emergence of an innovation ecosystem. Commercialization opportunities also play an important role in the emergence of an innovation ecosystem, enabling the creation and appropriation of value.

Promoting collaboration

Most of the programs offered by INNOV5G are collaborative in nature, including the “Partnership and Innovation Program”, the “Collaborative Research Initiative”, and the “Skills Enhancement Program”.

The Partnership and Innovation Program requires several SMEs to collaborate with a beneficiary entity, such as a large company, a university, an NPO or students. This creates a diversity of collaborative projects between different types of organizations. INNOV5G offers specific funding for these projects, making it easier to pool efforts and launch new collaborative projects. Additionally, this program has facilitated companies in reestablishing connections with partners who were seeking collaborative opportunities, thereby offering them the necessary platform for such engagements.

> I would even say that INNOV5G has simplified collaboration with our partners by providing financial support. When there’s money, everything is easier. **CEO of an SME specializing in augmented reality**

Innovation intermediaries can also help bring together organizations wishing to undertake a partnership project but lacking partners.

> It was essential to establish connections, sometimes identifying and finding missing expertise within other companies in our ecosystem. **RII2 Manager**

The Collaborative Research Initiative project also offers SMEs the opportunity to collaborate with multinationals. Funding is offered to SMEs selected to participate in these projects. Multinationals publish challenges on INNOV5G website, corresponding to specific 5G issues they wish to address in collaboration with SMEs. In addition, SMEs seeking additional resources can apply for access to talent and funding via the Competency Building Program. Through these programs, INNOV5G provides SMEs with numerous opportunities for collaboration.

In addition, events organized by INNOV5G and experimentation sessions at innovation hubs enable SMEs to meet other companies, opening the door to new collaborations. Some employees of founding multinationals or innovation intermediaries have also facilitated the introduction of SMEs to potential partners, although this is not part of their official mandate.

Despite these initiatives, our interviews reveal mixed opinions. Some SMEs hoped to establish partnerships with multinationals and other ecosystem players by participating in INNOV5G. Those who had tested their solutions in non-collaborative programs thought that INNOV5G would facilitate networking with other players.

> We exploited INNOV5G's platform to present our technology and to access other potential companies with which to establish partnerships...This was not the case. **Manager of an SME specializing in printed circuits**

The message from INNOV5G was not clear to some SMEs, who were unaware that their project would be limited to testing their solution on the platform. Although some people took the initiative to facilitate meetings, this was not included in the main objectives of INNOV5G. As a result, collaboration opportunities were limited for many SMEs.

Commercialization

Our interviews reveal that INNOV5G has set up several internal and external initiatives to support the commercialization of companies' 5G products and services.

Internal initiatives

INNOV5G enables SMEs to test, develop and demonstrate their technological solutions, thereby strengthening their credibility and attractiveness to potential customers:

> I demonstrated the effectiveness of my solution on a 5G network, which has been operational without interruption for a year, reinforcing its credibility and usefulness in the eyes of my potential customers. Using the 5G network for demonstrations enabled me to showcase the capabilities of my software live, offering tangible proof that it works. This experience was crucial for marketing, attracting attention for grants and investments. Thanks to this strategy, we have attracted the interest of many international customers. **CEO of an SME specializing in latency measurement**

INNOV5G also created a marketplace section on its website to promote the 5G projects tested and developed on its platform. In addition, events, webinars and information sessions were organized, attracting key players from the ecosystem and high-level policymakers, benefiting from extensive media coverage.

> At the information session, we had the opportunity to meet with representatives of the municipality, who then helped us get in touch with some of the telecom operators with whom it collaborated. **Manager of an SME specializing in printed circuit boards**

Additional efforts have been made to promote SMEs through video capsules, newsletters and the organization of events.

External initiatives

Several SMEs count telecom operators among their main customers or intermediaries. Faced with the absence of telecom operators among its main partners, INNOV5G has established Memorandums of Understanding (MoUs) with several 5G initiatives led by telecom operators. These MoUs enable operators to discuss business opportunities with SMEs in INNOV5G and offer interested SMEs the chance to participate in 5G initiatives led by these operators, with the aim of facilitating commercial collaborations.

Among these initiatives is a 5G laboratory, the result of cooperation between a company and a telecom operator, specifically geared to a particular sector. SMEs affiliated to INNOV5G and selected by this laboratory benefit from the opportunity to test their technology on the operator’s premises. These products or solutions could potentially be of interest to the operator, offering SMEs a valuable chance to gain direct access to a telecommunication operator.

Another example is an urban 5G initiative that brings together all the telecom operators in a major city in Province A. The aim is to create a space for experimentation to assess the challenges of deploying 5G infrastructure and the applications it supports. As a result of this agreement, certain SMEs within INNOV5G, with the approval of operators, can conduct tests in real-world conditions, thereby facilitating potential commercial collaborations. Another agreement has been established with a joint laboratory between a telecom operator and an innovation hub, offering SMEs the opportunity to develop their solutions in collaboration with one of the major telecom operators.

Some SMEs involved in INNOV5G program also benefited from a 5G initiative in collaboration with a major innovation incubator and international telecom operators. This initiative offered SMEs a platform to present their solutions to an operator interested in Canadian startups, exploring 5G business cases and applications:

> Of the seven companies that participated in the program with this operator and carried out tests, four or five had previously collaborated with INNOV5G. **IH1 Manager**

However, the number of SMEs in INNOV5G that were able to participate in these external initiatives was very limited. The vast majority did not have the opportunity to discuss business with telecom operators. Additionally, some of these initiatives were severely delayed by the pandemic, meaning that SMEs that had applied or already been accepted had, for some, still not begun their discussions with operators.

Interview results show that opinions are divided regarding INNOV5G ‘s contribution to facilitating market access for SMEs. Several of them point to insufficient exposure of their projects by INNOV5G, and a lack of efforts to actively promote their technologies to potential investors, customers and partners:

> We thought we’d develop a good network of contacts with telecoms operators and their customers, but it hasn’t turned out as hoped. **Manager of an SME specializing in printed circuit boards**

Our interviews reveal that, when the initiative was launched, the primary focus was not on commercialization or market access, as the context did not lend itself to this. Instead, the focus was on establishing a pre-commercial network enabling SMEs to familiarize themselves with 5G and test their product before the technology was officially deployed. Also, the performance indicators (KPIs) defined in INNOV5G ‘s contract with governments were not adapted to the commercialization context and focused more on attracting SMEs to the program than on commercializing their solutions or developing them on a larger scale.

Another marketing challenge highlighted by SMEs is customers’ perception of the added value of 5G, and the question of whether they should bear the additional costs associated with this technology. Many do not perceive the direct benefits of this technology for their operations. With their needs currently met by existing bandwidth and 4G, the value of upgrading to a faster connection is not obvious to them:

> When we detail the costs associated with 5G, our customers often choose to go with our traditional radio technology, because of the cost of 5G. **Manager of an SME specializing in IoTs in the smart city sector**

Finally, the still partial deployment of 5G by telecoms operators in Canada is an obstacle for SMEs, limiting their access to the market and their ability to attract potential customers and users. This situation reveals a mismatch between the ambitions of INNOV5G and the market conditions that have evolved with operators, where concrete 5G applications remain out of reach for the time being.

4.5.5 Ecosystem resilience

Finally, our results highlight the importance of “ecosystem resilience”, which involves adapting orchestration processes and mechanisms to external changes. INNOV5G faced unforeseen challenges due to the COVID-19 pandemic.

Adapting internal mechanisms

With the onset of the pandemic and the implementation of government restrictions, crisis committees were established to identify and implement appropriate solutions. The aim was to enable the program and ongoing projects to continue despite government restrictions. These challenges had to be managed while respecting evolving rules concerning space occupancy and reopening conditions. The aim of these meetings was to align all partners with a common vision and coherent information in times of uncertainty. In the innovation hubs housing the technology platforms, experts and members of the mobilization committee relayed information to SMEs.

Adapting sensibilization strategies

During the pandemic, the ecosystem's awareness of 5G technology encountered numerous obstacles. Assembly bans prevented the organization of events where innovation intermediaries could promote 5G and INNOV5G programs. Various types of information sessions could no longer be held. Also, the interruption of activities in INNOV5G test beds made the mobilization mission more difficult. The main argument for attracting SMEs was access to the test sites, and without this access, the promotional message lost its relevance.

To address this, outreach efforts shifted online, using numerous webinars. While this transition allowed outreach to continue, it limited the personal post-event interactions essential for in-depth discussions. Webinars were effective in presenting the features and potential of 5G but lacked the spontaneous interactions that occurred at face-to-face events. Despite these limitations, INNOV5G was able to continue its mission of raising awareness of 5G despite government restrictions.

Adapting experimentation strategies

During the pandemic, government measures led to the closure of sites, including those housing INNOV5G's test beds, preventing SMEs from conducting their tests. Roadblocks and curfews also made it difficult for SMEs from other cities to access the sites. Spaces dedicated to INNOV5G projects within multinational companies were also affected. For example, MNE2's spaces for collaboration between students and SMEs were closed due to restrictions, eliminating opportunities for cooperation and test preparation.

Even when the sites were not constantly closed, alternating between open and closed periods according to government decisions, their accessibility was hampered by other restrictions. The number of authorized persons was reduced to one or two simultaneously, and measures such as wearing masks, making appointments and signing health declarations were mandatory, complicating experimentation:

> When you're confined to a server room with masks, the heat rises quickly. It was far from ideal. **CEO of an SME specializing in software development**

To overcome the difficulties created by government restrictions and simplify testing for SMEs, INNOV5G adapted its terms and conditions, allowing SMEs to carry out their tests outside buildings as well as remotely. The remote access offered was severely limited, severely restricting testing possibilities. SMEs were able to connect to the network remotely to complete only a fraction of their projects. However, for more thorough and effective testing, physical presence on site was essential to take full advantage of network coverage. However, the introduction of remote access enabled SMEs to continue their work remotely, accessing their applications, making configurations and preparing for future tests. In this way, when they were able to visit the site, they were able to start work immediately without the need for further adjustments, as everything was already prepared in advance.

Adapting strategies to provide opportunities for collaboration and market access

The pandemic has considerably affected the commercial aspects of SMEs. Introducing new products, penetrating new markets, and promoting innovative technologies became particularly challenging without face-to-face meetings, travel, and participation in industry events.

5G initiatives aimed at increasing SME visibility among potential customers were also impacted. The pandemic delayed these initiatives, preventing SMEs from testing their solutions with telecom operators, thus delaying their access to the market. Our interviews reveal a drop in motivation and a slowdown in momentum for SMEs:

> This period was marked by a slowdown in initiatives, a demobilization of players and the departure of some participants, complicating the resumption of activities. This context not only delayed projects, but also altered the dynamism and initial momentum of developments. **Head of one of the 5G initiatives that collaborated with INNOV5G**

This is also corroborated by the testimony of a participant who applied for this initiative, who said:

> We thought the project had come to a complete standstill... Currently, the tests are scheduled to take place in August, September, and continue until December. So, between submitting the application and actually carrying out the tests, we've waited almost a year. **CEO of an SME specializing in augmented reality**

The pandemic also delayed the rollout of 5G in Canada, affecting SMEs ready to commercialize their solutions. The delay in the commercial development of 5G was a major obstacle. For example, the auction for the allocation of spectrum in the 3.5 GHz band, originally scheduled for December 2020, has been pushed back to June 2021. Facilitating market access and product commercialization for SMEs was not among INNOV5G ‘s initial objectives. However, some SMEs were expecting this kind of support. The pandemic has exacerbated difficulties in this area.

Adapting to ecosystem members issues

The pandemic has significantly affected the internal operations of SMEs. Several have had to postpone or suspend their projects with INNOV5G due to various complications directly linked to the pandemic.

SMEs adopted a survival mode, shifting their priorities towards short-term objectives rather than long-term investments, thereby relegating 5G technology to a lower priority. For many, the urgency was to stabilize their financial situation, pay salaries, and prevent the closure of their operations. Some sectors, such as digital arts, were harder hit than others, with activities coming to a complete standstill.

Supply chain problems have also caused delays or the abandonment of 5G projects. Rising costs and delivery delays have directly affected 5G projects with INNOV5G:

> As part of the project, we encountered difficulties in sourcing 5G equipment, making it more difficult to acquire 5G modems and equipment, including some modems or phones. **CEO of an SME specializing in latency measurement**

Labor shortages, exacerbated by the pandemic, were also a significant challenge. For example, international students recruited for collaborative projects found themselves unable to participate due to visa delays and airport closures.

All these complications led to significant delays or the complete shutdown of certain projects. INNOV5G was unable to control the impact of the pandemic on the SMEs participating in its program. To mitigate the negative impacts, it decided to extend the duration of its program. This extension was intended to compensate for the interruptions suffered by SMEs and redirect funding to those able and motivated to launch new projects or improve their solutions.

4.6 Discussion and conclusions

This study explores how temporary structures orchestrate the emergence of an innovation ecosystem. Our analysis is based on a case study centered on 5G technology. We conducted interviews with 53 key actors within the 5G ecosystem connected to INNOV5G and supplemented this with secondary data sources. Figure 4-2 presents a comprehensive framework summarizing our key findings, focusing on three main aspects: (1) the establishment of a collective temporary structure for orchestrating the pre-emergence phase of the innovation ecosystem, (2) the orchestration mechanisms essential for a temporary structure during the ecosystem's emergence, and (3) the resilience dynamics associated with collective temporary orchestrators. Our findings offer several theoretical and managerial contributions.

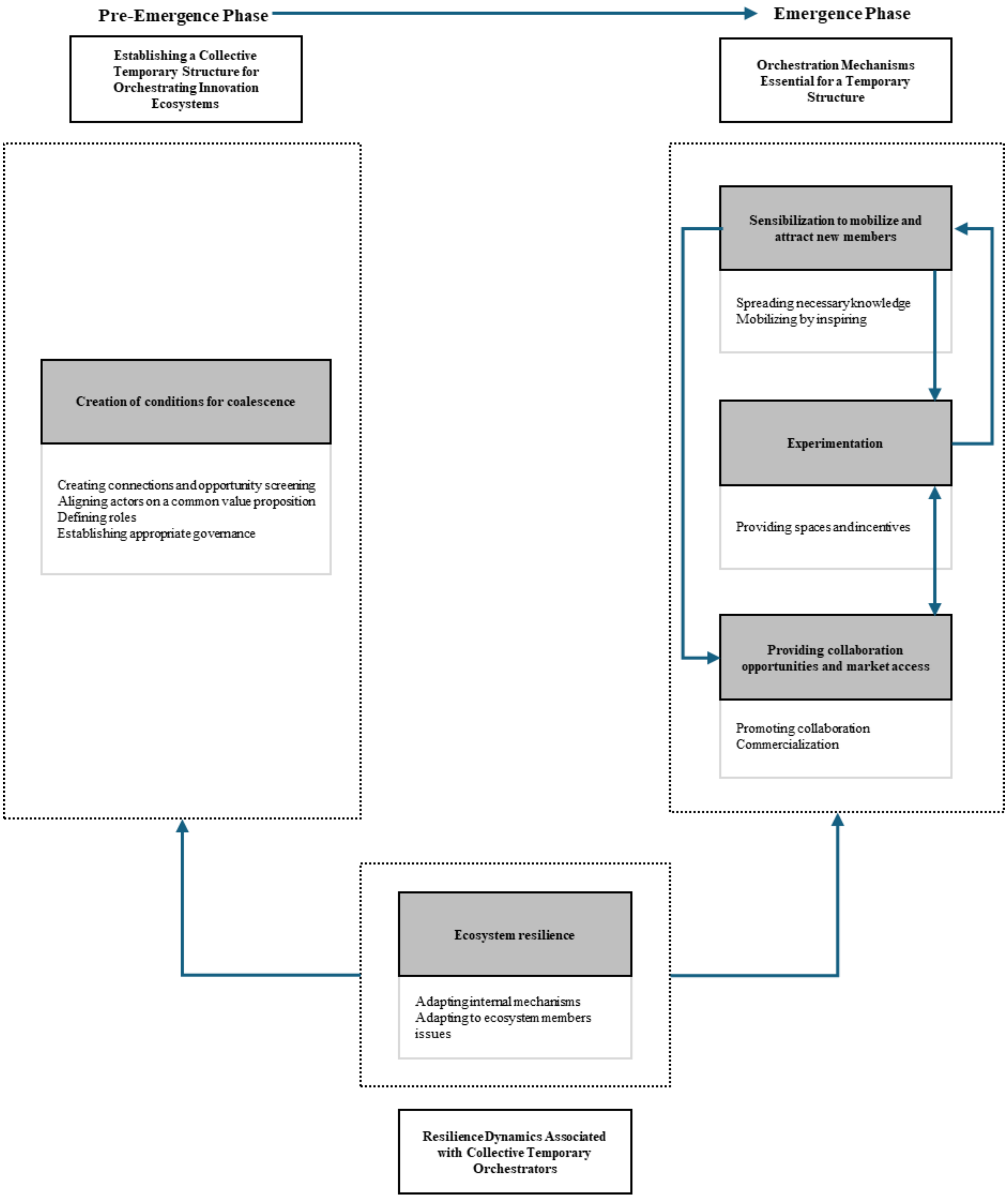

Figure 4-2. Temporary structures as orchestrators of emerging innovation ecosystems

4.6.1 Theoretical implications

The value of establishing a collective temporary structure during the pre-emergence phase of ecosystems

Our study highlights the importance of the pre-emergence phase in orchestrating innovation ecosystems, emphasizing the benefits of adopting a temporary structure to actively engage key stakeholders during this crucial period. Unlike traditional models where a central entity, often referred to as a "leader" (Moore, 1993), "platform leader" (Gawer & Cusumano, 2002), or "keystone" (Iansiti & Levien, 2004), unilaterally proposes the ecosystem's vision and design from the outset and subsequently attempts to align other key actors (Adner, 2017), our study presents a different approach with more collaboration from the start. We show that key stakeholders can collaboratively and proactively negotiate the vision, design, and roles in the future ecosystem right from the pre-emergence phase. This collective foresight helps address potential divergences or issues earlier, effectively laying the groundwork for the ecosystem's emergence, a phase that is inherently volatile.

For example, in our case study, we observed how a diverse group of actors, including multinationals, governments, and research intermediaries, came together in workshops and meetings to deliberate on the next opportunity. Together, they selected 5G technology and defined each party's roles, leveraging their respective expertise to ensure functional complementarity. Additionally, some of these multinationals, who are competitors in other markets, joined forces to co-design the upcoming ecosystem. This collaboration, facilitated by the temporary nature of the structure, enabled coopetition, an important characteristic of ecosystems (Moore, 1996; Bacon et al., 2020; Xin et al., 2023), as the actors were not bound by long-term commitments and pursued specific short-term objectives.

Establishing ecosystem governance from the pre-emergence phase is essential in such a complex environment. Managing governance among multiple key stakeholders, each with their own interests and viewpoints, collaborating within a temporary organization is more complex than in scenarios where a single firm acts as the hub orchestrator. Our findings align with Dedehayir et al. (2018), demonstrating that establishing governance mechanisms ensures participants adhere to their roles, coordinates internal actions among the key layers of the temporary structure, and enforces rules governing resource flows between partners. For example, in our case study, the partners chose to assign governance responsibilities to a newly created nonprofit organization specifically established for this purpose. This entity played an important role in ensuring coordination between the multinationals and the government for funding and claims, enforcing IP rules, and organizing events and information sharing among partners. Establishing governance principles early on clarified the rules to follow and mitigated the risk of governance-related issues during the emergence phase.

Mechanisms of emergence in innovation ecosystems orchestrated by collective temporary structures

The literature primarily focuses on well-established innovation ecosystems, analyzing orchestration mechanisms often led by a single organization (Linde et al., 2021; Marheine et al., 2021; Cui & Han, 2022). Our study reveals that some of these mechanisms, observed in mature ecosystems, are also active during the emergence phase, even when orchestrated by a temporary structure. These mechanisms include coordination among members, establishing strategic partnerships, providing platforms, and offering incentives to encourage joining the ecosystem.

Our study has also identified specific mechanisms that could be particularly effective when applied within the context of orchestration by temporary structures compared to permanent firms. One key mechanism is the potential for temporary organizations to enhance the “power of attraction” (Cohendet, 2021) within innovation ecosystems. For instance, in the case of INNOV5G, the assembly of highly influential and widely recognized actors within the ecosystem may have significantly bolstered the project’s legitimacy. This heightened legitimacy was an important factor in attracting members to join the initiative. Furthermore, our study shows that the opportunity to collaborate directly with these internationally well-known actors, grouped within the same organization, represents an attractive prospect for new members. These prominent actors can provide cutting-edge technologies and advanced knowledge, which are invaluable resources for smaller members. Additionally, collaborating with such high-profile partners can significantly enhance the credibility and visibility of smaller members, offering them a marketing advantage and helping to establish their reputation within the ecosystem. Our interview results indicate that some members joined specifically for these reasons.

Another mechanism highlighted by our research, which could be effectively facilitated within a temporary structure, is the cultivation of a culture of experimentation. Our findings align with those of Rinkinen & Harmaakorpi (2019) and Mahmoud-Jouini & Charue-Duboc (2017), who stress that the advancement of ecosystems is driven by continuous trials in environments that tolerate failure. In the case of INNOV5G, for instance, open-access platforms and targeted funding programs enable members to experiment with their products and services without the immediate pressure to succeed. While permanent organizations often focus on long-term stability and risk management, which can hinder the establishment of a culture of experimentation, temporary structures could be specifically designed to foster this culture. These structures provide a framework where the risks associated with experimentation are shared and mitigated.

Resilience dynamics in collective temporary orchestration structures

Resilience is recognized as a fundamental characteristic of innovation ecosystems (Iansiti & Levien, 2004; Thomas & Autio, 2019; Linde et al., 2021). Existing research has explored the resilience of innovation ecosystems across various settings (Floetgen et al., 2021; Liu et al., 2022; Chen & Cai, 2023; Wang et al., 2023; Abdi et al. 2024; Zhang et al., 2024). These studies provide valuable insights into how ecosystems cope with disruptions. However, they typically assess ecosystems as a whole, neglecting the impact of different types of orchestrators. Incorporating the concept of temporary structures as a distinct type of orchestrator, our analysis shows that such structures offer an alternative to traditional hub firm orchestration in managing external uncertainties and disruptions.

More specifically, our findings suggest that temporary structures, by bringing together diverse key stakeholders, enable dynamic and targeted interventions during the critical emergence phase of the ecosystem. Unlike a single orchestrating entity, which might operate with a singular perspective or limited resources, temporary structures leverage the strengths, expertise, and resources of multiple actors. This multiplicity of viewpoints and capabilities allows for more comprehensive problem-solving. As demonstrated by our case study on INNOV5G, the collaborative nature of these temporary structures facilitates resource pooling to tackle government restriction during the pandemic. INNOV5G modified its processes to comply with government restrictions and supported ecosystem members by forming a crisis committee to orchestrate collective efforts. Each partner in INNOV5G contributed according to their expertise, participating in a joint action plan that leveraged their individual strengths to share tasks effectively. The government adapted funding mechanisms to ensure continued support, despite the challenging conditions. Innovation intermediaries shifted their strategies to attract participants by organizing webinars and virtual events, ensuring ongoing engagement. Meanwhile, multinationals adjusted the technological aspects by enabling remote connections to the platform, allowing members to collaborate and access resources without the need for physical presence.

This ability to quickly adapt and respond, which can be challenging for large, permanent organizations acting alone as orchestrators, is made possible by the collective support and effort within these temporary.

4.6.2 Managerial implications

Our findings offer a guide for managers wishing to participate in building a temporary structure and orchestrate the emergence of an innovation ecosystem. Our study also highlights potential challenges that managers might face when using a temporary structure to stimulate the emergence of innovation ecosystems.

Managers can therefore draw insights from our study on how to engage stakeholders in discussions to identify and align on opportunities, which is crucial for defining the ecosystem's direction and establishing a shared value proposition. This step ensures that all participants are working toward common goals, which is vital for the ecosystem's success.

Managers can also gain valuable knowledge on how to implement clear governance mechanisms early in the process. These mechanisms are important for ensuring transparency in decision-making, equitable distribution of the value created, and preventing conflicts that could undermine collaboration. Establishing these structures from the outset helps maintain trust among participants and supports the long-term stability of the ecosystem. Additionally, managers could refer to our study for insights into orchestrating mechanisms during the emergence phase of the ecosystem. Our research suggests that a temporary structure could serve as an effective alternative to a single-entity orchestrator, particularly in navigating the complexities of the emergence phase. The study also highlights how temporary structures may offer greater resilience when facing external disturbances, providing a flexible framework that can adapt more readily to change than a permanent, single entity might. Our findings can also guide policymakers on how to effectively intervene in an emerging ecosystem. Policymakers should prioritize strategies that align key ecosystem players by encouraging collaboration and supporting initiatives that foster cooperation. In our case, government intervention was essential in forming a temporary structure, particularly through public-private partnerships and funding collaborative projects. In contexts where international competitiveness, cybersecurity, and geopolitical issues, such as those surrounding 5G technology, are critical, the government can play an important role in bringing together ecosystem key players. This could include promoting temporary structures that emphasize coopetition and prioritize the collective success of the ecosystem over individual interests.

4.6.3 Research limits

In their present state, our results do not allow us to generalize the conclusions drawn to other contexts or ecosystems. To address this, our approach could be applied in various national contexts to compare or validate our results. It would also be beneficial to carry out comparative studies including other technologies or ecosystems distinct from that of 5G. In this context, the comparative analysis of successful and unsuccessful cases could prove interesting. In addition, it would be relevant to broaden the spectrum of research by comparing the different forms of organization that assume the role of orchestrator during the emergence phase of an innovation ecosystem, beyond the framework of a public-private partnership as in our case.

Our study also has certain limitations in terms of sampling and data analysis. Future research could use a larger sample of organizations to validate our findings. For example, our study focused mainly on SMEs as organizations adhering to INNOV5G programs. The inclusion of a wider range of players, such as universities, research laboratories and government bodies, in future research could enrich our understanding of the emergence of the ecosystem. Furthermore, the data we have collected does not facilitate a detailed and accurate analysis of the impact of events organized by the temporary structure on specific mechanisms such as awareness, collaboration and market access. The informal nature of the interactions that occur during these events is a challenge in assessing their effects. In-depth studies, including observations and immersions, would be needed to shed further light on this issue.

Finally, quantitative studies will be relevant to empirically measure our results. Such studies could, for example, include statistical analyses to assess the effectiveness of the various support and incentive mechanisms put in place by temporary structures in the early phases of an ecosystem's life cycle. Such research would not only strengthen the validity of our findings, but also provide more precise, quantitatively based recommendations for actors involved in the construction and management of temporary structures aimed at fostering the emergence of innovation ecosystems.

CHAPTER 5 ARTICLE 2: POLITICIZING SCIENCE: HOW THE TURBULENT WATERS OF INTERNATIONAL POLITICS INFLUENCE 5G RESEARCH NETWORK

Anas Ramdani, Catherine Beaudry and Mario Bourgault

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5.1 Abstract

Geopolitical tensions, fueled by concerns of national security and espionage, are affecting international scientific collaboration. This research investigates how these conflicts are affecting the structural properties of 5G co-authorship network and international collaboration patterns. We extracted 21,124 papers on the fifth generation of mobile network technology (5G) from Web of Science. Using social network analysis, our results show a shift in collaboration patterns in 5G technology research between China and countries such as the US, UK, and Canada, coinciding with the period of geopolitical tensions. This shift was also reflected in changes to the network's centralization, with the network becoming less centralized. However, throughout this period of geopolitical tensions, the network consistently maintained its small-world properties. This research suggests that the recent geopolitical tensions between China and the U.S., along with its allies, may have influenced the structure of the international co-authorship network in the 5G domain.

Keywords: 5G, Geopolitics, Bibliometric Analysis, Social Network Analysis, Small-world network, Collaboration

5.2 Introduction

In recent years, geopolitical tensions have been rising around the world, especially between China and the Western nations. These conflicts have been particularly pronounced in the field of cutting-edge technologies, such 5G mobile network technology, where the US and several of its allies have banned Chinese firms like Huawei (Lee et al., 2022). In addition to having an impact on international relations, this unstable geopolitical environment has also penetrated the academic world (Shih et al., 2023). As a result, western nations are becoming less receptive to collaborating on scientific projects with scholars from other countries, particularly those in China. This shift emphasizes how important it is to determine how much these geopolitical issues are influencing the trends of international scientific collaboration.

Numerous research have been conducted in the literature on the relationship between recent geopolitical tensions and international scientific collaboration (Jia et al., 2022; Lee & Haupt 2021; Shih et al., 2023; Wang et al., 2023). Shih et al. (2023) conducted a comparative analysis of Sweden's and Australia's approaches to international scientific engagement during geopolitical tensions. The outcomes of this research highlight contrasting national strategies in managing research collaborations with Chinese entities. Also, Jia et al. (2022) show the impact of US investigations on the productivity of American scientists. Their findings show a decline in publications and citations for US scientists working with Chinese colleagues after the 2018 National Institutes of Health (NIH) investigations. Also, between 2019 and 2020, both the U.S. and China had fewer papers in areas most affected by these investigations, showing that political tensions impact scientific progress. Finally, the authors mentioned that scientists also expressed concerns about partnering with Chinese colleagues, fearing a loss of research quality and resources. Nonetheless, despite political concerns, Lee & Haupt (2021) demonstrated a steady rise in research collaboration between the US and China using Scopus co-publications over the previous five years. Additionally, their findings showed that in the previous five years, China's publishing rates would have increased without US engagement while US publication rates would have decreased in the absence of Chinese co-authorship. There is a specific gap in the literature regarding the influence of recent geopolitical tensions on the international scientific network and its structural properties, especially in the 5G domain, a technology that sits at the center of these conflicts.

Our study contributes to filling this gap by delving into the trends and patterns of international scientific collaboration over time (2014-2022), particularly in the context of rising geopolitical tensions. First, we explore how collaborations between countries, especially those between Western nations and China, are influenced by geopolitical dynamics. Second, our study assesses the response of co-authorship network properties to these geopolitical tensions. We focus on evaluating key structural properties, such as small-world characteristics and network centralization. Given the recent geopolitical issues centering around China, our analysis places special emphasis on the evolution of these measures in the context of bilateral collaboration between China and the U.S., as well as with some of its allies. This paper aims to investigate how geopolitical tensions may shape the domain of 5G mobile communication network technology research, a field at the nexus of innovation and strategic geopolitical interests. Considering this context, we formulate the following research question:

“What potential impact might geopolitical tensions involving China have on the patterns of international scientific collaboration in the field of 5G technology?”

Our investigation is conducted using a range of traditional SNA measures. We also analyze in detail the evolution of international collaboration for selected countries. This part of the research endeavors to detect any shifts in trends or patterns that might be linked to geopolitical impacts. Lastly, by tracking important metrics like the small-world score and network centralization measures over time, the effects of these conflicts on the structure of co-authorship networks are evaluated. These measures provide insight into how knowledge sharing within the network may have been altered in response to the evolving geopolitical landscape.

Our results show that throughout the time of geopolitical tensions, patterns and trends in collaboration changed. Our analysis indicates that China has reduced its collaborative efforts with the U.S. and some of its allies, such as the UK and Canada. Intriguingly, from the perspective of the U.S., the data initially showed an unexpected increase in collaboration with China during the geopolitical tensions, only to witness a recent decline. In terms of structural properties, there was a period of increased activity within the largest connected component, which subsequently stabilized, coinciding with the onset of geopolitical tensions. This shift is also reflected in the network’s centralization patterns, with the structure becoming less centralized around specific authors. However, a key observation from our study is that despite these shifts, the network continued to exhibit small-world characteristics throughout the period of geopolitical tensions.

The remainder of the article is organized as follows. The following section delves into the backdrop of these tensions, that justify our study. The paper then outlines the methodology, elaborating on the procedures and metrics employed to assess international collaboration patterns and trends in network structural properties. The subsequent section presents our findings. Finally, the paper concludes with a discussion and an in-depth analysis of the results.

5.2.1 Contextualizing recent geopolitical dynamics

In the realm of telecommunications, the tensions between China and the U.S. reached their zenith in 2018 during the Trump administration; however, the seeds of suspicion between the two nations had been sown even earlier. In 2012, as the 4G era emerged, the US House Intelligence Committee reported concerns about Chinese telecom firms like Huawei and ZTE, suggesting they might have surveillance connections to the Communist Party of China (Ruppersberger & Rogers, 2012). China perceives these actions as a broader strategy by the U.S. to impede its technological growth (Jaisal, 2020).

The tension between these nations reached a new height with the arrest of Huawei's CFO by the Canadian authorities, Meng Wanzhou, in December 2018, leading to heightened mistrust and scrutiny on Chinese tech firms on the global stage (Suh, 2019; Jaisal, 2020; Tang, 2020). The arrest of Meng Wanzhou in Vancouver marked the onset of heightened geopolitical tensions between Canada and China. In May 2022, after years of consideration, Canada ultimately decided to ban Huawei's 5G technology, a decision that followed an announcement in 2018 that it would examine the potential risks associated with adopting this technology amidst increasing pressure from allies, particularly the United States, due to national security concerns (Cecco, 2022). Before Canada's actions against Huawei, allies such as the United Kingdom had already initiated bans on the company. Several months after initially permitting Huawei a restricted role in its 5G networks, the United Kingdom changed its stance in July 2020 (Krolikowski & Hall, 2023).

The array of issues surrounding 5G technology, from its security implications to its potential for innovation, has led to a geopolitical contest, with nations engaging in a strategic rivalry to secure a leading position in this pivotal field. These geopolitical tensions are most pronounced between China and the U.S., along with its allies (Jaisal, 2020). The rise of Chinese tech Huawei in the 5G forefront has intensified these tensions, with concerns mounting over potential espionage opportunities (Jaisal, 2020; Ceci & Rubin, 2022; Creemers, 2020; Wu, 2020). Even though companies such as Huawei consistently deny these allegations (Mascitelli & Chung, 2019; Bown, 2020; Jaisal, 2020), the geopolitical reverberations have spread to other countries (Cheney, 2019; Jaisal, 2020; Tang, 2020).

Also, the geopolitical tensions surrounding 5G have not only affected governments and businesses but have also permeated the academic world. These tensions have created a negative atmosphere for international collaboration especially with China (Silver et al., 2019; Tollefson, 2019). According to Cao et al. (2020), China has seen an increase in research collaborations with the US and European countries up until 2017. However, with geopolitical tensions reaching a peak around this period, one must question how these tensions have affected the international scientific collaboration network, especially in the 5G domain.

5.2.2 Assessing potential geopolitical impacts on global network properties: small-world properties and network centralization

Several studies showed the presence of a small-world structure in co-authorship networks. For instance, Liu & Xia (2015) show that the co-authorship network's largest component in the multidisciplinary subject of "evolution of cooperation" has the characteristics of a small-world network. Their findings indicate that the development of the field of "evolution of cooperation" is marked by the expansion of the major component in its collaborative network. Starting with the combination of several local clusters, this main component has transitioned from a small cluster to a small-world structure. Andrikopoulos et al. (2020) investigated the existence of a small-world structure of scientific collaboration in auditing research. Their results show that the presence of the small-world phenomenon is influenced by star nodes. When these star nodes are removed from the auditing scholars' network, the small-world characteristic no longer persists. Ebadi & Schiffauerova (2015) measured the small world indicators of a Canadian natural science and engineering co-authorship network and assessed its relationship with the productivity and the quality of papers, and team size. They found that the network has small-world characteristics. In this network, connecting with field experts boosts team productivity and article quality, but is inversely related to individual publication frequency. While numerous articles have explored the small-world structure of co-authorship networks across various disciplines, there remains a notable gap in our understanding of how geopolitical tensions, in our case those between China and the U.S. concerning 5G technology, influence the persistence of this small-world structure in 5G co-authorship. Also, to further enrich our understanding of the 5G co-authorship network's structure, we examined the concept of network centralization. Network centralization is a measure that quantifies the extent to which connections in a network are focused around one or a few central nodes (Freeman, 1978). To assess how geopolitical tensions may influence the structural dynamics of scientific collaboration, evaluating small-world properties and network centralization is critical. This approach offers a comprehensive perspective on the changes that could occur within the international co-authorship network during periods of geopolitical tensions.

5.3 Data and Methodology

As suggested above, one of the best tools to assess international scientific collaboration combines bibliometrics as the quantitative analysis of research publications (Belter, 2015) and social network analysis (Zhuang et al., 2013) to understand the structure, characteristics, and trends of research activity. The paragraphs below describe the data collection and analysis used in this article.

5.3.1 Data collection

We extracted articles focusing on 5G technology in two distinct phases. The first phase, executed on October 31st, 2022, involved the retrieval of articles published up until the end of 2020. The second phase of data collection took place on July 7th, 2023, and included articles from the remaining months of 2022. Papers containing the term '5G' in the title, abstract or keywords were retrieved from Web of Science database and cover the period 2000-2022. We restricted our data extraction to the term '5G' reflects our desire to eliminate specific technologies not exclusively related to 5G, for example: millimetre wave, edge-computing, or massive-MIMO[18]. Then, to remove false positives, i.e. articles containing the acronyms "5G"[19] but which do not relate to the last generation of mobile communication, we manually examined each article (title, abstract and keywords) to exclude non relevant articles. After extracting all articles on 5G from Web of Science, we filtered out any entries that did not list their authors in the database. Subsequently, we found 21,124 articles related to 5G.

5.3.2 Networks construction and visualisation

For this study, two collaboration networks were constructed: the international collaboration network among countries and the co-authorship network. We constructed these two undirected networks utilizing two primary R[20] packages: igraph (Csardi & Nepusz, 2006) and bibliometrix (Aria & Cuccurullo, 2017). The former facilitated the direct transformation of databases extracted from Web of Science into an adjacency matrix representing collaboration among countries and co-authorship relationships. Meanwhile, the latter provided a suite of functions integral to social

[18] Multiple-Input Multiple-Output (MIMO).

[19] The use of the term '5G' is not exclusive to the fifth generation of wireless communication. For instance, several articles using the term '5G' referred to items containing 5 grams or 5 GHz. These articles were removed manually.

[20] R is an open-source software.

network analysis, encompassing node and network centrality measures, and cohesion metrics. The visualization of the networks was performed with Gephi.

5.3.3 International collaboration

First, for each of the articles, we determined whether it was a product of international collaboration, national collaboration, or was authored by a single individual. Utilizing the author addresses provided by the Web of Science, we identified the countries involved for each article. From this, we calculated the proportions of international, national, and single-authored papers within the entire article corpus.

Subsequently, we computed the proportion of international collaborations, domestic collaborations, and single-authored articles for each country. Taking Canada as an example, from all papers originating from the country - indicated by the presence of a Canadian author - we ascertained the ratio of international to domestic collaborations and the proportion of single-author papers relative to the entire corpus of Canadian papers.

Additionally, for each country present in our database, we calculated the proportion of its international collaborations with other countries relative to its total collaborations. In order to provide a more comprehensive picture of each country's research collaboration, we have opted to include both domestic and international collaboration. This methodology facilitates the comparison of the degree of international collaboration in the larger framework of a country's overall research collaborative efforts. However, a limitation arose from the dataset extracted from Web of Science. Specifically, while the dataset provides author addresses, it condenses identical addresses for multiple authors into a singular entry. For instance, in a paper with three authors, if two share the same affiliation and the third does not, our metadata would only display the shared affiliation once. This poses a challenge in discerning which affiliations or countries should be factored in more than once. This complicates the use of a fractionalized counting method, as we cannot accurately discern repeated affiliations for authors on the same paper. Also, this limitation presents a challenge in accurately assessing each country's contribution to collaborative research. To address this and factor in the country's weight in the collaboration, we adopted a different approach. Instead of counting each country once, regardless of the number of affiliations within that country, we considered each unique affiliation separately. Let's take the United States and Japan as an example to illustrate our approach. To determine the proportion of collaboration between the U.S. and Japan, we count each unique collaboration affiliation. For instance, if a research paper involves the U.S. and has two authors from Japan, each from a different affiliation, we count this as two separate collaborations. This count is then divided by the total number of collaborations (international and domestic) involving the U.S., giving us a weighted view of the U.S.-Japan collaborative relationship within the broader spectrum of U.S. research collaborations.

Finally, to pinpoint the most central countries within the collaborative network of countries, we employed social network analysis. More specifically, we leveraged the most used centrality measures in the literature: degree centrality, betweenness centrality, closeness centrality, and eigenvector centrality.

The degree centrality[21] of a node is the number of nodes that are directly connected to that node (Zare-Farashbandi et al., 2014). More central actors therefore collaborate more. Eigenvector centrality[22] is an extension of degree centrality that accounts for the centrality of the nodes to which a node is connected. For instance, a high eigenvector centrality score for a node means that the node is connected to other nodes that have high scores themselves (Bihari et al., 2016).

A node's betweenness centrality is described as the ratio of all geodesics connecting pairs of vertices that contain this vertex (W.de Nooy et al., 2005). Thus, a node with a high value demonstrates the importance of that node in transmitting knowledge and information between different groups in the network (Zare-Farashbandi et al., 2014). Thus, a node is more central if it is more often located between other actors, especially if it is positioned on the shortest paths between these network members. Closeness centrality[23] offers a metric to measure how much a node is close to all the other nodes in the network. Nodes that manifest higher values of closeness centrality are more central, suggesting their capability to connect with other nodes in the network in comparison to those with low centrality values (Freeman, 1978).

In our study, centrality measures stated above were measured for the largest network component only. First, it is easier to interpret and compare the results of centrality measures for nodes belonging to the same component. Second, closeness and eigenvector centrality measures can only be calculated in a connected network, i.e., for the principal component. In addition, the main

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[21] The R *degree()* function calculates the normalized degree centrality for each node.
[22] This measure is normalized and given by the function R eigen_centrality().
[23] The R closenness() function calculates the normalized closeness centrality for each node.

research activities take place mainly in the largest component of the network (Ebadi & Schiffauerova, 2015).

We considered all the countries from our database in the previous steps. However, for the purposes of brevity and relevance, this paper primarily presents the results from countries that demonstrated the highest productivity and centrality levels.

5.3.4 Structural properties of the co-authorship network

First, to investigate the structural properties of the scientists' collaboration network, we initiated by observing the evolution of the primary component's composition over time. In other words, this will enable us to determine whether the network is fragmented across different periods. Also, we conducted an analysis of the evolution of the main component of three distinct subnetworks within the global scientific collaboration network: China with each of its three major partners (U.S., UK, and Canada). Our goal is to determine whether ongoing political tensions surrounding 5G technology may have influenced the structure of the collaboration network among China and these countries. By analyzing the main component of each subnetwork over time, we aimed to discern whether there have been changes in the patterns and intensities of collaborations, potentially indicating shifts in the scientific partnerships due to the external geopolitical context. To carry out this investigation, we selected only those research articles that featured collaborations between a Chinese author and another author from either the U.S., UK, or Canada. For instance, when examining the evolution of the largest component of the co-authorship network between China and the U.S., we exclusively chose articles in which at least one author was affiliated with a Chinese institution and at least one other author was affiliated with a U.S. institution.

Second, we complemented this analysis by examining the network centralization of the co-authorship network to gain further insights into how knowledge is shared within the research community. According to Freeman (1978), network centralization is described as the extent to which communication predominantly flow through one or several members of an organization, rather than being evenly distributed amongst all. Network centralization has been measured in various ways in the literature. For this study, we expanded upon the four node centrality measures described before, applying them at the network level.

Degree centralization[24] explains how much network cohesiveness is centered around specific focal nodes (Bales et al., 2014). A network exhibiting high degree centralization is characterized by a limited number of nodes possessing numerous connections, with most nodes having minimal links. Essentially, this suggests that a minority of nodes predominantly govern the network's connections. High betweenness centralization[25] suggests that a select number of nodes predominantly influence the network's flow or act as key intermediaries within the structure. A network exhibiting high closeness centralization[26] is characterized by a limited set of nodes having a more efficient reach to all other nodes compared to the rest. A network with high eigenvector centralization[27] is dominated by nodes that are connected to other influential nodes. We have conducted an analysis of the evolution of network centralization measures for China co-authorship network and each of its three main partners: the U.S., the UK, and Canada.

Finally, another approach to assess the network structure and information flows within the network is by determining whether the network exhibits small-world network characteristics, and thus presents an optimal structure for a good knowledge diffusion. A short average path length value and a high clustering coefficient are characteristics of small-world networks. The network clustering coefficient [$CC_l(G)$][28] , in some cases called transitivity, is the ratio of the number of closed triangles to the number of triples in the network (Watts & Strogatz, 1998; Ebadi & Schiffauerova, 2015). In other words, the clustering coefficient measures how connected a node's neighbors are to one another (Hansen et al., 2020). The average path length [l_G][29] is the average number of links on the shortest path connecting any two of the network's potential node pairs.

To verify the existence of a small-world structure, it is necessary to compare these two properties with that of a random network[30] with the same number of nodes and approximately the same density as the original network. A small-world structure has the following two properties (Telesford et al., 2011):

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[24] The R function centr_degree() allows to calculate the degree centralization of a network.
[25] The R function *centr_betw()* allows to calculate the degree centralization of a network.
[26] The R function *centr_clo()* allows to calculate the degree centralization of a network.
[27] The R function *centr_eigen()* allows to calculate the degree centralization of a network.
[28] The clustering coefficient has been computed in R with the *transitivity()* function.
[29] The function R *mean_distance()* is used for the calculation of the average path length.
[30] Random networks are generated by the R function *erdos.renyi.game()*.

$$\frac{l_G}{l_{rd}} \approx 1 \; et \; \frac{CC_l(G)}{CC_l(rd)} \gg 1$$

Where $CC_l(rd)$ and l_{rd} represent clustering coefficient and the average path length and of a random network, respectively. It is possible to combine these equations to obtain the small-world variable SW, defined by the following equation:

$$SW = \frac{\frac{cc_l(G)}{CC_l(rd)}}{\frac{l_G}{l_{rd}}}$$

If SW[31] > 1, a small-world structure is present. We additionally investigated whether the co-authorship networks between China and each of its three main partners, the U.S., the UK, and Canada, exhibit small-world properties.

In presenting our findings, we chose to aggregate data in periods of 3 years rather than presenting them annually. First, it helps smooth out annual variations and better shows long-term patterns. Second, our emphasis is on discerning broader trends over time, and clustering data into these multi-year periods aids in highlighting these patterns more effectively. Last, such an aggregation simplifies the presentation, making visual representations more comprehensible and less cluttered.

5.4 Evolution of international collaboration

Figure 5-1 shows the evolution of the number of '5G' papers between 2005 and 2022. The first 5G paper appeared in 2005. From 2014, 5G research shows a strong annual growth that stabilizes to more linear growth in 2016 and thereafter. In 2022, there was a noticeable increase in the number of articles. This surge can be largely attributed to the update of the new version of Web of Science[32]. This update introduced a range of new journals, thereby enriching the database. Moreover, a

[31] In our study, we recognize the influence of network size on the small-world (SW) metric's sensitivity. We explored the use of a size-adjusted metric, as suggested by Telesford et al. (2011), which employs a latticization algorithm. However, we ultimately chose the conventional SW metric because the alternative method's computational demands were too high. Throughout our analysis, we have meticulously accounted for the effects of network size sensitivity to guarantee a precise interpretation of our results.

[32] Given the vast volume of historical data and the logistical constraints associated with re-extracting this data post-update, we maintained our original dataset for this period to preserve the integrity and continuity of our analysis. When analyzing the data, especially for 2022, we have considered the potential impact of the database's expansion on our findings, ensuring that our conclusions are drawn with an understanding of these contextual factors.

significant inclusion has been the articles from conferences "proceeding papers". These additions played a significant role in the rise in the number of articles for that year.

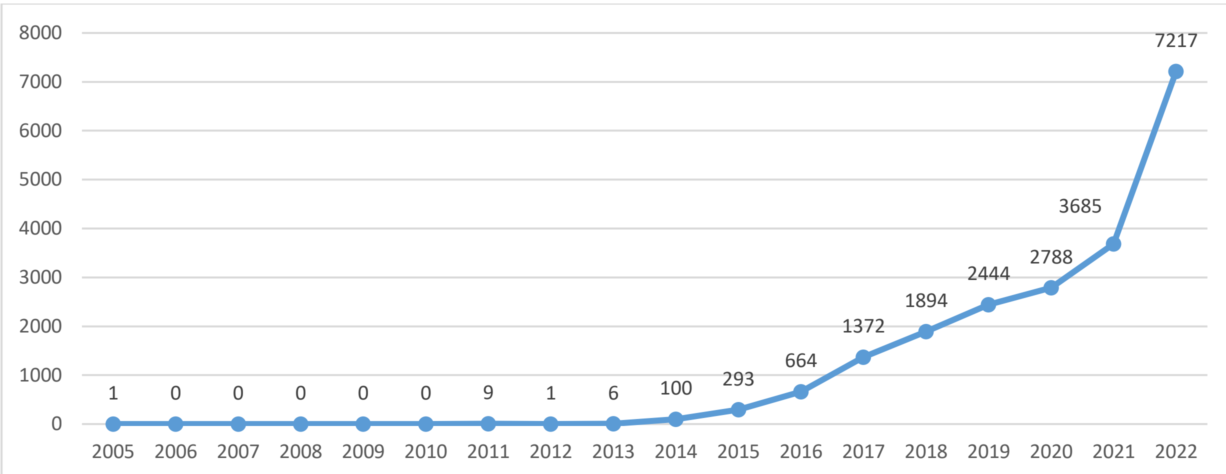


Figure 5-1. Number of papers per year

We opted to start our analysis in 2014, a decision informed by the volume of articles available: 2014 saw a notable increase, with over 100 articles published. As there are very few articles between 2005 and 2014, the results presented in the remainder of the article will focus on the period 2014-2022.

Table 5-1 presents the proportion of international versus domestic collaborations and single-authored paper in our entire corpus. Out of 20,704 papers, 36% were the result of international collaboration involving authors from different countries, 60% were co-authored by authors from the same country and 4% were single-author papers.

Table 5-1. Proportion of international collaboration

International Collaboration	**Domestic Collaboration**	**Single-authored paper**
7,476 (36%)	12,403 (60%)	825 (4%)

However, Figure 5-2 illustrates the slight decrease in the proportion of internationally collaborative papers over time. The latter represented 45% in the first period but only 33% in the last period. This negative trend in the proportion of international articles is accompanied by a proportional increase in articles produced by intra-national collaborations. Hence, the growth in number of publications observed over the period 2014-2022 is more attributable to intra-country than international collaboration.

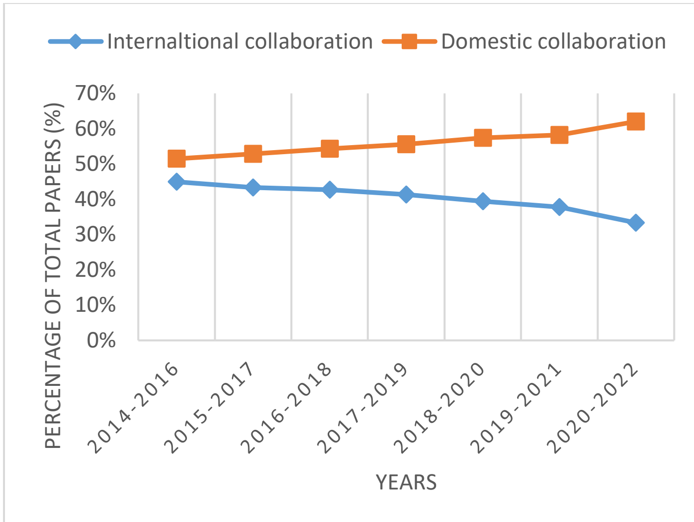


Figure 5-2. International collaboration

Table 5-2 presents the international publication rate for the top eleven[33] countries selected: i.e., China followed by the next ten most prolific countries (see Appendix A). Except for India, China, Japan, and South Korea, most of the other countries favor international collaboration.

Table 5-2. Intensity of co-authorship collaboration from 2014 to 2022

Country	Total number of articles	% of Total Articles		
		Multiple Countries (%)	Single Country (%)	Single-Authored (%)
China	6,835	**39%**	58%	3%
U.S.	2,873	61%	35%	4%
India	1,906	**33%**	65%	2%
South Korea	1,523	**47%**	50%	3%
United Kingdom	1,762	80%	18%	2%
Spain	1,131	60%	39%	1%
Canada	1,269	70%	29%	1%
Italy	985	65%	33%	2%
Finland	724	73%	26%	1%
Japan	748	**39%**	57%	4%
Sweden	672	77%	21%	2%

[33] The choice of the top 11 countries (rather than a more natural top 10) stem from the inclusion of Sweden where Ericsson is an important contributor to 5G technology.

To understand the decline in international collaboration for 5G research, we now analyze the trend by country. Figure 5-3 shows the evolution of international collaboration of these countries. China, for example, saw its proportion of international papers decrease from 52% in 2014-2016 to 42% in 2020-2022. Among the countries that prioritize international collaboration, only in Sweden did international collaboration grow over the period 2014-2022. Canada, the United Kingdom, and South Korea experienced a rather stable, slightly positive trend in international collaboration. Other countries, however, experienced a negative trend in international collaboration. These trends are marked from the 2016-2018 and 2017-2019 period.

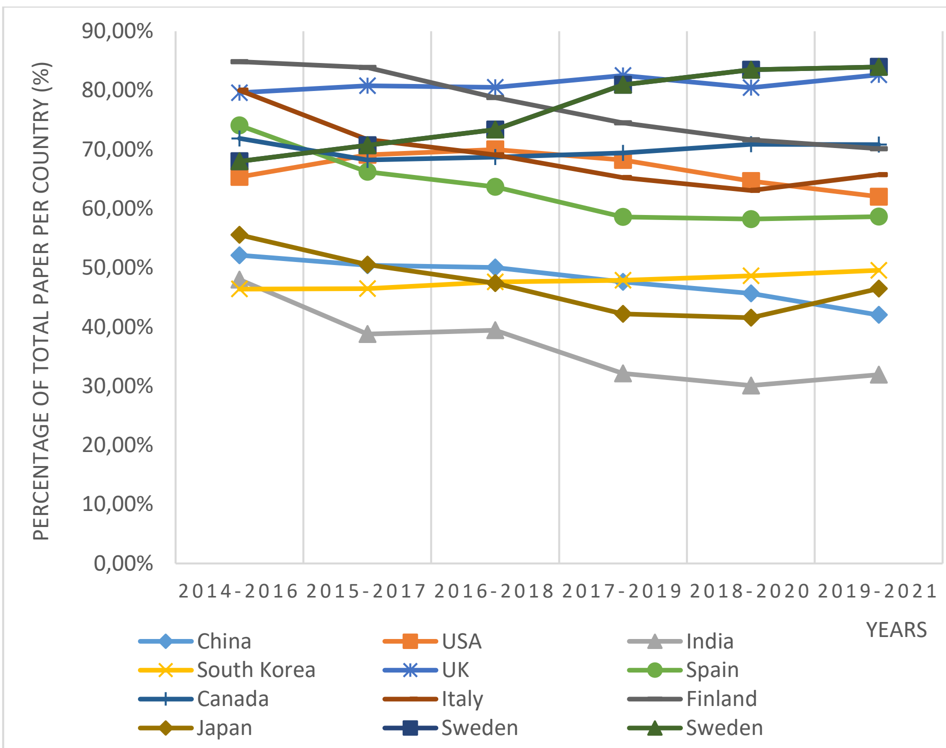


Figure 5-3. International collaboration by country

Table 5-3 shows the top three collaborators from the ten most productive countries. Note that the percentages represent the rates of papers co-published with author(s) from another country. For example, 19% of papers with one author from China are co-published with at least one author from the US. Thus, we notice that most of the countries in Table 5-3 have China as their first partner. Exploring the reverse point of view, i.e., the evolution of their collaboration with China and their main partners is also informative (Appendix A presents the collaborative trends over time of each of the countries with their main international partners). Figure 5-4 presents the international collaborations involving China and its three primary partners in the 5G research domain: the U.S., the UK, and Canada.

As far as North America is concerned, the United States is the first partner for China and vice versa. However, we note that the evolution of their collaboration does not seem to adopt the same trend. From China's point of view, collaboration with the United States exhibits a negative trend. The opposite case is true from the point of view of the United States, which experienced a marked growth in collaboration with China over the period. Despite the U.S. government's warnings to universities about collaborating with China around 2018, U.S. scientists continued to collaborate with Chinese researchers. Canada also experienced a decrease in collaboration with China from the period 2016-2018. The same is true for China in relation to its collaboration with Canada.

The picture is different for European countries. There was an increase in collaboration with China for most European countries during the first periods. Then, the trend reversed or stabilized in the 2019-2021 period.

In the Asian region, there was an increase in collaboration with China for Japan and India while the trend is reversed for South Korea especially from 2016-2018 onwards.

The observed decline in international collaborations with China may be attributed to various governments worldwide adopting stricter collaboration guidelines, particularly concerning partnerships with China.

Table 5-3. Top 3 countries partners

	Percentage of international collaborations		
China	U.S. (19%)	UK (14%)	Canada (9%)
U.S.	**China** (32%)	UK (6%)	South Korea (6%)
India	**China** (11%)	U.S. (10%)	South Africa (10%)
South Korea	**China** (15%)	U.S. (15%)	Pakistan (10%)
UK	**China** (26%)	U.S. (7%)	Spain (6%)
Spain	Italy (12%)	Germany (11%)	UK (10%)
Canada	**China** (32%)	U.S. (12%)	UK (6%)
Italy	Spain (13%)	Germany (9%)	France (8%)
Finland	**China** (10%)	U.S. (10%)	France (7%)
Japan	**China** (36%)	U.S. (13%)	Germany (5%)
Sweden	**China** (12%)	U.S. (9%)	Germany (8%)

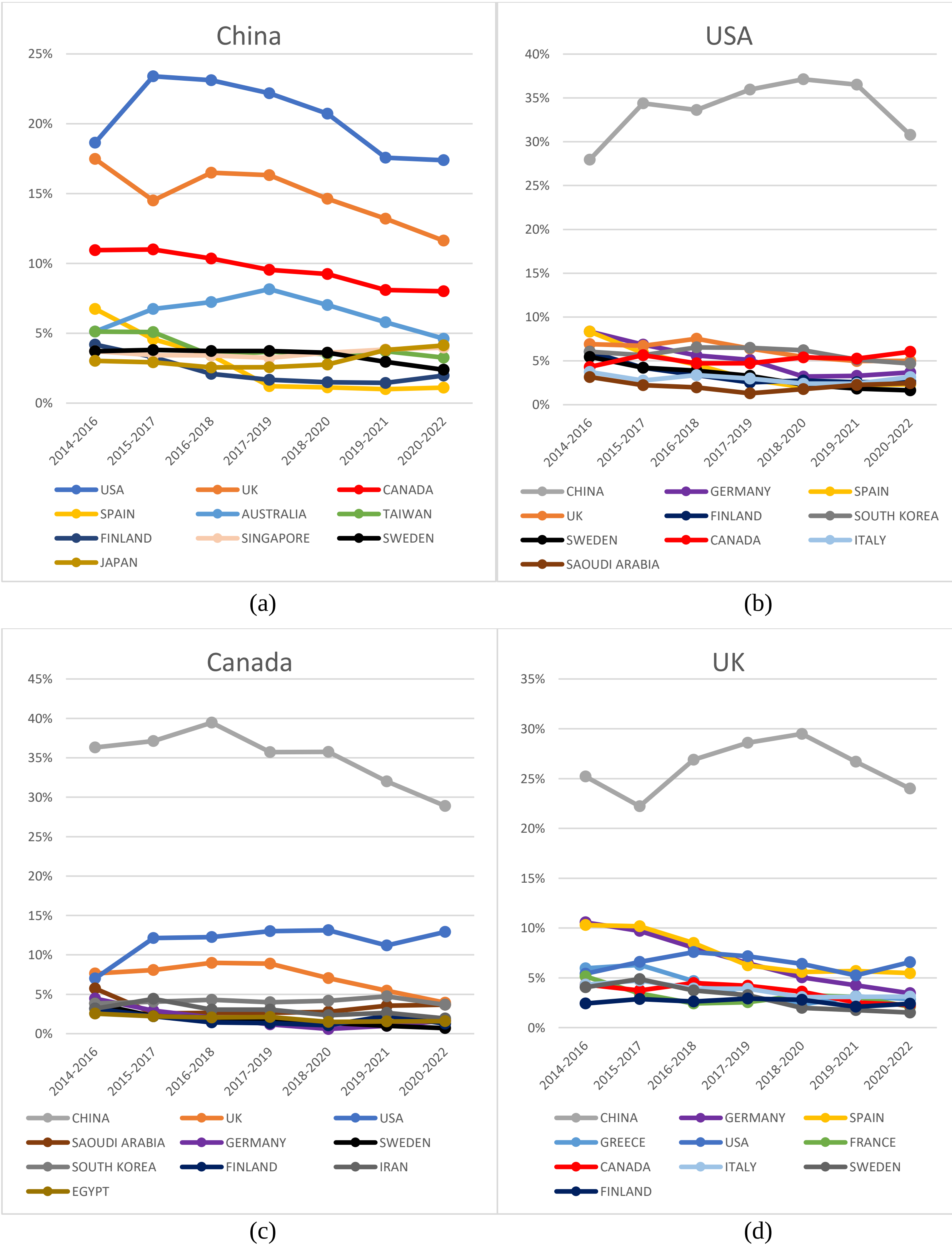


Figure 5-4. International collaboration for (a) China, (b) U.S., (c) Canada, and (d) UK

5.5 Evolution of countries centrality measures over time

Figure 5-5.a indicates that during the initial period, normalized degree centrality is on the rise for all countries, signaling an overall increase in international research collaborations. However, this trend does not persist; subsequent periods show a decrease or stabilization in normalized degree centrality for most countries, except for the UK, which continues to exhibit a positive trend. The UK's consistent position as the most central country in degree centrality is corroborated by Table 5-2, which shows it has the highest proportion of international publications, and by Figure 5-3, which confirms that about 80% of its publications are internationally co-authored, a rate that has remained stable over time. The centrality of the UK in the research collaboration network is further affirmed by its eigenvector centrality score, which is the highest, indicating that the UK is connected to the most influential countries.

China's degree centrality has seen noticeable increases, positioning it as the second most central country in the network. China's rise in degree centrality, surpassing the United States between 2017-2019, followed by a decline, aligns with its strategic pivot towards more intra-national collaboration, reducing its rate of international partnerships during the same period. China has also demonstrated a similar pattern in eigenvector centrality, with significant increases that have elevated it to the second-highest position, followed by a period of stabilization. Similarly, the United States saw a reduction in degree centrality from 2016-2018, reflecting a decreased engagement in international collaboration. The U.S. exhibits a slight downward trend in eigenvector centrality.

Canada's normalized degree centrality exhibits a slight negative trend from 2017-2019 to 2018-2020 that stabilizes in the latest periods, despite the proportion of international collaborative papers holding steady at around 70% from 2014 to 2021 (see Figure 5-3). Canada shows a constant trend in terms of eigenvector centrality.

Betweenness centrality (Figure 5-5.b), eigenvectors (Figure 5-5.c) and closeness centrality (Figure 5-5.d) were also calculated. The closeness centrality mirrors the exact pattern of degree centrality. Here again, UK, France, China, and the United States stand out in all three measures.

The betweenness centrality for the UK shows a fluctuating pattern: it decreased from 2014-2016 to 2017-2019, then rose from 2017-2019 to 2019-2021, only to decline again in the most recent period. China and France, much like the UK, also display a variable pattern in betweenness centrality. The USA, in contrast, maintains stability in normalized betweenness centrality, with a noticeable decrease observed between the periods of 2018-2020 and 2019-2021.

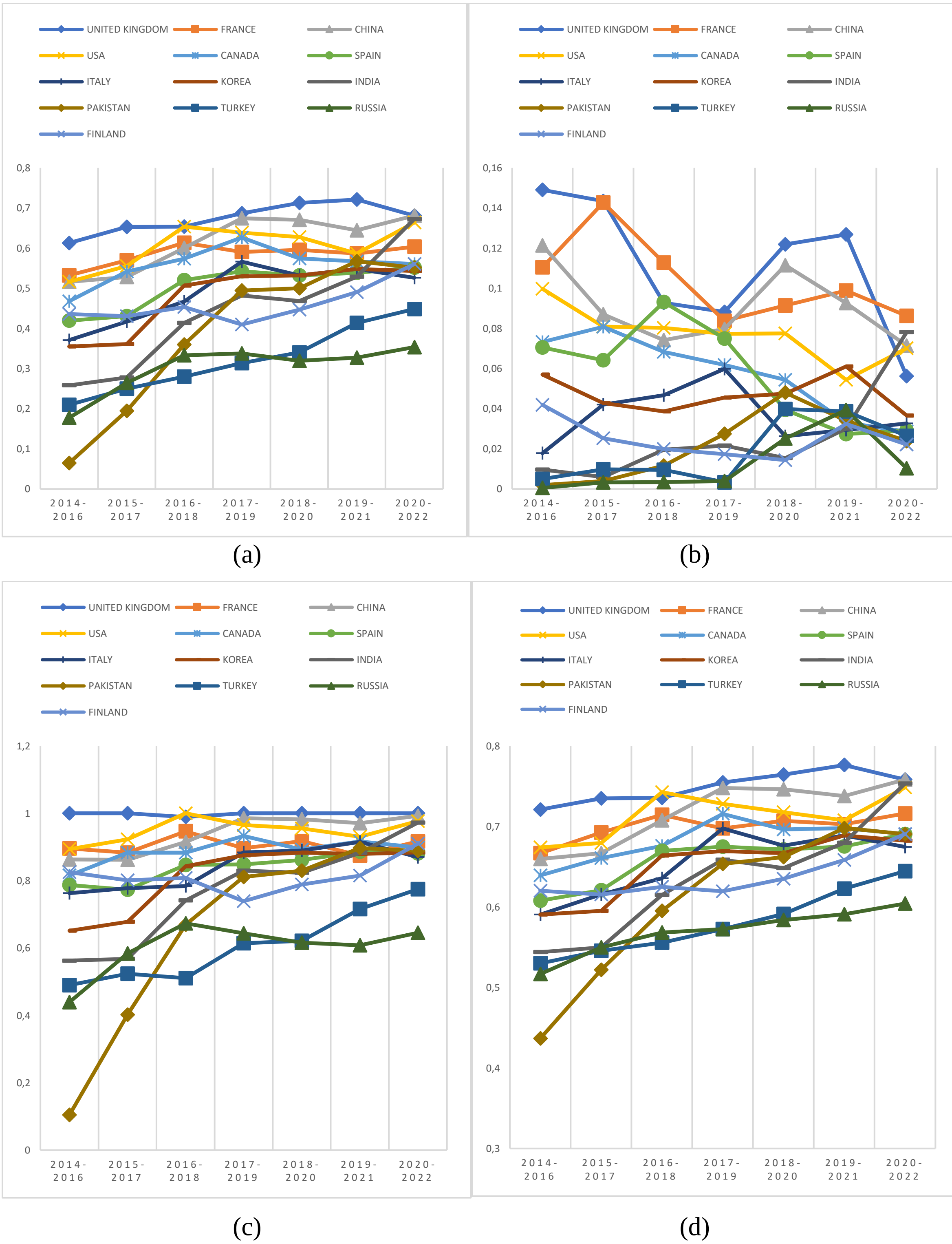


Figure 5-5. Centrality measures: (a) degree, (b) betweenness, (c) eigenvector, and (d) closeness

5.6 Co-authorship network results

Most publications in the 5G domain are the product of collaborative efforts (see Appendix A). Over the period of interest, the network exhibits a rapid expansion (see Appendix A). Figure 5-6 presents the evolution of the proportion of network nodes and edges that compose the main component. As the latter comprises more than half of the researchers and about 70% of the links, most of the collaborative activities occur in the main component. In examining the co-authorship network over time, we have observed an interesting trend. For the first three periods, there was a clear increase in the proportion of the main component of the network, indicating growing collaboration and interconnectedness among researchers. However, the stabilization becomes evident from 2018-2020 onwards.

Figure 5-7 illustrates the evolution of the main component of the researchers' network. After conducting a thorough examination of the fragmentation of the co-authorship networks over time, it is interesting to investigate whether the network structure of the main component has undergone any significant changes. To achieve this, we conducted an analysis of the network centralization metrics (See Figure 5-8). These measures provide insights into how connections are distributed within the network, complementing our understanding gained from the evolution of the composition of the main component. The results reveal notable shifts in the network's structural dynamics. Over time, we have observed a consistent negative trend in the degree, betweenness, and closeness centralization metrics of the network. This indicates a clear shift towards a more decentralized structure. Specifically, the decreasing trend in normalized degree centralization, starting around 2016-2018, suggests a more even distribution of connections among the nodes. As time progresses, the network's connectivity becomes less dominated by a select few scientists. Concurrently, the decline in both closeness and betweenness centralization, starting in 2018-2020, shows that specific scientists are no longer uniquely positioned to reach others more efficiently; instead, there is a growing equitability in the reachability of nodes. The eigenvector network centralization is consistently high and stable over time. In sum, the network is becoming more decentralized, but a few key scientists continue to hold significant influence due to their connections with other well-connected scientists.

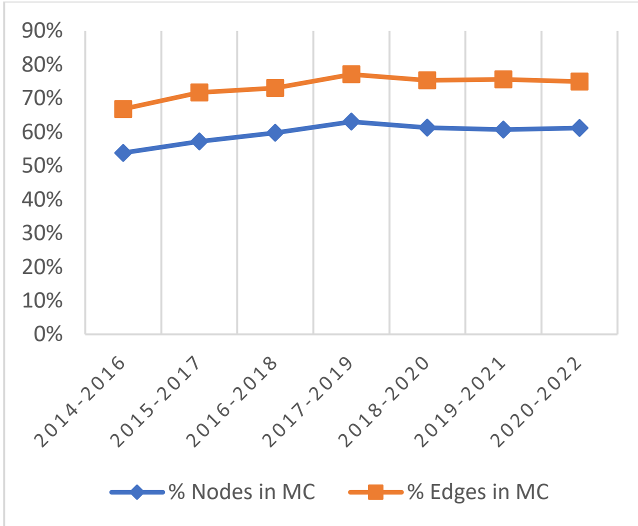


Figure 5-6. Proportion (%) of nodes (in blue) and edges (in orange) in the main component (MC)

The observed stabilization in the composition of the main component, accompanied by a trend towards decentralization, may be attributed to two potential explanations. First, the network may have reached a mature stage, as evidenced by the relative stability in the size of the main component despite the overall growth of the network. The decreasing centralization may further support this interpretation, indicating a network that has matured and become more balanced in terms of influence and connectivity. Second, the stabilization and decentralization of the main component could be influenced by external factors, such as geopolitical tensions, which might have affected the patterns of collaboration and interaction within the network.

To further investigate whether geopolitical tensions between China and the U.S., along with its allies, may have had an impact on collaboration among scientists, we next study the evolution of the structure of three co-authorship sub-networks involving Chinese scientists and their counterparts in China's top three partner countries. Specifically, we will analyze the CHINA-U.S., CHINA-UK, and CHINA-CANADA networks.

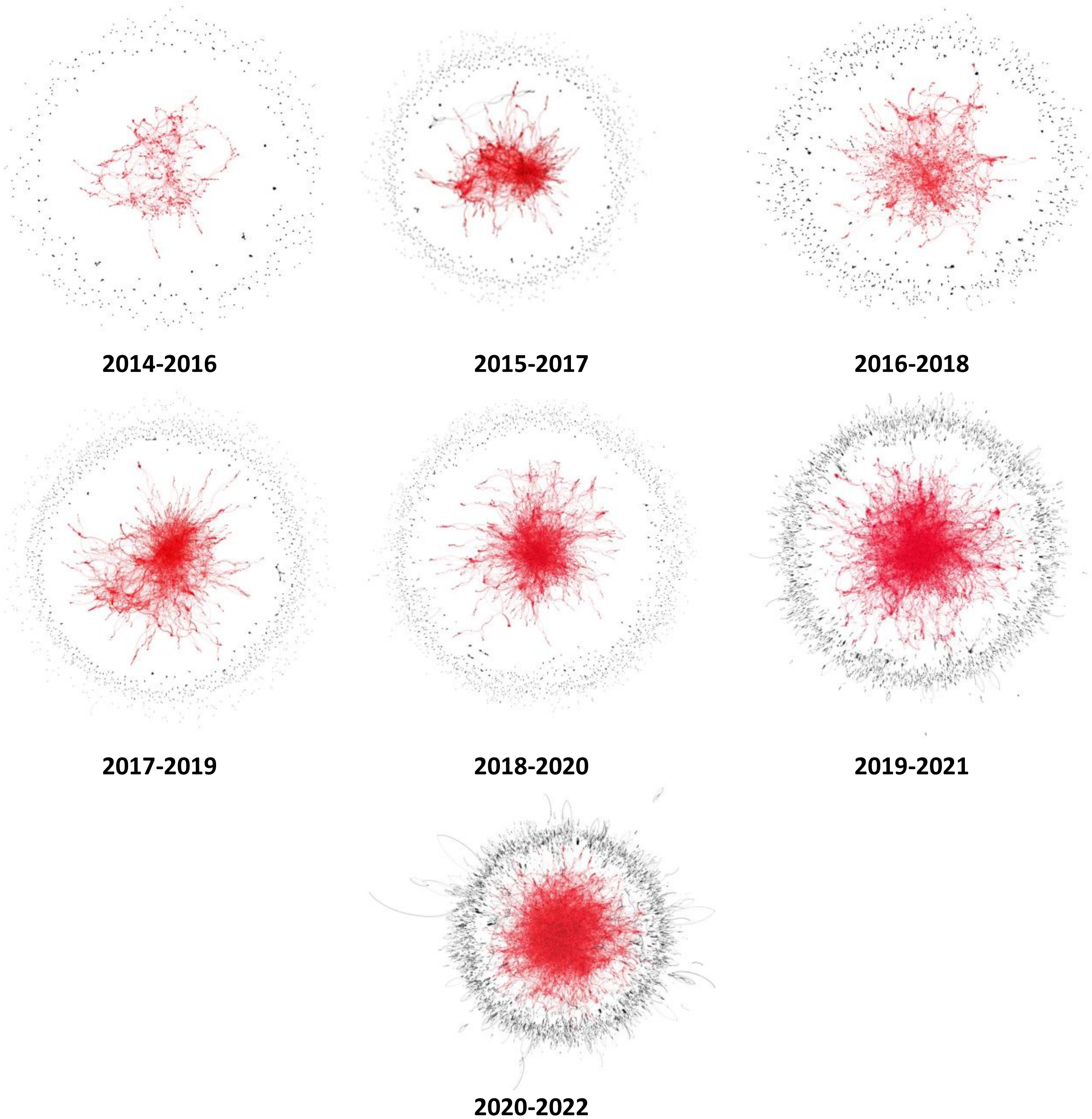
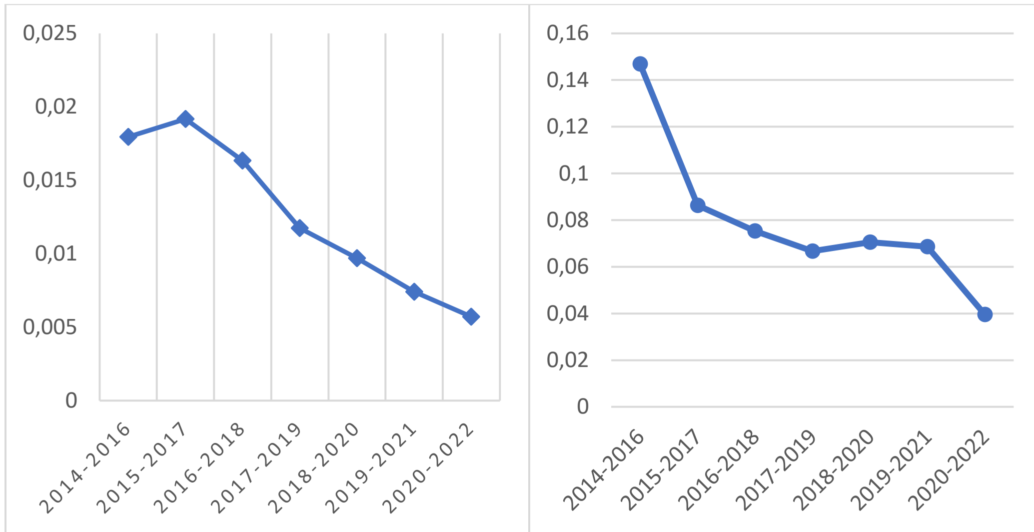
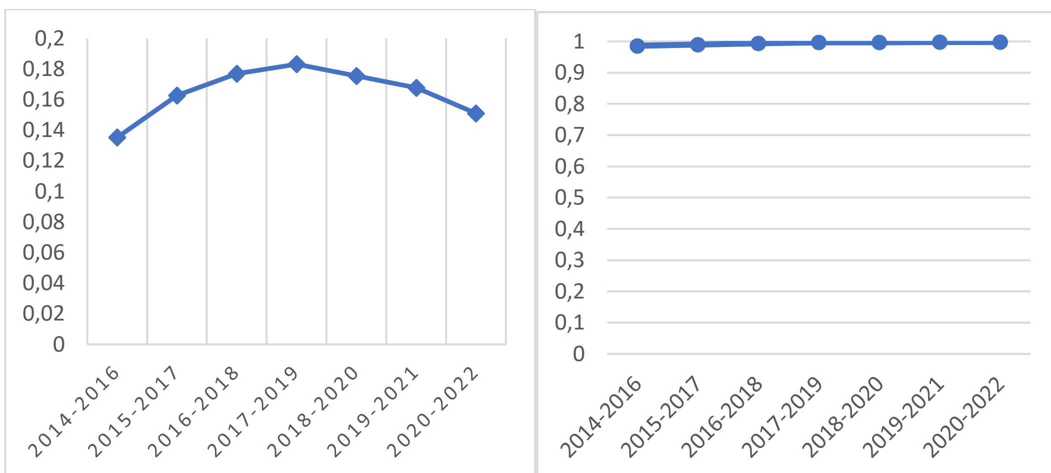


Figure 5-7. Evolution of the main component over time



(a) (b)



(c) (d)

Figure 5-8. (a) Degree centralization, (b) betweenness centralization, (c) closeness centralization, (d) eigenvector centralization

Figure 5-9 depicts the evolution of the nodes and edges that constitute the main component of China's co-authorship collaborative network with the U.S., UK, and Canada. Across all three networks, there is a noticeable expansion during the initial periods. However, beginning around 2018, a discernible trend towards fragmentation emerges. Interestingly, this year aligns with the peak in geopolitical tensions between the US and its allies, suggesting potential impacts on the collaborative dynamics. Also, the trend in the co-authorship networks between China and each of its three main partners, the U.S., the UK, and Canada, closely follows the same trend observed in the global network (see Appendix A).

While a fragmentation of the network begins around 2018, both the China-UK and China-Canada networks maintain lesser fragmentation, with over 50% of their nodes persisting in the main component; in contrast, the China-U.S. network exhibits a more pronounced fragmentation, with the main component encompassing only around 42% of the nodes in the 2020-2022 period. During this time, the US government and institutions started to exercise caution regarding collaboration with Chinese scientists, driven by security concerns over technological advancements in the 5G space. Additionally, the US government's lobbying efforts against Chinese tech giants, such as Huawei and ZTE, coupled with scrutiny over Chinese funding in universities, may have contributed to creating a negative environment not conducive to collaboration. As a result, it appears that the initial enthusiasm for collaboration was tempered, leading to the decrease of activities in the main component of these three co-authorship networks.

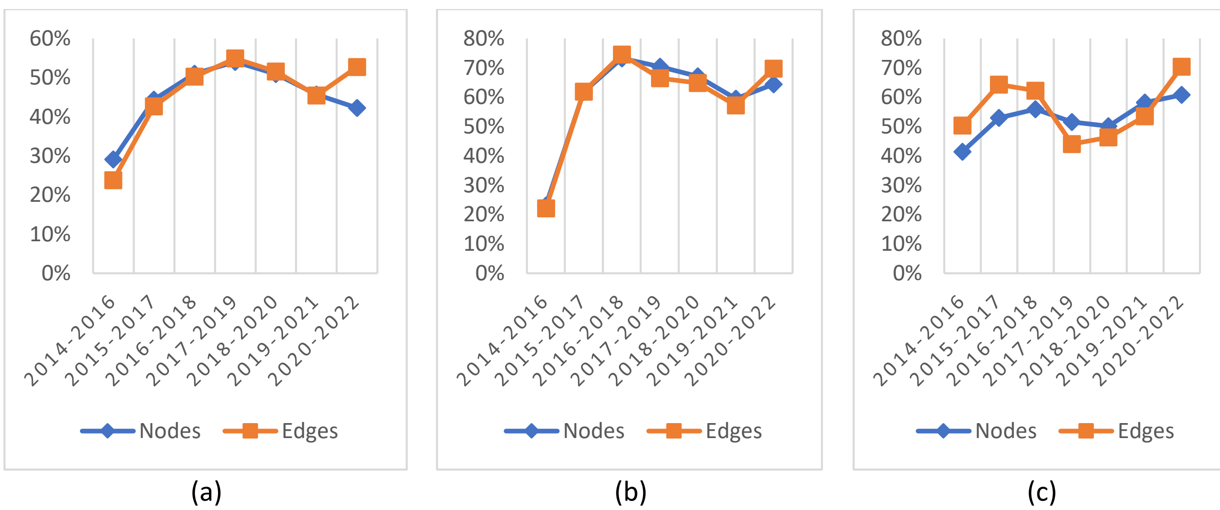


Figure 5-9. Proportion (%) of nodes and edges in the main component (a) China-U.S., (b) China-UK, and (c) China-Canada

Figure 5-10 shows the evolution of the main component of the China-U.S. researchers' network. As illustrated in Figure 5-10, the network cohesion appears to strengthen during the first four periods, with the largest connected component becoming progressively more dominant within the entire network. Conversely, after the 2017-2019 period, the trend suggests network fragmentation, as an increasing number of nodes are not included in the largest connected component. The evolution of the main component for the China-UK and China-Canada networks can be found in Appendix A.

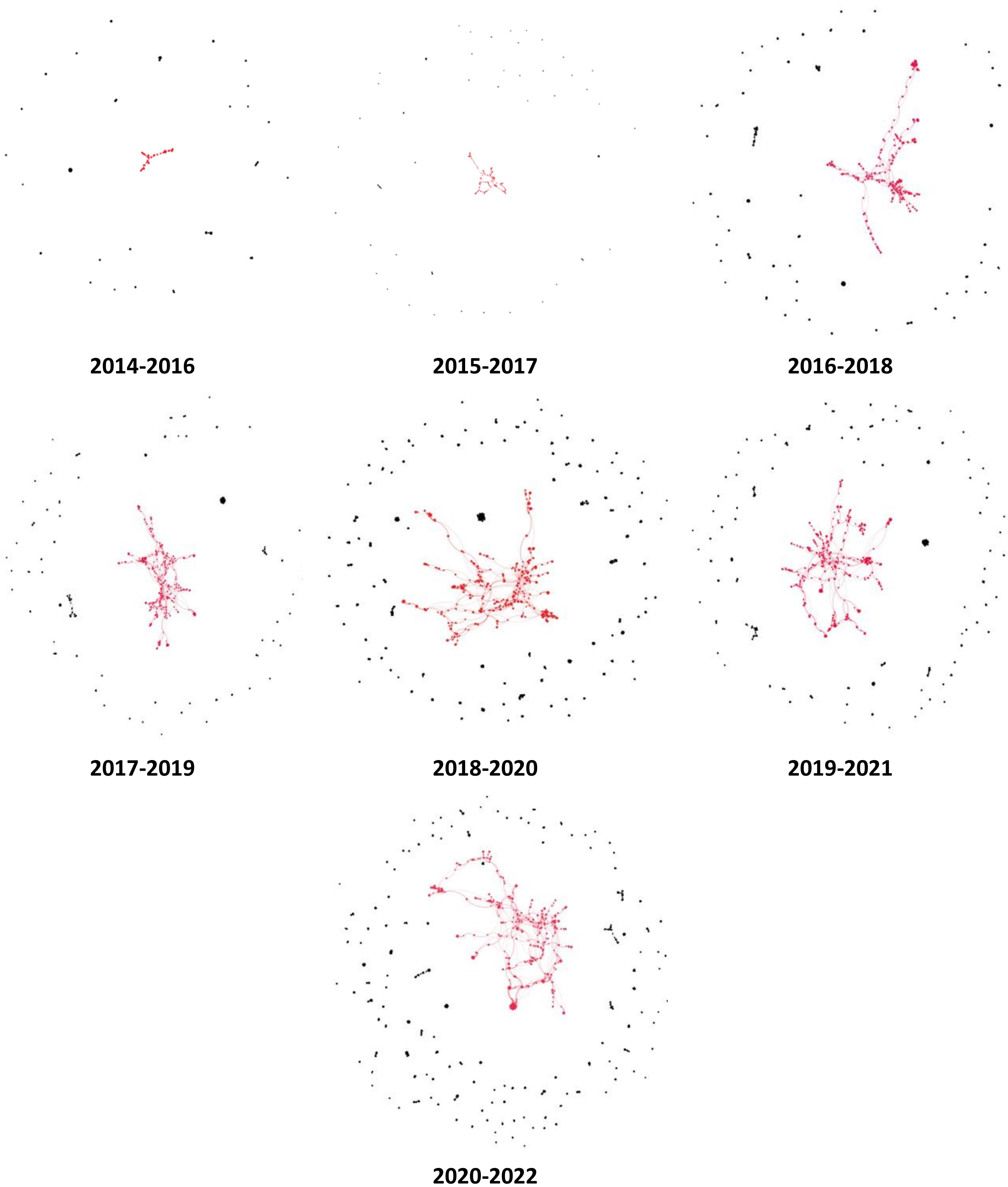


Figure 5-10. Evolution of the major component over for co-authorship network between China and U.S.

5.7 Small-world properties

Our results show that the small-world structure is present in the main component of the network year after year (see Table 5-4): the clustering coefficient (CC_l) is high and stabilizes at about 0.5

and significantly larger than that of a random network [$CC_l(rd)$]; and the average path length [l_G] is of the same order of magnitude as that of a random network of the same size [l_{rd}]. The Small-World (SW) indicator consistently demonstrates a value much greater than one (1) across all examined periods, highlighting the persistent small-world properties of the network throughout its evolution. From the results presented in Table 5-4, it is evident that despite ongoing geopolitical tensions between countries, the network has maintained its small-world characteristics throughout the observed periods. It is important to note that the observed increase in the small-world (SW) score in Table 5-4 is likely attributable to the expansion of the network size.

Table 5-4. Small-world properties

Period	Nodes	% of main component	CC_l	l_G	$CC_l(rd)$	l_{rd}	SW
2014-2016	1,805	54%	0.598	6.382	0.0038	3.87	**93.34**
2015-2017	3,742	57%	0.564	6.035	0.0025	4.11	**151.22**
2016-2018	6,121	60%	0.484	5.982	0.0013	4.44	**258.53**
2017-2019	9,185	63%	0.498	6.148	0.0010	4.55	**354.95**
2018-2020	11,349	61%	0.475	6.367	0.0007	4.75	**491.26**
2019-2021	14,569	61%	0.490	6.533	0.0006	4.81	**586.76**
2020-2022	22,542	61%	0.465	6.609	0.0002	4.99	**1,335.01**

Having analyzed the entirety of the 5G scientific collaboration network and observed its consistent small-world structure across time, we now shift our focus to a more granular level. Specifically, we examine China’s collaborative networks in relation to its three primary collaborative partners. From the data presented in the three tables below (Table 5-5, Table 5-6, and Table 5-7), it is evident that China’s networks with each of its primary collaborative partners consistently exhibit small-world properties, as reflected by the small-world indicator being greater than one 1 in all instances. Despite the earlier observation of the onset of fragmentation in these networks around 2018, the inherent small-world structure remains intact. This persistence ensures an optimal flow of knowledge among scientists, fostering robust channels of information, despite ongoing geopolitical tensions with China.

Table 5-5. Small-world properties for China-U.S. co-authorship network

Period	Nodes	% of main component	CC_l	l_G	$CC_l(rd)$	l_{rd}	SW
2014-2016	76	29%	0.563	4.338	0.0725	2.69	**4.82**
2015-2017	232	44%	0.594	5.887	0.0330	3.24	**9.91**
2016-2018	398	51%	0.473	6.609	0.0136	3.57	**18.70**
2017-2019	550	54%	0.494	4.845	0.0140	3.44	**24.96**
2018-2020	639	51%	0.488	5.335	0.0133	3.49	**23.97**
2019-2021	614	46%	0.501	5.223	0.0116	3.60	**29.83**
2020-2022	714	42%	0.729	5.713	0.0119	3.20	**34.22**

Table 5-6. Small-world properties for China-UK co-authorship network

Period	Nodes	% of main component	CC_l	l_G	$CC_l(rd)$	l_{rd}	SW
2014-2016	56	23%	0.501	2.607	0.0985	2.37	**4.63**
2015-2017	222	62%	0.502	5.043	0.0271	3.12	**11.46**
2016-2018	422	73%	0.402	3.953	0.0170	3.22	**19.26**
2017-2019	549	70%	0.412	3.861	0.0135	3.33	**26.27**
2018-2020	583	67%	0.461	4.102	0.0165	3.24	**22.10**
2019-2021	635	60%	0.578	5.767	0.0109	3.37	**31.00**
2020-2022	828	64%	0.741	6.250	0.0113	3.30	**34.61**

Table 5-7. Small-world properties for China-Canada co-authorship networks

Period	Nodes	% of main component	CC_l	l_G	$CC_l(rd)$	l_{rd}	SW
2014-2016	46	41%	0.507	2.319	0.1538	2.20	**3.14**
2015-2017	107	53%	0.470	3.493	0.0515	2.71	**7.11**
2016-2018	204	56%	0.420	4.716	0.0333	3.00	**8.02**
2017-2019	258	52%	0.403	4.593	0.0243	3.10	**11.18**
2018-2020	307	50%	0.432	4.564	0.0238	3.11	**12.37**
2019-2021	407	58%	0.551	5.867	0.0196	3.22	**15.43**
2020-2022	559	61%	0.781	5.332	0.0169	2.98	**25.71**

5.8 Discussion and conclusion

The primary objective of this study is to investigate the potential impact of recent geopolitical tensions on both the international scientific collaboration network and its structural properties. The focus on 5G technology is of particular interest, given its centrality in current geopolitical issues, including intellectual property disputes, cybersecurity concerns, and significant economic implications.

In this paper, we used social network analysis and metrics to assess the trends and patterns of international collaboration, as well as to examine the changes in the network's structural properties. To conduct this study, we extracted articles related to 5G technology from WoS database, covering the period from 2014 to 2022. The primary findings of our study reveal a notable negative trend in international collaboration involving China and several countries, particularly allies of the U.S. This trend aligns temporally with periods of heightened geopolitical tensions. These tensions have also impacted the structural properties of the network.

Several factors could account for the observed decline in collaboration between China and the U.S., along with its allies, in the field of 5G technology research. First, prior to the COVID-19 pandemic, the U.S. government put in place very strict visa restrictions for Chinese researchers and students, which reduced opportunities for collaboration (Yoon-Hendricks, 2018; Silver et al. ,2019; Lee & Haupt, 2021; Maher & Van Noorten, 2022). Second, the negative trend of collaboration also coincides with the beginning of the COVID-19 pandemic (Van Noorden, 2022). The United States' entry limitations during COVID-19 pandemic worsened an already downward trend in collaboration since most research collaborations started with in-person meetings rather than video conferences (Silver, 2020). In addition, to protect itself from intellectual-property theft and espionage, the U.S. government put in place several measures against Chinese and U.S. researchers having relations with China. In 2018, the U.S. government under the Trump administration started the "*China Initiative*" program. This program accused China of being an intellectual threat and aimed to protect the national security of the United States by investigating alleged Chinese spying in research and industry (Silver, 2020). This led to the FBI's arrest of several scientists (Silver et al., 2019; Subbaraman, 2020). In this context, Chinese scientists started to be reluctant to travel to the United States and collaborate with U.S. researchers (Silver, 2020).

Our findings suggest that the level of collaboration between the United States and China increased gradually over time and reached a stable point in the last two decades, despite the implementation of various measures by the U.S. government. The Chinese diaspora's contribution to the United States can account for this trend. A substantial Chinese researcher diaspora around the globe has established a connection between researchers in China and other nations (Tian, 2016; Xie & Freeman, 2020). Lee (2022) states that numerous scholars in the United States found other ways to maintain their collaboration despite U.S. policies. For example, several researchers have sought non-federal grants as an opportunity to avoid inquiries conducted by the federal government. Other scholars avoid official probes by refraining from engaging in transactions between the two countries. The renunciation of dual affiliation by certain scholars in the United States may have further contributed to the situation. Researchers have been using the "*Thousand Talents Program*" (TTP) for several years. This program enables scholars to have affiliations with both a research institution in China and another one overseas (Jia, 2018). The arrest of several scientists engaged in the TTP program has led numerous scholars to terminate their relations with Chinese universities and exclusively publish under their American affiliation (Van Noorden, 2022).

Additionally, our findings show a negative trend of collaboration between China and important allies of the United States, such as Canada, the United Kingdom, and nations within the European Union. The decline could be the result of the United States' pressure on these nations. The U.S. has pressured its allies to ban Chinese telecom company Huawei from deploying 5G infrastructure on the continent. In fact, U.S. government warned allies who do not ban Huawei that they will be deprived of American intelligence (Rühlig et al., 2019). The academic sphere has not been immune to these tensions. Huawei's partnerships with global universities have faced intense scrutiny, primarily due to concerns over espionage and intellectual property theft. For example, in 2019, both MIT and the University of Oxford made significant decisions concerning their relationships with Huawei. MIT chose not to enter new partnerships or renew current ones with Huawei and ZTE, citing federal probes into alleged sanctions breaches (Perper, 2019). Similarly, the University of Oxford opted against seeking new funding from Huawei for research and philanthropy, though they maintained ongoing projects (Davies, 2019). This backdrop of political tensions has urged the European Union and some European countries to adopt guidelines for scientific collaboration with China (Vanttinen, 2021). For example, the Finnish government with the collaboration of the country's universities published "*Recommendations for academic cooperation with China*" (Ministry of Education and Culture, 2021). Similarly, Sweden published "*Approach to matters relating to China*" (Government of Sweden, 2019) to highlight challenges of collaborating with China. Also, in response to the shifting geopolitical landscape, Canada's major national research agencies implemented strict measures on February 14, 2021 (Mervis, 2023). They declared a halt to funding proposals that involve foreign collaborators deemed to pose a security risk. Although these guidelines did not specifically mention China, they are in line with protective actions taken by other countries.

Our research provides crucial insights for policymakers, especially in strategic areas like 5G technology. Our study allows policymakers to measure the influence of their science policies on global scientific collaboration and the spread of knowledge, enabling them to modify their approaches as needed. This study is a first step toward a more in-depth analysis of the 5G science ecosystem. Moreover, the limitations of this research are multiple. Among the limitations, we can mainly mention the choice of the sample of scientific articles. In this context, we believe that the current method of restricting to articles containing the term “5G” could be improved by going for other 5G-specific keywords. The help of experts would be of great help in this regard. One of the limitations of this study is that our data frame does not provide the capability to associate each affiliation with a specific author. This impedes our ability to conduct a more granular analysis of the collaboration patterns based on individual researcher affiliations, which could offer additional insights into the dynamics of the co-authorship network. Nonetheless, to gain a comprehensive understanding of the effects of these tensions on co-authorship, further research, including qualitative studies, is essential for more informed policy guidance.

CHAPTER 6 ARTICLE 3: NAVIGATING GEOPOLITICAL STORMS: ASSESSING THE ROBUSTNESS OF CANADA'S 5G RESEARCH NETWORK IN THE WAKE OF THE HUAWEI CONFLICT

Anas Ramdani, Catherine Beaudry, Mario Bourgault, and Davide Pulizzotto

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6.1 Abstract

Amid geopolitical tensions over 5G technology, concerns about foreign firms like Huawei collaborating with academia have surfaced. This paper examines Huawei's role in Canadian research, analyzing its impact on network robustness and research themes over time. Robustness in network research has been extensively explored, yet there remains a notable gap in understanding the influence of geopolitical factors and foreign corporate presence, such as Huawei's, on these networks. The main results of this research show that: (1) The 5G network exhibits a decreasing trend in network robustness, with the potential for fragmentation increasing over time; (2) The impact of Huawei's removal on the network's Largest Connected Component (LCC) is relatively minor; (3) The network retains its small-world properties irrespective of Huawei's presence, and its removal has a minor impact on knowledge transfer efficiency; (4) Huawei's removal does not significantly affect network centralization, nor does it influence the prevailing trend observed over time; (5) Hierarchical clustering and specificity analysis identify Huawei's strategic focus on the silicon and optical photonic domain within the 5G research; (6) The collaboration-topic network shows a high degree of robustness, suggesting that Canada's research contributions in these areas are unaffected by the absence Huawei. This study provides a nuanced view of Huawei's role in Canadian 5G research, suggesting that while the company is a significant player, its impact is in general neither singular nor irreplaceable within the academic network.

6.2 Introduction

In the current geopolitical landscape, where tensions surrounding advanced technologies like 5G and the rift between China and the Western world are intensifying, these conflicts have begun to permeate the academic research sector. Amidst growing suspicion in the West regarding collaborations between academia and foreign firms such as Huawei, it has become crucial to examine their role and influence within the academic research sphere. In a country where "business-funded R&D in the higher education sector is relatively high and the number of academia-business research partnerships is increasing" (Council of Canadian Academies, 2018, p.11), this may have important repercussions.

Network robustness is defined as the ability of a network to maintain its overall functionality despite the removal or failure of some of its components, such as nodes or edges (Liu et al, 2017; Nguyen et al, 2022). There is a vast literature on network robustness, with geopolitical contexts frequently mentioned in domains such as energy (Chen et al., 2022; Wei et al., 2022) and air transport networks (Zhang et al., 2021; Papadopoulos et al., 2023). However, in our knowledge, there is a gap in such robustness studies of academic-business networks within geopolitical tension frameworks. A network's robustness is assessed by simulating perturbations, such as the removal of links or nodes. This process is commonly referred to in literature as "attacks". Previous literature has explored the impacts of attacks on network centralization (Rueda et al., 2017). For small-world networks, the focus has often been on how they withstand attacks, particularly in comparison with other network types like scale-free and random networks (Duan et al., 2016). Additionally, some studies contrast the effects of targeted versus random attacks on small-world networks (Sawai, 2013). However, there is a lack in the literature when it comes to assessing the impact of targeted attacks within the context of academic-business research networks.

Our study contributes to the literature by assessing the robustness of academic-business networks in the context of geopolitical tensions using both business-academic and collaboration-topics network analysis. We examine how networks composed of a range of businesses, including large multinationals, and academic researchers respond to targeted attacks by evaluating key structural properties, such as small-world characteristics and network centralization. By also considering research themes as a third node type in the collaboration-topics network, we analyze the effects of such disruptions on the thematic research direction in the Canadian 5G network. More specifically, given the recent geopolitical tensions surrounding China, we will focus on Huawei's involvement in the Canadian research network. We will explore the company's impact on the structural robustness of this network over time (2010-2021) and its influence on the thematic research directions within Canada. Following this context, the research question we pose is:

"How does the presence and geopolitical conflicts involving Huawei affect the network structural robustness and the landscape of the 5G research topics network in Canada?"

The results of our study point to a downward trajectory in the robustness of the 5G network. The structural properties of the network experience minimal disruption upon the exclusion of Huawei. The analysis of the collaboration-topic network reveals a high level of robustness, suggesting that Canada's research contributions in these 5G topics remain strong, even in the absence of Huawei. The remainder of this paper is organized as follows. The next section reviews the backdrop of geopolitical tensions that justify this study. The subsequent section presents the social network analysis literature pertinent to assess network robustness. The paper then presents the methodology, which details the procedures and metrics used to evaluate network robustness and Huawei's specific impact on the structural properties of the network as well as on 5G research topics. The subsequent section presents a detailed analysis of the findings. The final section of the paper concludes by summing up the implications for 5G research and Huawei's role.

6.3 Canadian science amid escalating tensions between China and the USA

Geopolitical tensions between China and the USA reached a peak in 2018 under Trump's administration. Adopting a confrontational approach towards Chinese businesses, it particularly targeted Huawei (BBC, 2019; Jaisal, 2020; The Star, 2022). The U.S. Commerce Department took the significant step of prohibiting American firms from doing business with Huawei (The Globe and Mail, 2018; U.S. Department of Commerce, 2020). At the heart of the U.S.'s concerns with Huawei were not just trade imbalances with China but profound national security fears (Kaska et al., 2019; Parsons, 2020). The U.S. expressed apprehensions about Huawei's technological capabilities, suggesting that they could be exploited by the Chinese government to compromise 5G networks (Kaska et al., 2019; Jaisal, 2020). Starting in 2019, the U.S. imposed tough sanctions on Huawei, labeling it a security risk (BBC, 2019; Hertzberg & Platt, 2022; The Star, 2022).

This broader U.S.-China conflict saw Canada inadvertently drawn into the fray on December 1, 2018, in Vancouver, Canada. On that day, Canadian officials detained Huawei's Chief Financial Officer, Meng Wanzhou, at the US government's request (Jaisal, 2020; The Globe and Mail, 2018; Friis & Lysne, 2021; Azad, 2022). In what many perceived as a retaliatory move, China detained two Canadians on charges of endangering Chinese national security (BBC, 2019). After several years of escalating geopolitical tensions between China and Canada, the Canadian government announced on May 20, 2022, its decision to ban Huawei from participating in its 5G networks (Hertzberg & Platt, 2022).

The conflict between Huawei and Western nations has had ripple effects in the academic world (Owens, 2022). The concerns over intellectual property theft and potential espionage began to overshadow the ethos of open collaboration (Friis & Lysne, 2021). In response to the evolving geopolitical landscape, on February 14, 2021, Canada's major national research agencies introduced stringent measures (Mervis, 2023). They announced that they would no longer fund proposals involving foreign collaborators that pose a security risk. While these guidelines did not explicitly name China, they echoed similar protective measures adopted by other nations (Mervis, 2023), such as Sweden (Ministry of Foreign Affairs, 2019) and India (Kumar, 2019). In Canada, researchers seeking grants from the Natural Sciences and Engineering Research Council (NSERC) were now required to undergo a security risk assessment. These guidelines specifically highlighted concerns about organizations, such as Huawei, potentially acting against Canadian interests (Wexler, 2022). The atmosphere of suspicion in the academic sector indeed predates the official government ban on Huawei and the formalization of funding agency guidelines for research collaboration with foreign firms. Canada's response in banning Huawei and imposing these guidelines was relatively delayed compared to other Western countries. The Canadian government's limited communication regarding the progress of its decision on banning Huawei can be attributed to the delicate situation involving the two Canadians arrested in China (Tunney & Raycraft, 2022).

Huawei's financial commitment to research and development, both globally and in Canada, is substantial. Between 2009 and 2019, Huawei invested at least $630 million (CAD)[34] in Canada. More specifically, from 2014 to 2019, the company contributed over $56 million (CAD) to Canadian universities (Parsons, 2020). This funding was channeled into research labs, scholarships, and various academic-focused research initiatives, underscoring Huawei's significant role in supporting Canadian academia (Parsons, 2020).

Having delineated the complex geopolitical landscape and its ramifications on the Canadian research area, the aim of this paper is to gain a deeper understanding of Huawei's impact on Canadian 5G research. One effective method to study Huawei's impact in academic-business

[34] Amount converted to CAD from Parsons (2020), where the reported amount was $500 million USD.

collaboration is through network analysis. By mapping the network, we can thoroughly identify the significance of various nodes (academics and businesses), understand the intricacies of their interconnectivity, and analyze the overall structure of the network. In network analysis, one of the most insightful avenues to simulate and understand the importance of nodes or edges on the network's properties is through the lens of robustness. By employing robustness metrics, we gain a comprehensive understanding of the network's robustness and stability, especially in the context of Huawei's involvement.

6.4 Network robustness in the literature

Network robustness has become a central focus in network studies, highlighting the ability of a network to withstand disruptions (Bilal et al., 2018). At its core, robustness represents the enduring ability of a network to maintain its functionality, even when subjected to disruptions (Dekker & Colbert; 2004; Carchiolo et al., 2019; Nguyen et al., 2022). The concept of robustness transcends theoretical applications and holds significant value in real-world scenarios. For instance, Xie et al. (2021) applied this notion to evaluate the robustness of the international oil trade network. By simulating disruptions such as national bankruptcy and economic sanctions, their research explains the network's susceptibility to such geopolitical events. Lordan et al. (2014) defines and apply a robustness-oriented methodology to identify airports whose isolation would critically undermine the global air transport network's connectivity. This robustness assessment helps in planning contingency plans to maintain network integrity in the event of such airport closures. The use of robustness as a key analytical tool extends into other disciplines, including mathematics, biology, and physics (Morales et al., 2018).

Assessing network robustness is complex, with many methods available in the literature. A widely adopted approach involves the systematic removal of nodes or edges, followed by an analysis of the subsequent structural changes. This method aims to measure the repercussions on the network's interconnectivity as its nodes/edges are progressively eliminated. Two foundational metrics in this context are node and edge connectivity (Wu et al., 2011; Liu et al., 2017). They measure the minimal number of vertices or edges that need to be removed to fragment the network.

The evolution of the Largest Connected Component (LCC) is frequently referenced in the literature as a metric for robustness. It tracks the changes in the size of the most extensive group of interconnected nodes in the network (Iyer et al., 2013; Nguyen et al., 2021). Expanding on this, serves as one of the key metrics for assessing network robustness, particularly regarding targeted node attacks (Schneider et al., 2011). This measure not only pinpoints the moment the network fragments but also monitors the size of the LCC throughout the node removal process, providing a nuanced understanding of network robustness (Ma et al., 2016). When considering the evolution of network robustness over time, measures such as the composition of the LCC and the robustness measure R are more direct and relevant than others commonly found in the literature, like network diameter (Beygelzimer et al., 2005; Liu et al., 2017) and assortativity (Rotolo & Frickel, 2019; Nguyen et al., 2022).

Additionally, two other structural network properties metrics used in robustness literature are small-world network score and network centralization metrics. These measures are particularly insightful for our study of an academic-business research network, as they shed light on how effectively information spreads (Cowan & Jonard, 2004) and how central knowledge hubs contribute to the overall knowledge exchange (Hu et al., 2023).

Small-world networks are optimal for efficient knowledge dissemination. They are characterized by a low average path length and a high clustering coefficient. The ratio of closed triangles to triples in the network is represented by the clustering coefficient (Watts & Strogatz, 1998; Ebadi & Schiffauerova, 2015). Essentially, it quantifies the interconnectedness of a node’s immediate neighbors (Hansen et al., 2020). On the other hand, the average path length denotes the mean number of connections in the shortest path between any two nodes in the network (Chen, 2023).

Research on network robustness explores small-world network characteristics in response to various attacks. For instance, Zhang et al. (2014) developed a method aimed at improving the robustness of small-world networks under attack. In a similar vein, Duan et al. (2016) examined the reactions of small-world networks to different types of attacks compared to scale-free, random, and regular networks. Their findings indicate that networks, despite varying topologies, can exhibit comparable levels of robustness according to the metrics used for assessing robustness. Despite these contributions, there seems to be a gap in understanding the persistence of small-world features when an academic-business network faces targeted attacks that remove a key node, such as Huawei.

Network centralization provides insights into the structural characteristics of a network. Central nodes in a highly centralized network are crucial for quick information spread. However, if these central nodes fail, they can become bottlenecks, slowing down or even halting communication within the network (Luke et al., 2013). Network centralization is also employed as an indicator of network robustness. In this context, Rueda et al. (2017) show that networks with high centralization values generally exhibit greater robustness. In our study, we employ network centralization alongside small-world analysis to examine the effects of targeted attacks on network structure. By investigating how these properties change following targeted removals, particularly the extraction of a key node like Huawei, we aim to provide a comprehensive picture of the network's structural robustness.

In social network analysis, it is possible to model a network disruption and evaluate the ensuing effects. This is known as an "attack" in the literature. Networks can be subjected to two primary types of attacks: random and targeted (Xiaohong et al., 2020). Random attacks involve the removal of nodes or edges with an equal probability, without any specific targeting (Liu et al., 2017; Nguyen et al., 2022). In contrast, targeted attacks are more strategic and deliberate. In these attacks, the most important node or edge is removed sequentially based on specific metrics like centrality measures (Iyer et al., 2013; Louzada et al., 2015; Ma et al., 2016; Liu et al., 2017).

According to Nguyen et al. (2022), there are two main strategies within targeted attacks. The initial attack strategy operates on a predetermined hierarchy, typically based on centrality measures such as degree, closeness, and betweenness. This approach aims to swiftly disrupt the network by targeting its most influential nodes from the outset. The objective is to observe the network's response and determine if it will disintegrate or maintain its structural integrity despite the targeted removals (Iyer et al., 2013). In contrast, the recalculated attack strategy adopts a dynamic approach. After each node or edge removal, the significance of the remaining entities is reassessed. This iterative process, which prioritizes nodes by their nodal degrees, persists until the network disintegrates into isolated nodes (Yang et al., 2015; Moore et al., 2021). The underlying objective of these targeted strategies is to inflict maximal disruption, with the network's robustness measured by the proportion of nodes it can afford to lose without breaking apart. In this study, to measure the robustness of our network, we employ a targeted attack strategy. Adopting a targeted attack strategy is appropriate, as it aligns with our objective to examine the repercussions of specific geopolitical tensions and the influence of Huawei on the network.

6.5 Data and methodology

6.5.1 Data

The data necessary for this research stem from three sources: two research funding databases from the Natural Sciences and Engineering Research Council of Canada (NSERC), Mitacs, and Clarivate's Web of Science (WoS). The complete database is built by pulling together information from various sources to complement the main data from NSERC on 5G research in Canada.

NSERC is a federal agency that supports national research and funds both university and industry-related projects, fostering a collaborative environment between them. The NSERC data, which are publicly available, provide details on project funding, researcher collaborations, and university-industry partnerships. These data have been structured into three distinct annual CSV files since 1991. The "Awards" files provide in-depth project details, name of principal applicant, affiliated institutions, research themes, grant amounts, and project abstracts, among other metadata. The "Co-applicants" files link principal researchers to their co-applicants using unique installment identifiers. Finally, the "Partners" file bridge researchers and co-applicants to their corresponding institutional partners.

The NSERC database assigns a unique identifier to each annual funding installment for a project, which leads us to count the project on an annual basis. For instance, a project that spans three years will be considered as three distinct entries when analyzing the academic-business network. This method ensures that the temporal dimension of collaboration is captured. We focused on projects from 2010-2021[35] that had references to 5G in their title or abstract. This first search yielded 877 yearly installment- projects. The exclusive use of '5G' as the keyword was key to ensure the selection of projects genuinely related to the fifth generation of mobile communication[36]. Recognizing that 5G is an umbrella term for a myriad of technologies[37], opting for broader terms might lead to inaccuracies because they are not specific to 5G and could be related to other topics

[35] This specific timeframe was chosen for two main reasons: First, very few projects and grants exist prior to 2010; Second, NSERC has not released the databases for 2022 and 2023.

[36] We initially extracted articles using keywords such as network slicing, massive MIMO, network function virtualization (NFV), millimeter wave (mmWave), and software-defined networks (SDN), resulting in a total of 10,360 final yearly installment-projects articles. Following expert consultation, we adopted the strategy of selecting only those articles where the term "5G" is explicitly mentioned, ensuring the elimination of false positives. This process resulted in a final selection of 5,537 yearly installment-projects.

[37] The term 5G is not exclusive to 5th generation. For example, some projects contain this abbreviation to refer to 5 grams. These projects have been removed from our database.

or goals. To mitigate this, a manual review was conducted to filter out non-relevant projects. After this step, we were left with 840 yearly installment- projects. After this, we pinpointed the co-applicants and industrial partners associated with each project.

To enhance the completeness of the database, we integrated data from MITACS and Web of Science. This method allowed us to enrich our dataset with pertinent NSERC projects by adding researchers focused on 5G, whom we identified through MITACS and Web of Science databases. MITACS is a national organization that primarily funds university-industry partnerships. We extracted data on project titles that included the term '5G' for the 2010-2019 period. Researchers from these projects were then cross-referenced with the NSERC database and additional NSERC project subsequently added to the main database. This additional step added 24 researchers to the database.

From the Web of Science, we extracted the articles that referenced '5G' in the title, abstract or keywords for the 2010-2021 period, that was coauthored by had at least one Canadian author. Each article was manually scrutinized for its relevance. After identifying Canadian researchers from the metadata of these articles, we incorporated the specific NSERC projects associated with these additional researchers into our database. Adding the 370 additional authors yields a final database that comprises 5,537 NSERC yearly installment- projects which correspond to 1,871 NSERC unique multi-year projects in which 947 researchers and 774 partners are involved.

A significant aspect of this process was the manual standardization of researcher names. Name disambiguation was carried out both within each individual database and between the three databases to rectify inconsistencies and variations in name representation. This ensured that any identical or similar names were accurately differentiated. The process was further supported by bibliometric information and references from official university web pages. This comprehensive approach ensured a robust database of '5G' NSERC-funded projects.

As previously mentioned, NSERC provides abstracts for each project, which we used to identify the key topics for constructing our collaboration-topics network. The initial step, however, was to clean our textual data to ensure accurate clustering results. We followed these steps:

- Exclusion of French abstracts: The NSERC database includes projects with abstracts in both French and English. Due to the limitations of our traditional text mining techniques, which do not easily support a multilingual framework, we opted to exclude the less represented language. Given the predominant presence of English projects, those in French were systematically excluded to ensure consistency across our final database. This approach led to the exclusion of approximately 339 French unique multi-year projects.

- Removal of empty abstracts: We identified and removed 4 empty abstracts from our dataset.
- Morphosyntactic analysis: Leveraging the Udpipe package from the R library (Wijffels et al., 2019), we executed tokenization and lemmatization of abstracts. This tool also facilitated the categorization of each term's grammatical nature. Since our methodology was specifically designed to analyze the most frequent and significant topics, we focused on retaining only nouns and adjectives[38]. This approach is based on the assumption that these parts of speech can effectively capture the main topics of a corpus. This selective retention of words is recognized as a standard approach by the literature (see Jacobi et al., 2018; Parinov et al., 2021; Lind et al., 2022). To address variations in similar words, we prioritized lemmas over tokens in our analysis.
- Term filtration and document-term matrix construction: After iterative evaluations, a decision was made to adopt n-grams of size 2. Only terms recurring more than five times and manifesting in over twenty distinct documents were preserved. This filtration strategy was pivotal in omitting less significant terms. Subsequently, a document-term matrix was devised, showcasing term frequencies across abstracts.
- Term weighting strategy: Numerous methodologies exist for term weighting in textual computer analysis. Among them, Tf-IDF (Term Frequency-Inverse Document Frequency) stands out as a widely recognized technique (Roul et al., 2017). This approach involves the multiplication of two metrics: TF (Term Frequency) and IDF (Inverse Document Frequency). Consequently, a term is assigned a higher weight if it frequently appears in a document (elevated TF) but is scarcely found across other corpus documents (low DF, amplified IDF).

Following the preprocessing of our database, we were left with a total of 1,528 unique multi-year projects. Given our primary aim to evaluate Huawei's influence on specific topics in comparison to other industrial partners, we first start with the count of projects for each industrial partner that applied for NSERC funding, as shown in Figure 6-1. This figure shows that Ericsson (63 projects)

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[38] We manually examined the verbs, nouns, and adjectives in the dataset and chose to retain only the nouns and adjectives, as verbs were not pertinent for extracting the most significant topics.

and Huawei (54 projects), the two primary competitors in Canada's 5G landscape, are at the forefront in terms of the number of projects.

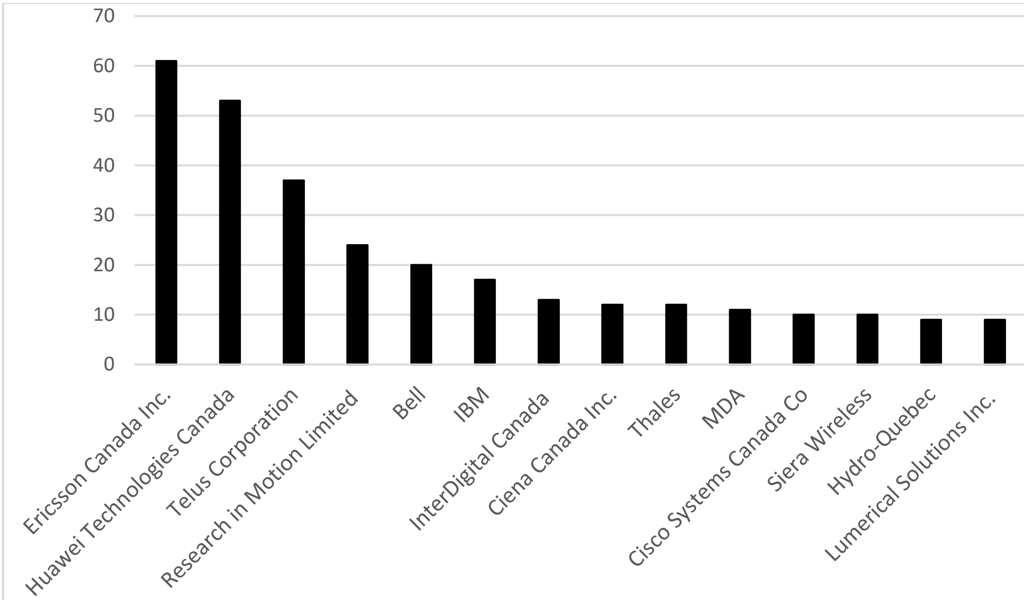

Figure 6-1. Number of projects for industrial partners

6.5.2 Assessing the Academic-Industry collaboration network

Centrality measures

Measures of node centrality serve two purposes in our analysis. First, they provide a clear picture of how the most central nodes in the network change over time. Since our focus is on Huawei, understanding the position of the company within the network is crucial for interpreting robustness findings. Second, the robustness measure, R, calculation requires to remove the nodes with the highest to the lowest centrality. We use three specific centrality measures: degree, betweenness and closeness[39] .

The degree centrality of a node represents its direct connections to other nodes. Nodes with higher centrality are more collaborative in nature (Zare-Farashbandi et al., 2014). The betweenness centrality of a node quantifies its function as an intermediary or bridge within the network. It measures the frequency with which a node is found on the shortest path connecting other node pairs (de Nooy et al., 2005). Nodes with high betweenness centrality values play a pivotal role in

[39] In the interest of conciseness, we will show only the degree centrality results for evaluating robustness (R), as the conclusions drawn are consistent with those from the other centrality measures.

facilitating knowledge and information flow across diverse network groups. Lastly, closeness centrality determines how close a node is to all its peers in the network. It provides insight into a node's ability to efficiently interact with others. Nodes with higher closeness centrality are better positioned to connect with the entirety of the network, underscoring their central role (Freeman, 1978).

Attack strategy and metrics

Measuring the network's overall robustness to targeted attacks first requires building a baseline to which the attacks will be compared. For this purpose, we calculate the Schneider et al. (2011) robustness measure, R. We then employ a targeted attack strategy. Targeted attacks are particularly relevant for our analysis in comparison to random attacks, given that we are specifically examining the impact of geopolitical tensions surrounding Huawei on the network. Our approach is twofold:

- Overall network robustness using R as a robustness indicator for the entire network: Nodes are first ranked based on their centrality. We then simulate a targeted attack by systematically removing nodes, starting from those with the highest centrality and progressing towards those with lower centrality. This sequential removal allows us to compute the robustness measure R, providing a comprehensive understanding of the network's robustness against targeted attacks. Proposed by Schneider et al. (2011), the robustness measure, R, is defined as:

$$R = \frac{1}{N}\sum_{i=1}^{N} s(i)$$

Where N represents the total number of nodes in the network, while s(i) denotes the size of the largest connected component[40] (LLC) following the removal of i node. In a star network, the minimum value of R equals 1/N, while in a complete network, the maximum value of R is 0.5 (Nguyen et al., 2022). This measure focuses on the evolution of the LLC as the highest-degree nodes in the network are systematically targeted and removed. This process corresponds to what is referred to as a series of targeted attacks, with the robustness being assessed after each node's removal. The larger the value of R, the more robust the network is deemed to be.

[40] The size of the largest connected component (LLC) of the network is given by the number of nodes that are directly connected to each other.

- Comparative robustness assessment: Our next objective is to discern the network's robustness in the context of Huawei's removal and compare this with the removal of each of the other nodes. In our analysis, we contrast the impact of Huawei on the network's robustness with that of other key players in the Canadian ecosystem, particularly focusing on Ericsson, Huawei's main competitor in the country. We systematically eliminate each node from the network, also taking out nodes that only collaborated with the node being removed. We measure the subsequent changes in the following metrics: The size of the Largest Connected Component (LCC), the network's centralization, the small-world indicator. These metrics are described below.

The size of the LCC

This allows us to measure the impact of each node's absence on the overall network robustness. Specifically, by measuring the change in the size of the LCC after each node removal, we can determine the relative importance of each node, including Huawei, to the network's robustness.

Small-world indicator

Another method to evaluate a node's effect on network robustness is by determining its influence on the network's small-world characteristics. With our targeted attack strategy, we assess the small-world properties of the network following the removal of each node.

To verify if a network has a small-world structure, it needs to be compared with a random network of similar size and density. A network is considered to have small-world characteristics if its average path length [l_G] is similar to that of a random network and its clustering coefficient [$CC_l(G)$] is much greater than that of a random network (Humphries et al., 2006):

$$\frac{l_G}{l_{rd}} \approx 1 \; et \; \frac{CC_l(G)}{CC_l(rd)} \gg 1$$

Here, l_{rd} and $CC_l(rd)$ stand for a random network's average path length and clustering coefficient, respectively. These equations can be combined to calculate the small-world metric, known as SW:

$$SW = \frac{\frac{cc_l(G)}{CC_l(rd)}}{\frac{l_G}{l_{rd}}}$$

A value of SW greater than 1 indicates the existence of a small-world structure. We start by confirming whether our network exhibits small-world characteristics. After establishing this, we then examine how Huawei's presence affects the small-world score, SW[41] . Given the high sensitivity of the small-world (SW) score to randomness, we conducted 100 simulations to measure it accurately. For both the initial network and for each subsequent node removal, we calculated the average of the SW scores to ensure a reliable analysis.

Network centralization

The final approach in evaluating the effect of node removal on network robustness involves analyzing changes in network centralization. We start by observing the progression of network centralization over time. Next, we evaluate the influence of each individual node on the network centralization.

Freeman (1978) defines network centralization as the degree to which communication is concentrated through a few key members, rather than being uniformly spread across all members. While there are multiple ways to measure network centralization, for our study, we extended the previously mentioned node centrality measures to a broader network context.

Degree centralization assesses how much the network's cohesion is centered around specific pivotal nodes (Bales et al., 2014). In a highly degree-centralized network, a few nodes have many connections, while most others have fewer edges. This indicates that a small fraction of nodes primarily controls the network's interactions. High betweenness centralization implies that a few nodes mainly dictate the network's flow, serving as crucial bridges. Networks with pronounced closeness centralization feature a select group of nodes that can efficiently access all other nodes.

Our analysis will focus on the network's robustness and Huawei's impact on it over time. This will allow us to observe the evolution of Huawei's role and identify any notable patterns that emerged during the period when geopolitical tensions involving Huawei increased. We have segmented the timeline into three-year periods.

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[41] We acknowledge the sensitivity of the small-world (SW) metric to network size in our study. An alternative size-adjusted metric proposed by Telesford et al. (2011), which involves a latticization algorithm, was considered. However, due to the computational complexity of this approach, we opted for the traditional SW metric. In our analysis, we have carefully considered the impact of network size sensitivity on our findings to ensure accurate interpretation of the results.

6.5.3 Assessing topic robustness

Hierarchical clustering

The next step involved carrying out the hierarchical clustering process on our prepared database. First, we calculated the cosine distance between the TF-IDF weighted terms in our document-term matrix. In the context of text data, this metric effectively captures the semantic similarity between documents.

With the cosine distance matrix in hand, we proceeded to perform hierarchical clustering. The Ward's minimum variance method was employed, with the objective of reducing the overall within-cluster variance.

The two clusters that have the smallest distance between them at each phase are combined. To facilitate visualization and further analysis, the hierarchical clustering result was then converted into a dendrogram structure.

After obtaining the dendrogram from the hierarchical clustering, a more nuanced approach was adopted to determine the optimal number of clusters. Instead of conventionally cutting the dendrogram at a predetermined height or specifying the number of clusters a priori, an iterative manual parsing was employed to ensure the coherence and relevance of each cluster. Each branch of the dendrogram was meticulously examined. The coherence of a cluster was primarily determined by inspecting the most frequent words within that cluster. If the words collectively suggested a clear and distinct topic, the cluster was deemed coherent. In instances where a branch did not exhibit coherence, it was further split. This division continued iteratively until the resulting sub-clusters were coherent, as evidenced by their most frequent words aligning with a clear topic. Conversely, there were scenarios where two distinct branches, when evaluated separately, seemed to share thematic similarities. In such cases, the two branches were amalgamated to form a single, coherent cluster with a well-defined topic.

This iterative and manual approach to dendrogram parsing ensured that each cluster was contextually meaningful. By prioritizing the semantic coherence of clusters, this method provided a more refined and contextually relevant clustering outcome, tailored to the nuances of the dataset.

After the iterative dendrogram parsing and cluster refinement, the next pivotal step was to assign meaningful labels to each cluster. To ensure the labels accurately represented the content and essence of each cluster, we read the most representative abstracts within them. These representative abstracts were identified by computing the cosine similarity between them and the centroid of their respective clusters. Centroid is the mean of the Tf-IDF frequency scores of documents within the same cluster. By thoroughly reading these abstracts, we were able to discern the predominant themes and topics that characterized each cluster.

With the clusters clearly defined and labeled, we proceeded to analyze the involvement of specific nodes, with a particular focus on Huawei. For each cluster, we identified abstracts that had contributions from Huawei. This allowed us to ascertain the thematic areas and research domains where Huawei had made significant contributions.

Assessing Huawei's effect on clusters robustness

To evaluate Huawei's involvement in each cluster, we approached it in four distinct ways. First, we measured Huawei's research priorities by determining the proportion of their projects within each cluster (RP score):

$$RP = \frac{Number\ of\ Huawei's\ projects\ in\ the\ Cluster\ k}{Total\ number\ of\ Huawei'sprojects}$$

In other words, the RP score is the distribution of Huawei's projects across different clusters. Next, we computed the share of Huawei's projects relative to the total projects in each cluster (RI score):

$$RI = \frac{Number\ of\ Huawei'sprojects\ in\ the\ Cluster\ k}{Total\ number\ of\ projects\ in\ the\ Cluster\ k}$$

Also, we assessed Huawei's contribution to the uniqueness of each cluster in comparison to others (RS score). Finally, we constructed a network that includes both academics, partners, and topics as nodes, and then measured the impact of Huawei's removal on the centrality of these topic nodes.

First, to assess Huawei's contribution to the uniqueness of the clusters, we start by conducting a keyness analysis[42] (Bondi & Scott, 2010) to identify terms that are uniquely prevalent within a cluster when compared to others. This was achieved through the application of the Chi-square test, which allowed us to statistically determine whether the frequency of certain terms in a cluster was significantly different from their distribution across other clusters (Durán-Muñoz, 2019). To ensure

[42] The R package "quanteda" and the function textstat_*keyness()* were used to carry out the keyness analysis (Benoit et al., 2018).

the robustness of our specificity analysis, we further refined our results by considering only those terms that met a statistical significance threshold. Specifically, only words with a p-value smaller than 0.01 were retained, ensuring that the terms we highlighted were statistically significant. Finally, for each cluster we extracted the most specific words and their Chi-square scores that we named α in the equation below. Subsequently, for each cluster, we quantified the extent to which Huawei's project terms contributed to the terms that are distinctive to that cluster using the following equation:

$$RS_k = \frac{\sum(\alpha_k * PH_k)}{\sum(\alpha_k * PT_k)}$$

α is defined as a collection of chi-squared statistics that correspond to specific words within each cluster k; PH represents the sum of normalized frequencies of the words in α for cluster k for Huawei's documents in k, and PT is the total sum of normalized frequencies for all words in α across documents belonging to cluster k.

Second, we use the attack strategy typically used for assessing network robustness to instead measure the effects on specific nodes. In this context, we are focusing on the impact on individual nodes within the network. Our aim is to evaluate whether Canada risks losing research contribution in certain topics if the network faces targeted attacks.

We constructed a Canadian 5G research network integrating academics, researchers, and previously identified clusters (topics) as its nodes. With this framework set, our primary focus was to evaluate the robustness of the network in terms or research contribution (topics) considering Huawei's potential absence. Our strategy was to measure the impact of Huawei's removal on these nodes and then compare this effect against the impact of removing any other player in the Canadian ecosystem, particularly Ericsson.

We employed a simulation-based approach with a targeted attack strategy to measure the robustness and vulnerability of cluster nodes. We removed each node from the network, ensuring that nodes exclusively collaborating with the removed node were also eliminated. After each removal, we recalibrated the centrality measures of the cluster nodes. We use the same centrality measures we described earlier. Through this approach, we aimed to identify which cluster nodes were particularly robust to nodes removal (i.e., Huawei's removal) based on changes in their centrality measures after each node removal.

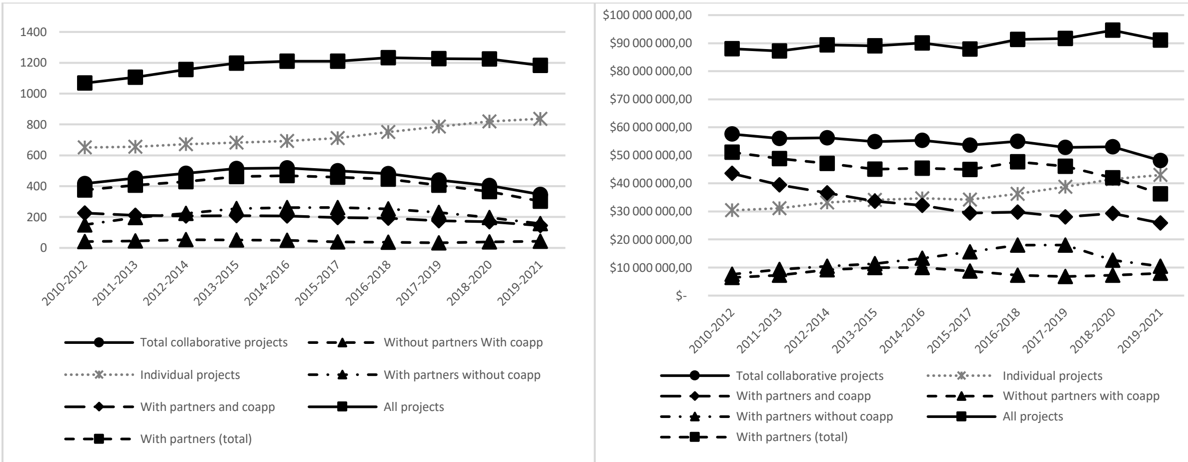
6.6 Results

6.6.1 NSERC 5G collaborative projects

For a comprehensive understanding of our network landscape, we categorized the NSERC collaborative projects into two main groups: those with partners (both with and without co-applicants) and those without partners. Various types of organizations partner with academics on those grants: research institutions, private sector companies, non-profit organizations, and governmental agencies. Industrial partners, constitute the bulk (over 83%) of the partners in our 5G database. From Figure 6-2.a, a discernible trend emerges[43]: while the total number of yearly instalments remained relatively stable after increasing until 2014-2016, those associated with collaborative projects (with co-applicants and/or partners) followed the same trend until the 2014-2016 period, after which the number has declined steadily.

Correspondingly, the overall budget allocated to collaborative projects (Figure 6-2.b) has declined over the period, mainly due to a displacement between projects with co-applicants and partners towards projects involving only partners[44], but only up to 2017-2019. The decline in the most recent period is evident. More specifically, the budget for collaborative projects with partners has seen a substantial reduction, dropping from $46 million during 2017-2019 to $36 million in the 2019-2021 period.

[43] The amounts provided in the NSERC data are presented in current Canadian dollars.
[44] This can be attributed to the predominant presence of the Engage program grants (49%). The Engage program, designed for short-term collaborations spanning six months, aims to catalyze partnerships between academics and partners who have not jointly applied for a grant previously.



(a) (b)

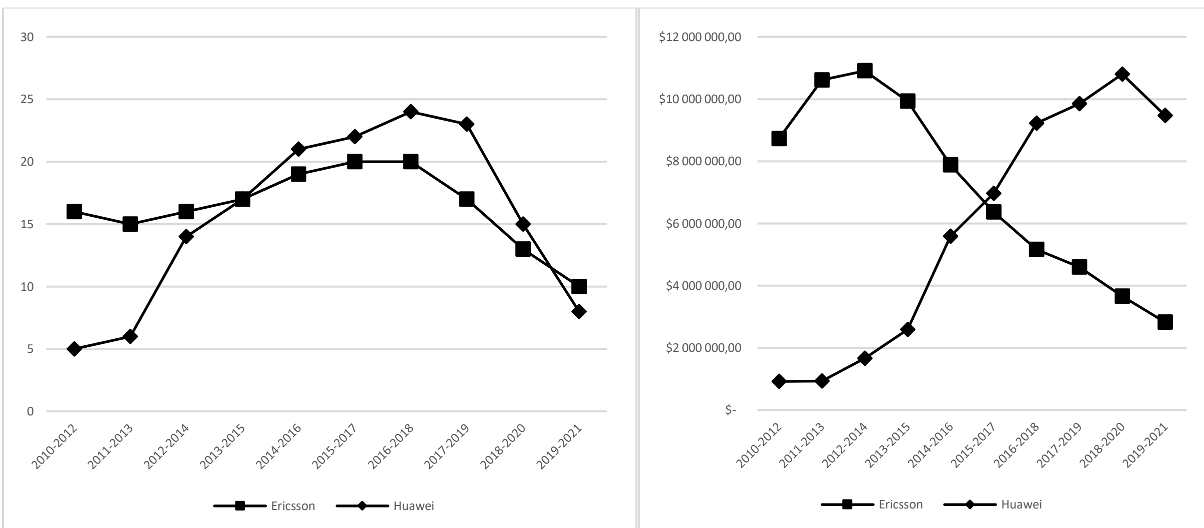
Figure 6-2. Evolution of the number of (a) NSERC instalments and (b) the grant amounts in Canadian dollars (CAD)

This decline can be attributed to multiple factors. One plausible explanation is the maturation of 5G research, suggesting that as the technology matured, there might have been fewer collaborative projects initiated. Figure 6-2 illustrates a clear trend: while the number and budget of collaborative projects with industrial partners are declining, individual project numbers and budgets are on the rise. This divergence suggests that the research field itself remains vibrant and growing, as evidenced by the sustained increase in the number of scientific publications and patents (Mao, 2021; Zhang et al., 2021; Mendonça et al., 2022) during the same period when collaborative efforts declined. The observed decline in collaborations with partners in 5G projects could also be explained by the introduction of new funding programs within Canada. One significant development is the establishment of ENCQOR 5G[45] in 2017, a consortium that includes several firms, most notably Ericsson, a key competitor of Huawei in the country. This consortium is a public-private partnership dedicated to fostering research and collaboration opportunities in the realm of 5G technology.

Also, this timeframe aligns with heightened geopolitical tensions surrounding 5G and a deteriorating environment in the scientific community regarding collaborations with specific firms. To further understand the implications of this shift, we will delve into the trends of Huawei's projects. Figure 6-3 displays the evolution of the number and budget of projects in which Huawei

[45] https://quebec.encqor.ca/

and its main competitor, Ericsson, are named partners. Figure 6-3.a seems to suggest that the involvement of both Huawei and Ericsson slowly diminishes after 2016-2018. As mentioned before, after that period, Ericsson becomes involved in a large, coordinated entity called ENCQOR 5G, and its participation both in terms of numbers and grant amounts of projects dwindles away. Figure 6-3.b shows that the budget allocated to projects involving Huawei follows an upward trend over time, yet there is a noticeable decrease during the last period, 2019-2021.The decline in collaborations with Huawei can be attributed to the increasing apprehensions within the academic community about engaging with the company, concerns which ultimately culminated in the establishment of guidelines such as those introduced by the Natural Sciences and Engineering Research Council of Canada (NSERC) in July 2021 (Fife & Chase, 2021).

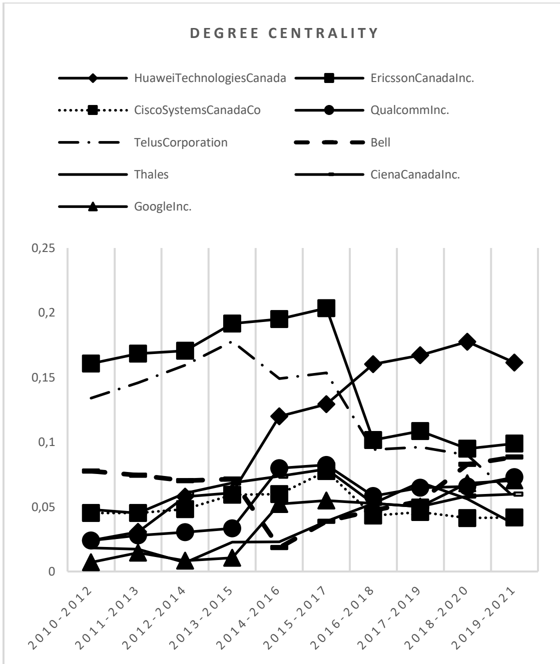


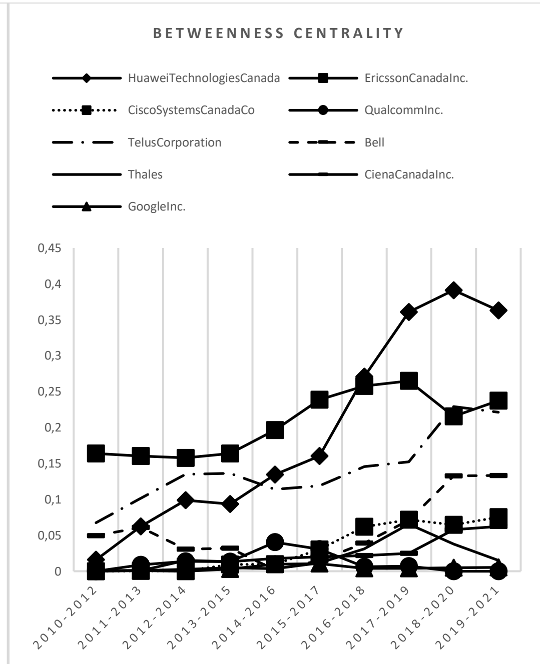
(a) (b)

Figure 6-3. Evolution of (a) the number of projects and (b) the grant amounts of the projects in which Huawei and Ericsson are involved

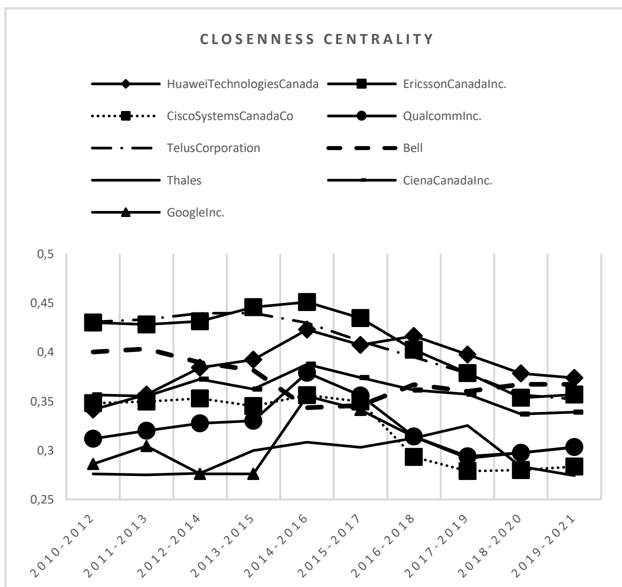
6.6.2 Centrality dynamics of industrial partners in NSERC 5G network

Central nodes often play a critical role in the network's robustness. Three centrality measures are tracked over time: degree centrality, betweenness centrality, and closeness centrality. The results, showing the most central industrial partners over the years, are presented in Figure 6-4.





(a) (b)



(c)

Figure 6-4. Degree (a), betweenness (b), and closeness (c) centrality measures for most central industrial partners

Huawei, Ericsson, and TELUS[46] emerge as the most central industrial partners over time. Ericsson relinquished its top position to Huawei during the 2016-2018 period across all three metrics. Specifically, in the subsequent four timeframes, Huawei not only established the most connections with other entities (as indicated by degree centrality) but also emerged as a pivotal bridge linking various academics and companies (highlighted by betweenness centrality). Furthermore, Huawei surpassing Ericsson in closeness centrality indicates that Huawei is, on average, closer to all other nodes in the network, enhancing its accessibility and influence within the collaborative network. This shift in centrality dynamics occurred amidst heightened government scrutiny on Huawei. During this specific period, Canadian academics continued to receive NSERC funding for partnerships with Huawei as we previously showed in Figure 6-3.b.

6.6.3 Robustness of the NSERC 5G network

Measuring R and LCC size

Figure 6-5 shows that the NSERC 5G network exhibits strong initial connectivity. The largest connected component consistently encompasses over 80% of the nodes in the network across different time periods and stays strongly connected in the last two periods (63% in the last period). Such a high proportion suggests a well-integrated network.

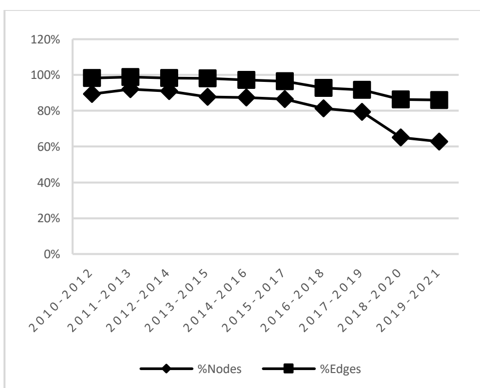


Figure 6-5. Evolution of the largest connected component (LLC)

To delve deeper into the network's robustness and its ability to withstand targeted disruptions, let us examine the evolution of R over time. Two key observations emerge regarding the robustness

[46] Telus is a major telecommunication company in Canada: https://www.telus.com/en.

of our network (see Figure 6-6). First, the R value is consistently low. Throughout the observed periods, it remains below 0.2, far below the maximum threshold of 0.5, indicating inherent vulnerabilities in the network's structure. Secondly, beyond the low scores, there's a clear downward trajectory in the R value. By the 2019-2021 period, it reaches a mere 0.05. Such a value, nearing zero, underscores a pronounced vulnerability in the network's robustness, which seems to be intensifying over time. This diminishing robustness implies that our network is increasingly vulnerable to targeted disruptions. Specifically, if strategies focus on eliminating the most central nodes, the network experiences swift fragmentation. This rapid disintegration of the largest connected component upon removal of pivotal nodes is illustrated in Figure 6-7.

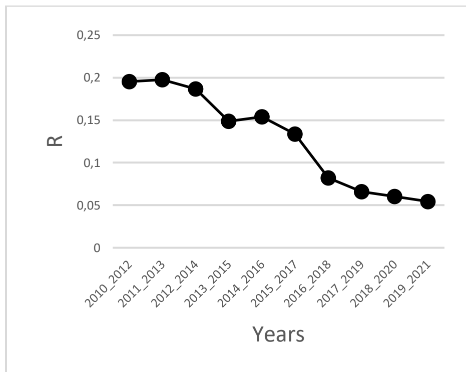


Figure 6-6. Evolution of the robustness measure R

During the initial three periods, the network becomes disconnected after the removal of approximately 25% of its central nodes (see Figure 6-7). This vulnerability intensifies in the subsequent periods, where a mere removal of less than 10% of the nodes leads to graph disconnection. These observations clearly show that the network is not robust, and its robustness is diminishing over time. Moreover, the network exhibited signs of declining robustness prior to the escalation of geopolitical concerns regarding Huawei and the 5G technology.

The observed decline in the R value and the swift decomposition of LCC after the removal of only a small fraction of the most central nodes intriguingly coincide with Huawei's ascent to a high centrality position in the 5G network. To definitively ascertain whether Huawei plays a pivotal role in this dynamic, we assess the impact on the LCC when Huawei is specifically removed from the network and juxtapose this effect with the consequences of removing other central nodes. To provide a comparative perspective, we also included the effects of removing Ericsson, another central node in the network. The results of this analysis are presented in Figure 6-8.

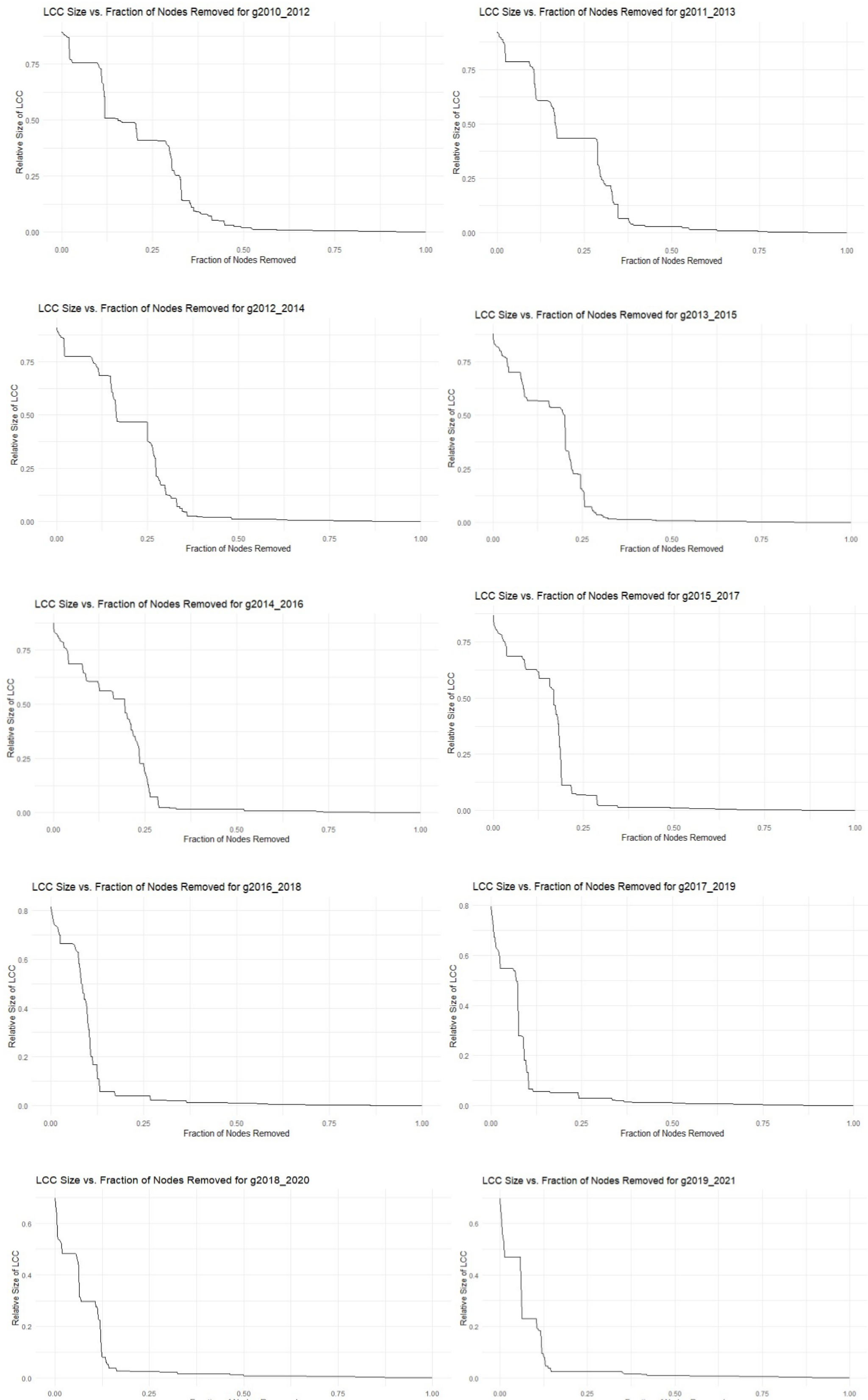


Figure 6-7. LCC size vs Fraction of nodes removed

A multifaceted trend about the influence of Huawei's removal is apparent on the LCC over time. Throughout the observed periods, the repercussions of Huawei's removal remain relatively low, reaching a maximum of 6% during 2019-2021. An intriguing pattern emerges between 2010-2012 and 2013-2015. Despite Huawei's less central position in the network compared to other entities, its extraction leads to a more pronounced contraction in the LCC. This phenomenon can be traced back to the methodology of node removal, where a node's exclusive collaborators are also removed. Huawei had more unique partners that only worked with it. On the other hand, Ericsson, even with its strong position during this period, had fewer unique partners, leading to a smaller impact when it was removed.

The story changes between 2013-2015 and 2014-2016, where the impact of Huawei's removal decreases, coinciding with Ericsson's strong presence in the network. After 2014-2016, as the importance of Huawei grows and becomes more central in the network, the impact of its removal on the LCC starts to increase, even more so than in the initial phase. Although the company was among the industrial partners with a higher impact score on the LCC, the magnitude of this impact was comparable to other major players in the field. This observation implies that Huawei doesn't have a unique or dominant role in influencing the robustness of the network and its impact stays relatively minor over time.

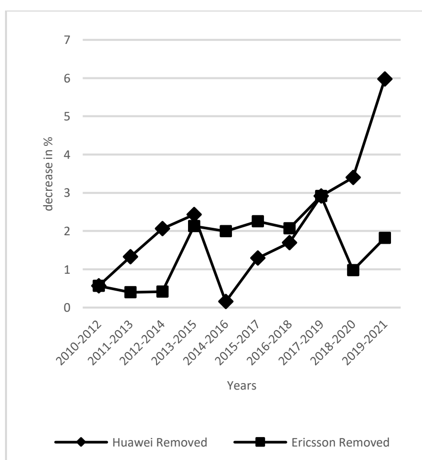


Figure 6-8. Impact of the removal of Huawei and Ericsson on LCC Trends

Small-world properties

As the size of the LCC is a rather crude measure, this article proposes to explore the impact of targeted attacks on the small-world properties of the network. Table 6-1 shows that the network exhibits a small-world structure in every period, with the SW score being consistently greater than 1, which represents an optimal structure for knowledge and information flow, which is particularly crucial in the context of a research collaboration network. In our case, despite the decreasing size of the network over time, the small-world (SW) score remains relatively stable, indicating consistent small-world characteristics irrespective of network size changes.

Table 6-1. Small-World score

	Number of nodes	**SW score**
2010-2012	710	19.3
2011-2013	755	20.8
2012-2014	728	19.5
2013-2015	659	24
2014-2016	652	23.2
2015-2017	620	25
2016-2018	532	27.9
2017-2019	480	23.6
2018-2020	412	18.4
2019-2021	385	23.2

Table 6-2 presents the influence of both Huawei and Ericsson on the network's small-world properties. A key observation is that, upon the removal of either Huawei or Ericsson, the network retains its small-world characteristics, as evidenced by the SW score consistently remaining above 1.

Table 6-2. Impact of Huawei and Ericsson Removal on SW

		SW score after removing		**Impact (%) of removing**	
	Initial SW score	Huawei	Ericsson	Huawei	Ericsson
2010-2012	18.9	18.8	18.7	-0.8%	-1.0%
2011-2013	20.5	20.1	20.7	-2.3%	1.0%
2012-2014	20.3	19.7	20.6	-3.0%	1.4%
2013-2015	22.4	21.7	22.5	-3.0%	0.7%
2014-2016	23.8	24.1	23.6	0.9%	-0.9%
2015-2017	24.5	24.0	24.2	-2.4%	-1.3%
2016-2018	29.2	29.5	27.9	0.9%	-4.8%
2017-2019	26.8	25.9	25.8	-3.4%	-3.7%
2018-2020	22.3	21.0	21.6	-5.7%	-3.0%
2019-2021	21.3	20.8	20.5	-2.5%	-4.0%

The results presented in Table 6-2 indicate that the removal of Huawei does not substantially affect the small-world score of the network. While there is a minor decrease in the small-world score for nearly all observed periods, the overall impact is relatively minor. This suggests that Huawei, despite its central position in the network, is not a crucial dependency for most nodes. A similar pattern is observed when Ericsson is removed from the network, indicating that its absence also does not significantly impact the network's small-world score. The majority of nodes in the network seem to be well interconnected independently of both Huawei and Ericsson. This can be explained by the minimal changes in both the clustering coefficient and the average path length.

Upon comparing the impact of Huawei's removal with the effects of removing other nodes across each time period, our findings reveal that Huawei does not rank among the top nodes influencing the small-world score. In fact, several other industrial partners exhibit a more pronounced effect on the network's small-world properties than Huawei does.

Network centralization

Prior to the removal of Huawei and its subsequent impact analysis on network centralization, two distinct patterns emerged in the network's centralization trends over time. Firstly, the trends for degree and closeness centralization differ notably from that of betweenness centralization.

Specifically, during the initial periods, both degree and closeness centralization exhibit an upward trajectory, only to follow a declining trend in the subsequent periods. Figure 6-9.a shows a clear drop in degree centralization over time. This means that connections in the network are spreading out more evenly among nodes, rather than just a few nodes having most of the connections.

Contrastingly, when we examine betweenness centralization, its trajectory is opposite to that of degree and closeness centralization (see Figure 6-9.b). Initially, there's a decline in betweenness centralization during the early periods, but this trend reverses, showing an increase in subsequent periods.

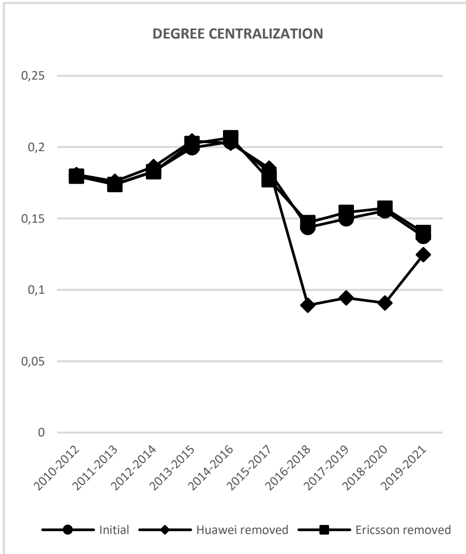
The decline in degree centralization, as depicted in Figure 6.9.a, not only corresponds with a reduction in the overall number of nodes in the network (see Table 6-1), but we also verified that some nodes, which were previously central, have either disappeared from the network or now possess fewer connections during this period of decreasing centralization. Concurrently, some nodes are emerging as critical bridges, connecting different parts of the network, which results in an increase in betweenness centralization. These shifts in node importance and the evolving network structure suggest that the network's overall robustness is on the decline.

Degree, betweenness and closeness (network) centralization measures offer a deeper understanding of the robustness of the network, as represented by the R value over time (see Figure 6-6). While connections are well distributed between nodes, the network structure is becoming heavily dependent on a few key nodes. The removal of these pivotal nodes compromised the entire network, leading to a decrease in its robustness (R).

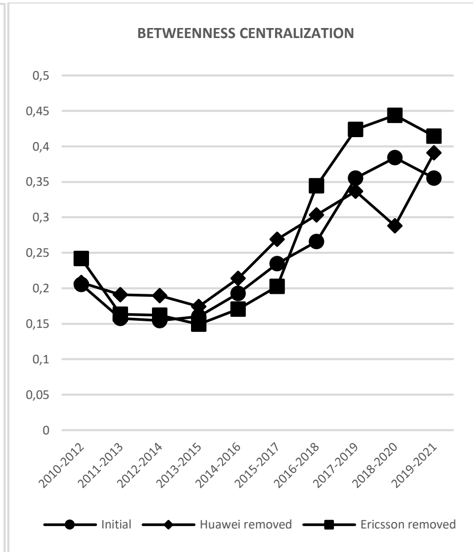
The removal of either Huawei or Ericsson from the network (in Figure 6-9.b and Figure 6-9.c) does not significantly alter the initial closeness and betweenness centralization values, suggesting that neither organization plays an overwhelmingly pivotal role in the network's structure. The overall network dynamics and interconnections remain largely consistent, even when either of these major players is excluded from the equation.

These results are a stark contrast to what we observe with degree centralization. In that case, Huawei's influence becomes more pronounced, especially post the 2015-2017 period. Its removal from the network during these later periods leads to a noticeable decrease in degree centralization. This suggests that Huawei had established itself as a significant node with numerous direct connections within the network. While several nodes displayed a decreasing trend in their degree centrality, as illustrated in Figure 6-4.a, Huawei's degree centrality was on the rise. This suggests that while some nodes were losing their direct connections or becoming less central in terms of immediate ties, Huawei was expanding its direct collaborations, further solidifying its position as a major hub within the network.

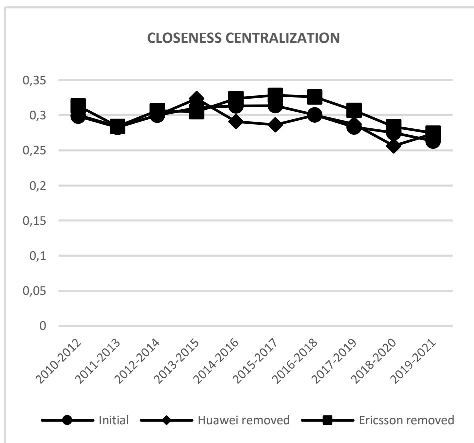
We found that Huawei's removal had the most noticeable effect when evaluating the effects of removing other nodes on degree centralization during the last period. Even while Huawei is a vital link in the network, the trend toward less centralization remains unchanged when it is removed, indicating that it is not the sole driver of this trend. However, the more pronounced decrease in degree centralization upon its removal underscores Huawei's role as an important node with extensive connections. This suggests that while Huawei contributes quantitatively to the network's centralization, it does not fundamentally change the network's overall structural shift towards decentralization.



(a)



(b)



(c)

Figure 6-9. Impact of the removal of Huawei and Ericsson on a degree, b betweenness and c closeness centralization

6.6.4 Key 5G topics

From a science policy point of view, it is relevant to examine whether the removal of one player in the network, here Huawei, creates a void of topics on which university and industry normally work hand in hand. In other words, observing various network characteristics changes following targeted attacks only tells part of the story. Firstly, we will employ a hierarchical clustering approach to identify distinct topics. Once the topics are identified, we will then proceed to analyze Huawei's contributions within each topic. Understanding Huawei's contribution to specific topics, requires a three-fold investigation: 1) assessing Huawei's research priorities (RP score); 2) examining Huawei's involvement in terms of projects within these research topics (RI score); and 3) measuring Huawei's contribution to the uniqueness of these topics (RS score).

A hierarchical clustering algorithm on 5G projects summaries from the NSERC database found 67 unique clusters (see Table B- 1 of Appendix B), each representing different 5G subtopics in Canada. Some of these include subtopics on the core technologies integral to 5G. The main topics associated with these clusters of projects highlight advancements and challenges in areas such as MIMO, millimeter-wave frequencies, edge computing, and innovations in both silicon and optical technologies. For instance, the integration of 5G with the Internet of Things (IoT) emerged as a significant theme, showcasing the potential of 5G to elevate and transform IoT applications. Security in the 5G framework was another main theme among the clusters, highlighting the focus on data privacy and creating secure 5G protocols. Another discernible theme revolved around energy management within the 5G infrastructure, emphasizing the balance between the capabilities of 5G and its energy demands. Furthermore, the results highlighted the application of 5G in interdisciplinary research areas, particularly its potential implications in sectors like health and aerospace.

Huawei's research priorities (RP score) within the 5G domain exhibit a pronounced concentration in Cluster 1, which focuses on silicon and optical photonic technologies (see Table 6-3): 32.08% of the research projects in which Huawei is involved align with this theme. Of lesser importance, Cluster 17, centered around MIMO technology, and Cluster 30, dedicated to network management and optimization, each capture 7.5% of Huawei's research collaboration. These percentages, although substantial, are far behind the overwhelming focus on silicon and optical photonic technologies (C1), indicating a primary research direction for the company in this domain. Conversely, Ericsson shows a more distributed research priorities approach across the various topics identified (see Table 6-3). While some clusters capture a notable proportion of Ericsson's research priorities, such as C21, which delves into edge and cloud computing (11.5%), and C30- Resource management for next-generation wireless networks, C12- Optimization and management in next-generation small cell cellular networks and C13- Innovative strategies for massive data traffic and low latency in 5G networks, centered on network management and optimization (with contributions of 9.8% and 6.6% respectively), the company's contributions span a broader spectrum of research topics, hence suggesting a multifaceted research strategy.

Table 6-3. Research priorities of Huawei and Ericsson

Cluster number	Huawei research priorities	Ericsson research priorities	Title
1	32.0%	4.9%	Advancements in silicon photonics and optical communication systems
12	3.7%	6.6%	Optimization and management in next-generation small cell cellular network
13	5.6%	6.6%	Innovative strategies for massive data traffic and low latency in 5G networks.
17	7.5%	4.9%	Advancements and challenges in MIMO and 5G wireless communication technologies
21	1.8%	11.5%	Cloud computing, resource management, and privacy in Fog Networks
30	7.5%	9.8%	Resource management for next-generation wireless networks

Note: The percentages in this table represent the Research Priorities (RP) scores for Huawei and Ericsson. These scores are calculated by dividing the total number of projects each company has in each cluster by the total number of projects conducted by the respective company.

Figure 6-10 emphasizes Huawei's role as a leading contributor in C1, which focuses on advancements in silicon photonics and optical communication systems. Here, the RI score 16.83%, reflects the proportion of Huawei's projects in this cluster relative to the total number of projects present in the same cluster. On the other hand, the RS score 17.51%, is a percentage that serves as a measure of Huawei's contribution to the distinct characteristics that make this cluster specific compared to others. It highlights how Huawei's projects contribute uniquely to the specific themes and topics of C1, surpassing all other entities. This data reinforces Huawei's significant commitment and leadership in the research areas encapsulated by C1.

However, beyond Cluster 1 where Huawei demonstrates a significant impact, the company does not particularly stand out in terms of contributing to the volume or specificity of other clusters when compared to other companies. In C17, which focuses on 5G innovations such as massive MIMO, mm wave communication, and wireless backhaul solutions, both Huawei and Ericsson significantly contribute to the cluster's uniqueness. Huawei is the leading contributor with 18.18% of the projects in this cluster (RI score), and its contribution to the cluster's uniqueness is substantial, at a 19.04% RS score. Ericsson, with a slightly smaller share of projects at 13.64%, closely matches Huawei's contribution to the cluster's distinctiveness with 17.15% in RS score. This highlights that despite having fewer projects, Ericsson's projects are nearly as impactful as Huawei's in defining the unique characteristics of C17.

Similarly, in C30, which focuses on resource management for next-generation wireless networks, the analysis in terms of specificity (RS) reveals a more significant role for Ericsson compared to Huawei. Ericsson contributes a substantial 25.99% to the cluster's specificity, underscoring its considerable involvement in the research topics of this cluster. This high contribution rate indicates that Ericsson's projects are not just numerous but also play a defining role in shaping the unique characteristics of Cluster 30. Also, in C13-Innovative strategies for massive data traffic and low latency in 5G networks, Ericsson not only has a larger share of projects in this key area but also exerts a stronger impact on the cluster's distinctiveness compared to Huawei.

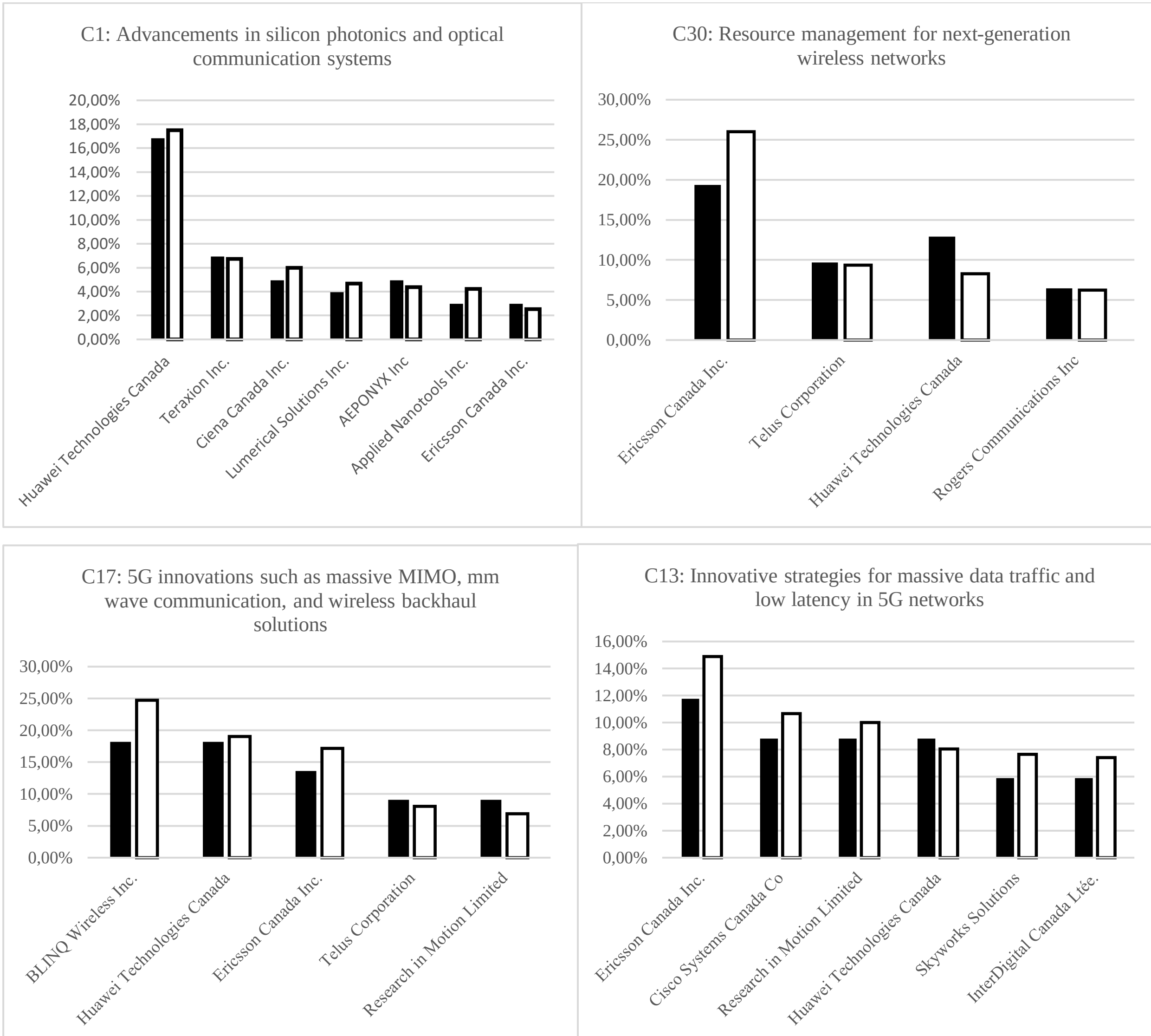


Figure 6-10. Contribution of Huawei and Ericsson in terms of project volume in the cluster (black) and on lexical specificity of clusters (white)

To sum up, Huawei differentiates itself from Ericsson and other industrial partners primarily in terms of silicon and optical photonic technologies (C1). This is evident in their research priorities, their role in populating this topic, and their significant contribution to the topic's uniqueness.

To gain a deeper understanding of Huawei's influence within the 5G research topics landscape, we will conduct a simulation that entails the hypothetical removal of Huawei from the network. This approach will allow us to analyze and quantify the impact of Huawei's absence on the 5G research topics. We add to the previously characterized network a new set of nodes that correspond to each of the 67 topics identified in Table B-1 of Appendix B. Then, we replicate the targeted attack approach to evaluate the robustness of this new 5G collaboration-topic network. The results presented below highlight the effects of a targeted attack strategy on the centrality measure of these topic nodes. When we specifically focus on the removal of Huawei, we identify some interesting observations related to certain clusters (see heatmaps of Huawei and Ericsson in Figure B-1 and Figure B-2 of Appendix B).

When Huawei is removed from the collaboration-topic network, three notable shifts occur in the dynamics surrounding C1-silicon and optical photonic technologies. First, there is a 7% reduction in degree centrality, highlighting Huawei's direct collaborations and ties to this topic. When comparing the effects of removing Huawei from Cluster 1 with the effects of removing other industrial partners, it reveals that the impact of Huawei's absence is the greatest, showing its significant influence within this cluster in term of direct connections. However, unlike the significant lead of Huawei in RI and RS scores within Cluster 1, the gap in terms of degree centrality is less pronounced. Here, Teraxion Inc[47] emerges as a close second, with its impact on the degree centrality of C1 being 4.21%.

Second, the betweenness centrality of silicon and optical photonic technologies (C1) increases by 5.88%. Despite Huawei's absence from the collaboration-topic network, the increased betweenness centrality of C1 suggests that the network retains strong collaborative and informational flows in this area. This change demonstrates the network's robustness, showing that its functionality and contributions to C1 do not overly depend on Huawei. This dynamic is not unique to this topic. Similar patterns emerge for the following topics: Implementation and application of polar and LDPC codes in 5G wireless communication systems (C11), Optimization and management in next-generation small cell cellular networks (C12), Innovative strategies for massive data traffic and low latency in 5G networks (C13), 5G innovations: massive MIMO, mm wave communication, and wireless backhaul solutions (C17), Data center networking and optimization (C29), Resource management for next-generation wireless networks (C30).

Third, compared with Ericsson, the decrease in C1's degree centrality is relatively modest, only 1.05%, which is substantially less than the impact seen with Huawei's removal. However, in terms of betweenness centrality, Ericsson's removal results in a more notable increase of 6.10%, exceeding the impacts observed when Huawei was removed from the network. When comparing the impact of Huawei's removal with that of other companies, it becomes evident that Huawei does

[47] Teraxion Inc is a company specialized in photonic solutions.

not exert the greatest influence on Cluster 1’s betweenness centrality. For instance, IBM Canada surpasses both Huawei and Ericsson, with its removal leading to an even more significant impact of 10.52% on the betweenness centrality of C1. This suggest that even in the absence of these large players, the collaboration-topic network exhibits a high degree of robustness, i.e. Canada does not lose out in terms of research contribution to these topics.

Another research priority (C29 – Data center networking and optimization) of Huawei compared to Ericsson presents distinct patterns when either Huawei or Ericsson is removed. Huawei’s removal results in a 13% decline in degree centrality of the topic, highlighting its substantial direct involvement with this topic. In contrast, Ericsson’s removal leads to a smaller 6% decrease. Once again, the dynamics shift when considering betweenness centrality. Despite Huawei’s stronger direct ties, its removal only increases the betweenness centrality of Data center networking and optimization (C29) by 8%. Conversely, the absence of Ericsson, with its fewer direct connections, results in a significant 16% drop in betweenness centrality of the topic. In practical terms, Huawei and the research topic (C29 – Data center networking and optimization) appear interchangeable in terms of their intermediary role in the collaboration-topic network, i.e. there is a high degree of robustness to the removal of Huawei (the topic occupies the void). The absence of Ericsson as a key integrator and intermediary of the network leaves a more fragmented collaboration-topic network, it has a greater impact on the network than the removal of any other industrial partner.

Huawei’s removal yields a negligible impact on closeness centrality across various topics. This further suggests a high degree of redundancy in the connections within the research collaboration-topic network. Specifically, even in the absence of Huawei, multiple paths connecting these topics to other industrial partners and academics exist in the network. As a result, the average distance between nodes remains relatively consistent, indicating that other nodes in the network effectively compensate for Huawei’s absence.

6.7 Conclusion

The purpose of this paper is to explore the impact of geopolitical tensions on 5G technology research, with a particular focus on Huawei’s role in Canadian academia. Amidst growing concerns about Huawei’s involvement, we assess the robustness of Canada’s 5G research network in response to growing geopolitical tensions related to Huawei. To achieve this objective, our evaluation focused on the robustness of two distinct networks: firstly, the business-academic network, and secondly, the collaboration-topics network.

In analyzing the business-academic network, we found that its robustness is low and decreasing over time. This means that the Canadian 5G research network is notably vulnerable to disruptions, especially when its key firms, the network's most central nodes, are targeted. These firms are essential in maintaining the network's structure, highlighting their irreplaceable role and the network's significant dependence on them. However, the dynamics shift when assessing the impact of Huawei alone on network robustness. By simulating geopolitical scenarios through the exclusion of Huawei, our analysis demonstrates that the network effectively endures this targeted disruption, thereby underscoring its sustained robustness even in the absence of Huawei's involvement.

First, our analysis reveals that the network retains its robustness, particularly in terms of its small-world properties, even when Huawei is removed. Despite Huawei being identified as the most central node, its exclusion has a minimal impact on these small-world characteristics. The network continues to maintain an optimal structure for knowledge diffusion within the Canadian 5G business-academic network. Second, the network maintains its robustness in terms of centralization even after the removal of Huawei, despite it being the most central node. Network centralization, which measures how much a network's activities are dominated by a few central players in the network, appears minimally affected by Huawei's absence. While its removal does lead to a slight decrease in centralization (in term of degree centrality), reflecting Huawei's role as a central hub, this change is consistent with the already observed decreasing trend in the network's centralization. Therefore, the ongoing shift towards a more distributed network structure seems to be occurring independently of Huawei's specific contribution.

These results imply that the structural properties of the network remain robust even without Huawei, indicating that Canada's research network does not depend solely on Huawei for optimal knowledge dissemination. Other players within the network can fill this gap, ensuring a continuous and effective flow of information.

In analyzing the robustness of the collaboration-topic network, especially in terms of research contributions to various 5G topics, we observed that the network consistently exhibits a high level of robustness, even in the absence of Huawei. These topics were identified by applying hierarchical clustering to summaries of NSERC projects. Our findings indicate that Huawei has specifically focused on silicon and optical photonic technologies (C1) in Canada, as evidenced by a large proportion of their projects being concentrated in this topic. Additionally, our analysis reveals that

Huawei is the leading contributor to C1 in aspects of this topic that are unique to this cluster compared to others. This suggests that this topic is a primary research focus for Huawei within the Canadian context. However, when simulating Huawei's absence from the collaboration-topic network, we observed that even though the topic of silicon and optical photonic technologies loses direct connections due to Huawei's significant contributions, it remains robust. This is evidenced by the minor impact on the topic's degree centrality and a slight increase in its betweenness centrality, indicating robustness to such a disruption. Furthermore, this pattern of high robustness in the face of Huawei's removal is consistent across other topics within the network. Moreover, upon comparing the impact of Huawei's removal on network robustness with the removal of other firms, we found that Huawei's absence does not stand out significantly. This suggests that the research network's topic-based robustness is not dependent on Huawei, indicating a broader robustness and diversity in contributions from various firms.

This study reveals that Canada's research ecosystem is robust and does not rely on a single player. Knowledge is transmitted between researchers and industry via multiple relationships. The majority of researchers maintain links with several players, ensuring the strength of the network even in the absence of a key player such as Huawei, whether in terms of knowledge transmission or contribution to 5G research. The study also shows that the robustness of this ecosystem can help policymakers assess the impact of geopolitical tensions on scientific collaboration and prevent these effects by promoting the construction of a robust research network.

There are several limitations on this study. First, one limitation pertains to the data extraction process. Since we extracted data from the MITACS and NSERC databases and extracted 5G publications from the Web of Science database, it's possible that some 5G projects were missed. A more involved participation of experts could help future research incorporate more pertinent keywords and identify 5G projects more precisely, thereby enhancing the accuracy and relevance of the selected articles. Moreover, details regarding the technological and financial contributions made by industry partners to the 5G projects are not available in the NSERC database. The information is limited to funds from NSERC and does not include information about resources that the companies contributed in exchange. Future research could address this restriction by doing a thorough qualitative study that would yield more in-depth details on this aspect. Furthermore, in order to evaluate the strength of the Canadian research network, our analysis relied only on the NSERC funding network. Other databases that include patents, scientific articles, and other pertinent documents, could be incorporated into future studies to provide a more comprehensive analysis.

One other limitation is the labeling procedure that is used after hierarchical clustering to identify each cluster. Although we read and interpreted the most representative documents of each cluster, some sub-themes may have been lost.

Also, in text mining techniques like hierarchical clustering, it is usually advisable to focus on particular parts of speech, as they are more likely to hold the substantive content of the text. The selection of words may also be tailored based on the objectives of the study and the characteristics of the corpus, depending on the task and the corpus involved. In our study, we chose to retain only nouns and adjectives to extract the most pertinent information regarding 5G topics. Future studies could include additional parts of speech to determine if the results regarding the impact of Huawei’s removal from the studied networks remain consistent.

Another limitation of our research is that we excluded French abstracts due to our methodology’s constraints in handling multilingual data. Future studies could employ a multilingual approach and compare their findings with ours to potentially enhance the comprehensiveness and applicability of the results.

CHAPTER 7 ARTICLE 4: IN THE SHADOW OF GEOPOLITICAL CONFLICT: IS COLLABORATION WITH CHINA KEY TO CANADIAN 5G RESEARCH SUCCESS?

Anas Ramdani, Catherine Beaudry and Mario Bourgault

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7.1 Abstract

Recent geopolitical tensions surrounding 5G technology have impacted academic world, particularly by affecting international scientific collaboration. In this context, collaboration with China, an international leader in 5G technology, is being heavily scrutinized by several governments, who are assessing the nature of these scientific partnerships. This is the case in Canada, where scientific collaboration with Chinese researchers has been called into question. Assessing the impact of these collaborations on the performance of Canadian researchers is therefore essential. Through an analysis of a comprehensive database containing information on collaborations, funding, publications and citations, we find that collaboration with Chinese researchers positively impacts the performance of Canadian researchers in the field of 5G. However, direct collaboration with Huawei negatively affects productivity, but positively moderates the relationship between international collaboration and productivity. While these collaborations are important, Canadian researchers have viable alternatives for improving their performance through collaborations with researchers from other countries.

Keywords: Geopolitical tensions; International collaboration; 5G; Huawei; Public funding

7.2 Introduction

In recent years, the global technological landscape has been shaped by geopolitical tensions (Danilin, 2022). Several countries are competing for leadership in key technologies that have an impact not only on economic development, but also on national security. In response to these challenges, new public policies and initiatives, such as the recent OECD publication, "*Agenda for Transformative Science, Technology, and Innovation Policies*", aim to provide guidance to science, technology and innovation (STI) policymakers in formulating and implementing reforms in this complex geopolitical environment (OECD, 2024). A key example that has led to these initiatives is the rising tensions around 5G technology. The United States has accused China of espionage using 5G equipment (Friis & Lysne, 2021). The security risks associated with 5G, combined with its high potential for technological innovation, have positioned this technology at the center of the competition for global technological leadership. Canada was also involved in these geopolitical tensions following the arrest of Huawei's CFO in Vancouver (Jaisal, 2020; The Globe & Mail, 2018; Friis & Lysne, 2021; Azad, 2022). These tensions have also had an impact on the academic world, particularly after Western institutions reassessed their international collaborations, especially with Chinese institutions. Indeed, collaboration between China and the USA began to decline in 2020 (OECD, 2023). These might have been influenced by rising geopolitical tensions as this decline intensified in 2021, particularly in the fields of engineering and natural sciences (OECD, 2023). Growing concern about security in research is also reflected in the OECD's publication of the report "*Integrity and Security in the Global Research Ecosystem*" (OECD, 2022). This report highlights the need for greater awareness and protective measures within the academic community, while stressing the importance of policies that guarantee research security while encouraging international scientific collaboration.

Given this context, it is crucial to analyze the significance of scientific collaborations involving Chinese university researchers and companies like Huawei. This study aims to assess whether, despite the geopolitical tensions, these collaborations continue to offer substantial benefits to Canadian researchers in terms of their performance and technological advancements

To this end, we reviewed the literature on the role of scientific collaboration in enhancing researcher performance (Lee & Bozeman, 2005; Abramo et al., 2009; Gazni & Didegah, 2011; Liao, 2011). Studies generally link scientific collaboration to improved researcher performance, manifested by greater productivity[48] and increased usefulness[49] of their publications. Lee & Bozeman (2005) conducted a statistical analysis with academic researchers in the United States, uncovering a positive correlation between the number of collaborators and the number of publications in scientific journals. Gazni & Didegah (2011) found that, across various fields, the

[48] "Productivity" usually refers to the number of papers produced by authors.
[49] "Usefulness" refers to how often a publication's content is practically applied, typically measured by citations. While some researchers view these citations as indicators of quality, we argue that they primarily indicate how the cited work is used (Sugimoto & Larivière, 2023).

number of collaborative publications at Harvard University significantly exceeds that of single-author publications.

The impact of collaboration on scientific performance varies according to the type of collaboration. Generally, the literature suggests that international collaboration positively influences researchers' productivity and the usefulness of their work (Lancho Barrantes et al., 2012; Wang & Shapira, 2015; Fu et al., 2018; Aldieri et al., 2019; Onyancha, 2021; Mwantimwa & Kassim, 2023; Veretennik & Shakina, 2024). However, when it comes to cross-sector collaboration, there is a lack of consensus on its impact, particularly between universities and companies (Banal-Estañol et al., 2013). For some researchers, cross-sector collaboration can negatively affect academic contributions, as companies often prioritize the protection of their intellectual property through patents (Louis et al., 2001; Czarnitzki et al., 2015). Other studies suggest that collaboration with companies can benefit researchers under specific conditions (Gulbrandsen & Smeby, 2005; Bikard et al., 2019).

Although several studies have explored the impact of scientific collaboration on researchers' performance, there is still a lack of studies focusing on the importance of these types of collaborations with a specific country, in a context of geopolitical tensions, national security concerns, and intellectual property theft. Our study addresses this gap by examining the significance of collaborations between Canadian researchers and their Chinese counterparts, including with Huawei. This study aims to evaluate the role of scientific collaboration with China within a context of geopolitical tension. Specifically, it seeks to answer the question: "What is the impact of scientific collaboration with China on the scientific performance of Canadian researchers in the field of 5G?"

We constructed a database containing bibliometric and collaboration data. By using panel data to account for changes in various attributes over time, we can assess the impact of collaborations with Chinese researchers and Huawei on scientific performance. First, we examine the effect of collaboration with China and Huawei on the productivity of Canadian researchers, measured by the number of publications. Second, we analyze the influence of collaboration with Chinese researchers and Huawei on research usefulness, assessed by the number of citations, and explore alternatives for Canadian researchers to collaborate with other prolific countries.

The main findings of this study, and our main contribution, indicate that collaboration with China generally has a positive impact on the performance of Canadian researchers. However, this collaboration is neither unique nor irreplaceable, as there are viable alternatives with other prolific 5G countries to enhance researcher performance. The remainder of the article is organized as follows: Section 2 presents the conceptual framework and hypotheses; Section 3 describes the data, econometric models, and methodology; Section 4 presents the results; and finally, Section 5 discusses and concludes the article.

7.3 Conceptual framework

Several studies suggest that, when fully implemented, 5G technology will significantly impact various economic sectors, including healthcare, automated industry, smart cities, and smart homes. 5G is often linked to increased GDP, job creation, and enhanced productivity. It is also expected to deliver significant social benefits, improving quality of life in areas such as transportation, education, and healthcare (Skouby & Lynggaard, 2014; Yu et al., 2017; Ahad et al., 2020; Rühlig & Björk, 2020). This convergence of diverse fields and the significant societal impact of 5G emphasize the need for scientific collaboration to fully understand and develop the full potential of this technology.

Research is increasingly conducted collaboratively due to the growing complexity of research and the increasing specialization of researchers, both of which require collaboration to tackle complex challenges. Additionally, the high costs of research and available funding also support this movement towards collaboration (Abramo et al., 2009; Sabah et al., 2019).

Scientific collaboration is often measured in the literature using bibliometric indicators, particularly through the co-publication of articles (Bordons et al., 2013; Veretennik & Shakina, 2024). Although scientific collaboration is not solely limited to co-publication, this indicator is widely recognized as a reliable and tangible measure of scientific cooperation. It also occurs at different levels: international collaboration involves researchers from various countries, and cross-sector collaboration involves cooperation between different types of organizations, such as universities and companies.

There is a positive relationship between international collaboration and increased researcher productivity, as well as the usefulness of scientific publications across various disciplines and countries. This is supported by several studies (Bordons et al., 2013; Puuska et al., 2014; Jeyasekar

& Saravanan, 2015; Polyakov et al., 2017). Aldieri et al. (2019) observed that international collaborations positively influence research quality in Italy. Similarly, Fu et al. (2017) demonstrated that international collaboration enhances citation rates for scientists in the highly regulated field of nuclear science and technology. Bordons et al. (2013) noted that publications from international collaborations receive a higher number of citations than non-collaborative publications. In Finland, Puuska et al. (2014) also found that international co-published articles are on average more cited than national publications. Our first hypothesis aligns with the literature:

H1. Researchers who collaborate more internationally have (a) greater scientific productivity and (b) their publications are more highly cited.

Collaborating with researchers from China, a leading country in the field of 5G that has invested considerably in this technology, may be highly beneficial for Canadian researchers. This cooperation provides access to new research ideas and state-of-the-art equipment, fostering innovative work at the forefront of technology, which could enhance the performance of Canadian researchers and increase their citation record. Based on this premise, we formulate the following two hypotheses proposing both a direct and an indirect (moderating) effect of collaboration with Chinese researchers:

H1.1. Researchers who collaborate more internationally with at least one Chinese researcher have (a) greater scientific productivity and (b) their publications are more highly cited.

H1.2. Collaboration with Chinese researchers has a positive moderating effect on the relationship between international scientific collaboration and (a) productivity and (b) scientific usefulness.

Unlike international collaboration, the impact of cross-sector collaboration, particularly between universities and firms, on researcher performance lacks consensus in the literature. Some studies suggest that cross-sector collaboration hinders academic contributions, primarily because private companies often hesitate to share proprietary knowledge, thus restricting the scope of national collaborations (Abramo et al., 2009). Researchers involved in such collaborations typically produce fewer publications, as companies aim to protect their intellectual property through patents, often restricting their academic partners from publishing until the patent is filed or granted (Louis et al., 2001; Kneller et al., 2014; Czarnitzki et al., 2015).

However, under certain specific conditions, cross-sector collaboration may be beneficial for researchers' performance. Banal-Estañol et al. (2013) suggested that project quality increases when collaborating companies possess specific characteristics, such as a below-average publication record, which may otherwise be less advantageous than no collaboration at all. Bikard et al. (2019) discovered that, under certain circumstances, university-industry collaborations can enhance the scientific contributions of researchers, especially in projects with high scientific and commercial potential. This type of collaboration fosters a productive division of labor: universities concentrate on fundamental scientific advances, while industrial companies handle commercialization aspects. These authors observed that researchers who collaborate with industrial companies tend to produce more subsequent publications and fewer patents than those who do not engage in such collaborations.

Furthermore, the impact of university-industry collaboration may differ across disciplines. Abramo et al. (2009) studied its effects on scientific performance and found notable variations between fields. For instance, in mathematics, computer science, medicine, agriculture, and veterinary medicine, collaboration does not influence academic performance. In industrial and information engineering, as well as in chemical sciences, collaboration demonstrates a weak correlation with the quality of publications when measured by indicators such as journal impact factor, which is based on citations. Conversely, in biological sciences, and to some extent in physical and earth sciences, frequent collaboration with private partners is associated with higher productivity.

In the field of 5G, we posit that cross-sector collaboration could enhance researchers' performance. First, given the rapid evolution of this discipline, such collaboration allows researchers to stay up to date with the latest technological advancements, potentially aiding the publication of scientific papers. Second, unlike theoretical research, 5G research heavily emphasizes practical applications, often necessitating access to state-of-the-art equipment for meaningful experiments. Collaboration with industry is thus necessary, as it provides the advanced technological resources necessary to increase the volume of publications and citations. Based on these considerations, we propose the following hypothesis:

H2. Researchers who engage in more intersectoral collaboration (a) have greater scientific productivity and (b) produce publications that receive more citations.

Collaboration with Huawei, a global leader in 5G, could be advantageous for Canadian researchers. This company provides access to advanced infrastructure and R&D resources typically unavailable in academia. Working with Huawei would allow researchers to explore the most promising new applications and research directions in 5G, addressing current challenges and fostering innovation at the forefront of technological development. Additionally, collaborating with a major player like Huawei could broaden their international research network and enhance researcher productivity. Such collaboration would also offer access to fundings that support a large number of research projects, potentially leading to an increase in the number of publications.

Since Huawei operates globally, it may act as a catalyst for broader international collaborations, increasing access to a large number of research projects and, consequently, the total number of publications. Furthermore, collaboration with Huawei could enhance the effectiveness of existing international partnerships. For instance, integrating Huawei's technology and technical expertise may accelerate research and experimentation, leading to faster and more frequent production of publishable results. Based on this information, we propose the following two hypotheses:

H2.1. Researchers who collaborate with Huawei have a greater scientific productivity.

H2.2. Collaboration with Huawei has a positive moderating effect on the relationship between international collaboration and scientific productivity.

7.4 Methodology

7.4.1 Database construction

Our database is compiled from three distinct sources: the Natural Sciences and Engineering Research Council (NSERC), The Mathematics of Information Technology and Complex Systems (MITACS), and Web of Science. NSERC, a Canadian federal agency, supports national research and funds research projects. The funding database contains information on the amounts awarded to researchers, along with other metadata related to participants and funded projects. The database is organized into three interconnected tables, each linked by a unique annual payment identifier. The first table primarily includes data related to the project's principal investigator (each project has a single principal investigator) and details about the project itself. This table records the full names of the researchers, their affiliations, the year of each payment, the amount of funding granted, as well as the funding program, title, and abstract of the project. The second table lists the co-applicants associated with the projects, including their affiliations (institution, country, province). The third table identifies the organizations involved in the projects, which may include companies, universities, intermediaries, government institutions, associations, or non-profit organizations.

We compiled our dataset by extracting projects containing the term "5G" in the title or abstract, covering the period from 2010 to 2021[50] . We exclusively used the term "5G"[51] as a keyword to ensure that the projects were specifically related to the fifth generation of mobile communication[52]. This search resulted in a total of 840 annual projects, involving 249 principal investigators and 92 co-investigators.

To enrich our database, we incorporated data from MITACS, a national Canadian organization that primarily supports partnerships between universities and industry. This database includes information such as researchers' full names, affiliations, and project titles. From here, we extracted projects that specifically mentioned "5G" in their titles, and the identified researchers were added to the existing NSERC database, totaling 24 additional researchers. At this stage, we added data from Web of Science by extracting articles containing the term "5G" in the title, abstract, or keywords from 2010 to 2021. We identified Canadian researchers using metadata from Web of Science. Projects associated with these Canadian authors were then incorporated into the NSERC database. This added 370 authors, bringing the total to 796 researchers in the NSERC database after manual disambiguation and the removal of duplicate names.

Additionally, for each of the 796 researchers, we extracted the necessary bibliometric data from the repository of the Observatoire des Sciences et des Technologies (OST) for Web of Science[53]. The OST has assigned a unique identifier to each Canadian researcher. The initial step involved identifying the unique identifiers for each of the 804 authors based on their names and affiliations. Once we obtained the researchers' identifiers, we were able to extract all their articles published between 2010 and 2021, along with all the associated bibliometric data. This data collection enabled us to calculate key variables of interest, such as the number of publications per researcher

[50] The specific time period was chosen for two main reasons: Firstly, very few projects and grants existed before 2010; Secondly, NSERC has not published databases for 2022 and 2023.

[51] We first extracted articles using keywords such as network slicing, massive MIMO, network function virtualization (NFV), millimeter wave (mmWave) and software-defined networking (SDN), giving an initial total. After consulting with experts, we decided to retain only those articles explicitly mentioning the term "5G", in order to reduce inclusion errors.

[52] The term 5G is not just used to refer to the fifth generation. In some cases, it can also refer to 5 grams. We have therefore excluded from our database projects that use this abbreviation in this context.

[53] The Observatoire des sciences et des technologies gave us access to their database built from the Web of Science, which contains bibliometric metadata for each article and author.

and the number of citations their publications[54] received. Collectively, these 796 researchers published 32,294 papers from 2010 to 2021.

Finally, we constructed a balanced panel for each researcher, organized into nested three-year periods, covering 2010 to 2021. Figure 7-1 in the document summarizes the entire process of database construction.

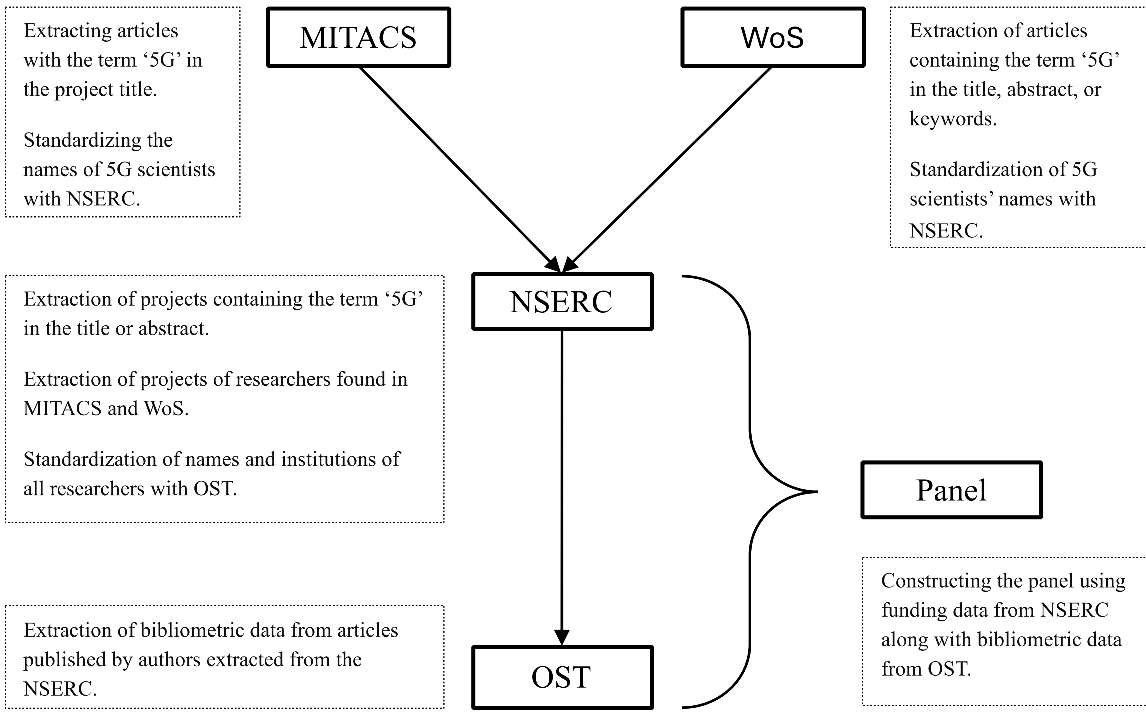

Figure 7-1. Data sources and panel construction process

7.4.2 Variables description

Scientific performance is evaluated by two indicators. Productivity is measured by the average annual number of publications each researcher produced (*AvgPaper*). Similarly, the usefulness of each researcher's publications is measured by the yearly average of the mean normalized citation scores of their publications (*Avgmnc*)[55].

[54] To carry out this process, it was necessary to manually disambiguate researchers' names, both within and between the various databases, to ensure better merging between the different databases. This step enabled identical or similar names to be correctly distinguished. This work was supported using bibliometric information and references from official university web pages.

[55] During the course of the research, we tested three different citation metrics: (1) the raw number of citations received by the article from its publication until the end of the period covered by the OST database (2023); (2) the mean normalized citation score of the article over a 10-year observation window following its publication; and (3) the mean normalized citation score from the publication of the article until the end of the period covered by the OST database (2023). The last option yielded the most consistent results and is reported in the paper.

Turning to our independent variables, we begin with those measuring different types of collaboration. For each Canadian researcher, we calculated the average number of articles co-published with an international researcher (*AvgInternatArt*) and the average number of articles co-published locally with another organization during each period (*AvgIntersectArt*). This metric reflects intersectoral collaboration between researchers affiliated with different types of organizations within Canada. Although the OST database provides the names of authors' organizational affiliations, it does not specify the nature of these organizations. We extracted all affiliations and manually classified each of these Canadian organizations into five distinct groups:

- Education and research establishments, which include universities, schools engaged in research, and independent research centers;
- Government institutions, which comprise branches of the federal and provincial governments.
- Hospitals, which also include clinics and other establishments providing healthcare or related services.
- Associations, which include professional associations, charities and non-profit organizations (NPOs).
- Companies, which represent all private companies and firms.

An article is therefore considered a cross-sector collaboration if it includes authors from at least two different organizational affiliations among these five groups.

To measure collaboration with Chinese researchers, we created a dichotomous variable (*dCHINA*), which takes the value of 1 for each Canadian researcher who co-published with at least one author affiliated with a Chinese institution in a given period, and 0 otherwise. Similarly, we applied a similar approach to create four other dummy variables to account for collaborations between Canadian researchers and those from other prolific 5G countries: the United States (*dUSA*), the United Kingdom (*dUK*), India (*dINDIA*), and South Korea (*dSKOREA*). We also developed a dichotomous variable to assess a Canadian researcher's collaboration with Huawei (*dHuawei*), assigning a value of 1 whenever a researcher is involved in an NSERC-funded project in collaboration with Huawei within a specific period, and 0 otherwise.

Research funding is known to influence researcher performance (Campbell et al., 2010; Benavente et al., 2012; Tahmooresnejad et al., 2015; Wang & Shapira, 2015; Ebadi & Schiffauerova, 2016;

Tahamtan et al., 2016; Gush et al., 2018; Checchi et al., 2019; Heyard & Hottenrott, 2021; Vurchio & Giunta, 2021). To assess the impact of funding on performance, we introduced the variable *AvgGovColGrant*, which measures the average amount of collaborative funding received by the researcher for each period. This amount only includes the portion of the funding specifically allocated to the researcher. To determine this share, the total amount awarded was divided by the number of researchers (PI and co-PIs) involved in the NSERC project. We also created a control variable related to funding, indicating whether the researcher held a research chair[56] (*dChair*), an indicator of academic recognition and access to additional funding resources. Years of experience have been shown to influence scientists' performance (Lee & Bozeman, 2005; Jacob & Lefgren, 2011; Benavente et al., 2012; Ebadi & Schiffauerova, 2016). To account for this factor, we included a control variable, *CareerAge*, which measures the number of years since the publication of the researcher's first article. This variable is generally considered a reliable proxy for the researcher's actual age (Nane et al., 2017; Robinson-Garcia et al., 2020).

There is a recognized relationship between a researcher's past and future performance, often referred to as the Matthew effect, which suggests that more influential researchers tend to gain even greater influence (Larivière & Gingras, 2010). To evaluate the impact of researchers' past performance on their future output, we incorporated two additional control variables into our econometric model. The first variable, $AvgPaper_{it-2}$, measures the average number of publications in the past, while the second, $Avgmnc_{it-2}$, quantifies the mean normalized citation score received in the past. These variables help us determine whether researchers who have published frequently and received extensive citations in the past continue to perform well in terms of publications and citations.

Additionally, we introduced a variable representing the proportion of articles published in a given year by authorship positions (first, middle, or last) held by researchers on the list of authors during the studied period. This variable, categorized into *PropArtFirst*, *PropArtMiddle*, *PropArtLast*, reflects the researcher's relative contribution to publications, providing further insight into their collaborative and leadership roles in research projects (Beaudry & Larivière, 2016; Peidu, 2019).

In our statistical model, other control variables were incorporated to account for their impact on researchers' academic performance: the NSERC funding program group linked to the funding

[56]We extracted these data from the Canada Research Chairs (CRC) database.

obtained by the researchers (*dProgram_ResPart, dProgram _Discovery, dProgram _Training)*[57] , the discipline group of their publications to reflect interdisciplinary differences (*dDisc_ssh, dDisc_life_health_sciences, dDisc _physical_chemical, dDisc _earth_space and dDisc _Engineering)*[58], and the researchers' Canadian province of residence to control for regional variations (*dProv_AB, dProv_BC, dProv_QC, dProv_ON, dProv_ROC*[59]).

7.4.3 Econometric models

Given that the dependent variables are continuous, we employed linear regression for panel data to estimate researcher productivity and the usefulness of researchers' papers in the 5G field. In addition to the variables described in the previous section, we incorporated non-linear effects, adding a quadratic term, for funding and career age variables, as the literature indicates that these factors can significantly impact the number of publications and citations (Tahmooresnejad et al., 2015; Beaudry & Larivière, 2016). To assess hypotheses H1.2 and H2.2, we tested moderating effects through the addition of interaction variables in the regression models. This approach enabled us to examine whether collaboration with Huawei and Chinese researchers moderates the impact of international collaboration on the dependent variables.

As individual effects were not adequately captured by random-effects models, we opted for fixed-effects models to estimate all regressions[60]. The model used to estimate the average number of articles published by Canadian researchers in the field of 5G is represented by Equation (1), while Equation (2) represents the model for estimating the yearly average of the mean normalized citation score received by researchers[61]:

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[57] The NSERC database provides the names of the programs to which the funding relates, but also groups them into different categories. Three program groups are found in our panel: Research partnership, Discovery and Training. More details on these groupings are provided in Appendix C.

[58] The OST database provides the disciplines of scientific articles. We have grouped these disciplines into five main families. More details on these groupings are provided in Appendix C.

[59] AB: Alberta, BC: British Columbia, QC: Quebec, ON: Ontario, ROC: Rest of Canada, which includes all the other Canadian provinces.

[60] Hausman specification tests showed that fixed-effects models were preferable to random-effects models.

[61] For the sake of conciseness, we have grouped the four 5G prolific variables, dUSA, dUK, dINDIA, and dSKOREA, under the composite variable dProlCountries in the subsequent equations; however, they are still treated individually within the analysis.

$$[AvgPaper_{it}] = f\begin{pmatrix} AvgInternatArt_{it-1}, AvgIntersectArt_{it-1}, dCHINA_{it-1}, dHuawei_{it-1}, \\ AvgGovColGrant_{it-2}, AvgGovIndGrant_{it-2}, \\ [AvgGovColGrant_{it-2}]^2, [AvgGovIndGrant_{it-2}]^2, \\ CareerAge_{it-1}, [CareerAge_{it-1}]^2, dProlCountries, dDiscipline, dProgram, dProvince, \\ dChair_{it-2}, PropArtFirst_{it-1}, PropArtLast_{it-1}, \\ [dHuawei \times AvgInternatArt]_{it-1}, [dCHINA \times AvgInternatArt]_{it-1}, \\ [dHuawei \times dCHINA]_{it-1}, [dHuawei \times dCHINA \times AvgInternatArt]_{it-1} \end{pmatrix} \quad (1)$$

$$[Avgmnc_{it}] = g\begin{pmatrix} (AvgGovColGrant_{it-1}), (AvgInternatArt_{it-1}), (AvgIntersectArt_{it-1}), \\ AvgPaper_{it-2}, Avgmnc_{it-2}, dProlCountries, dDiscipline, dProgram, dProvince, \\ dChair_{it-2}, PropArtFirst_{it-1}, PropArtLast_{it-1}, CareerAge_{it-1}, [CareerAge_{it-1}]^2 \\ [AvgInternatArt \times dProlCountries]_{it-1}, \\ [AvgInternatArt * dCHINA]_{it-1} \end{pmatrix} \quad (2)$$

To determine the appropriate temporal impact, several lag structures were tested including one-, two- and three-period lags. The most robust results were obtained with a one-period lag for the collaboration variables[62].

It is important to mention that researchers' past performance ($AvgPaper_{it-2}$ *and* $Avgmnc_{it-2}$) and average collaborative funding (*AvgGovColGrant*) co-evolve, which could be a source of potential endogeneity (Beaudry & Sedki, 2012; Tahmooresnejad et al., 2015). Therefore, a simple linear regression (OLS) for panel data is not suitable for this analysis. The potential endogeneity arises because higher-performing researchers tend to secure more funding from public agencies like NSERC, while the quantity and usefulness of their publications are heavily influenced by the level of funding they receive.

The use of instrumental variables (IV) is an effective method for addressing endogeneity issues. In this context, it is possible to perform a two-stage regression. We employed the xtivreg2 command in Stata to implement the two-stage least squares (2SLS) method.

The first stage involves estimating the endogenous variable using a combination of instrumental variables and the other explanatory variables from the main regression. This approach helps mitigate the bias introduced by the error term associated with the endogenous variable. By substituting the endogenous variable with its estimated value in the main regression equation, we effectively address the endogeneity problem. One key instrument is the past average individual funding a scientist has received (*AvgGovIndGrant*), which predicts future collaborative funding

[62] Using longer lags (two or three periods) in our panel, which is constructed with overlapping three-year periods, risks losing relevant observations and information, as well as diluting temporal effects.

amounts. This finding suggests that researchers who have secured substantial funding in the past are more adept at obtaining new research funds due to their enhanced networking capabilities, which enable them to identify and capitalize on funding opportunities. Additionally, we used a dichotomous variable representing past collaboration with industrial leaders, specifically Huawei (*dHuawei*) and its direct competitor Ericsson (*dEricsson*), as the second instrument. This variable underscores that partnerships with key actors significantly increase the likelihood of obtaining collaborative public funding. The resulting model is given by Equation (3):

$$AvgGovColGrant_{it-1} = f\begin{pmatrix} AvgGovIndGrant_{it-2}, [dHuawei \times dEricsson]_{it-1}, \\ \text{Variables2ndStage} \end{pmatrix}$$

$$[AvgCit_{it}] = f\begin{pmatrix} AvgGovColGrant_{it-1}, AvgInternatArt_{it-1}, \\ AvgIntersectArt_{it-1}, AvgPaper_{it-2}, AvgCit_{it-2}, dProlCountries, dDiscipline, dProgram, \\ dProvince, dChair_{it-2}, PropArtFirst_{it-1}, PropArtLast_{it-1}, CareerAge_{it-1}, [CareerAge_{it-1}]^2 \\ [AvgInternatArt \times dProlCountries]_{it-1}, \\ [AvgInternatArt \times dCHINA]_{it-1} \end{pmatrix} \tag{3}$$

7.5 Results

We first conducted endogeneity tests for both regressions[63]. For the regression estimating researcher productivity, measured by the average number of publications per researcher (*AvgPaper*), the test did not reveal any endogeneity However, for the regression estimating the yearly average mean normalized citation score (*Avgmnc*), the test confirmed that endogeneity is present, and that our chosen instruments are valid[64].The results related to our first dependent variable, *AvgPaper*, are detailed in Table 7-1. Contrarily to expectations, international collaboration does not have a significant direct effect on researcher productivity, which does not support our hypothesis H1.a. This finding contrasts with the prevailing results in the existing literature (Bordons et al., 2013; Puuska et al., 2014; Fu et al., 2018). However, our study finds that collaboration with Chinese researchers (*dChina*) is positively associated with greater scientific production, thereby validating hypothesis H1.1.a. Given China's leadership in 5G technology and substantial government investments in research and development, Canadian scientists collaborating with Chinese researchers can access significant resources and expertise, that further

[63] We used the ivreg2 command with the *endog()* option to assess endogeneity and verify the validity of our instruments. The presence of endogeneity is confirmed if the p-value of the endogeneity test is significant. Conversely, the validity of the instruments is ensured if the p-value of the overidentification test is not significant.
[64] These results are shown in Table 7-2.

contribute to enhancing their productivity. Nevertheless, this positive impact is not unique to collaborations with China, as partnerships with other prolific countries are also significantly associated with a higher average number of publications by Canadian researchers. Thus, while collaboration with Chinese researchers offers benefits, other effective avenues exist to enhance productivity.

Table 7-1. Impact on average papers[65]

Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**
ln($AvgGovColGrant_{it-2}$/10000+1)	**-0.038*** **	**-0.039*** **	**-0.038*** **	**-0.039*** **	**-0.037** **	**-0.038*** **
	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)
[ln($AvgGovColGrant_{it-2}$/10000+1)]^2	**0.031**** **	**0.031**** **	**0.031**** **	**0.031**** **	**0.030**** **	**0.031**** **
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
ln($AvgGovIndGrant_{it-2}$+1)	-0.025	-0.026	-0.025	-0.025	-0.024	-0.024
	(0.017)	(0.017)	(0.017)	(0.017)	(0.017)	(0.017)
[ln($AvgGovIndGrant_{it-2}$+1)]^2	**0.003* **	**0.003* **	**0.003* **	**0.003* **	0.003	0.003
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
$dChair_{it-2}$	0.039	0.039	0.040	0.040	0.038	0.041
	(0.027)	(0.027)	(0.027)	(0.027)	(0.027)	(0.027)
ln($PropArtFirst_{it-1}$*100+1)	-0.004	-0.004	-0.005	-0.004	-0.005	-0.005
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
ln($PropArtLast_{it-1}$*100+1)	**0.043**** **	**0.044**** **	**0.043**** **	**0.044**** **	**0.043**** **	**0.044**** **
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$AvgInternatArt_{it-1}$	-0.015	-0.021	-0.021	-0.027	-0.015	-0.023
	(0.018)	(0.019)	(0.018)	(0.020)	(0.018)	(0.020)
ln($AvgIntersectArt_{it-1}$*10+1)	**0.032**** **	**0.032**** **	**0.032**** **	**0.032**** **	**0.032**** **	**0.033**** **
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
ln($CareerAge_{it-1}$/10+1)	**0.990**** **	**0.995**** **	**0.990**** **	**0.996**** **	**1.000**** **	**0.998**** **
	(0.150)	(0.150)	(0.150)	(0.150)	(0.150)	(0.150)
[ln($CareerAge_{it-1}$/10+1)]^2	**-0.747**** **	**-0.752**** **	**-0.750**** **	**-0.754**** **	**-0.757**** **	**-0.756**** **
	(0.126)	(0.126)	(0.126)	(0.126)	(0.126)	(0.126)
$dUSA_{it-1}$	**0.106**** **	**0.106**** **	**0.105**** **	**0.105**** **	**0.106**** **	**0.105**** **
	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)
dUK_{it-1}	**0.077**** **	**0.077**** **	**0.078**** **	**0.078**** **	**0.077**** **	**0.078**** **
	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)
$dINDIA_{it-1}$	**0.152**** **	**0.152**** **	**0.152**** **	**0.152**** **	**0.151**** **	**0.150**** **
	(0.020)	(0.020)	(0.020)	(0.020)	(0.020)	(0.020)
$dSKOREA_{it-1}$	**0.058*** **	**0.058*** **	**0.059*** **	**0.058*** **	**0.059*** **	**0.059*** **
	(0.019)	(0.019)	(0.019)	(0.019)	(0.019)	(0.019)
$dCHINA_{it-1}$	**0.075**** **	**0.056*** **	**0.076**** **	**0.057*** **		
	(0.013)	(0.024)	(0.013)	(0.024)		
$dHuawei_{it-1}$	-0.009	-0.009	**-0.055* **	**-0.056* **		
	(0.024)	(0.024)	(0.037)	(0.037)		
$dHuawei_{it-1}$ x $AvgInternatArt_{it-1}$			**0.103** **	**0.102** **		
			(0.061)	(0.061)		
$dCHINA_{it-1}$ x $AvgInternatArt_{it-1}$		0.038		0.037		
		(0.038)		(0.038)		

[65] For variables hypothesized to have a positive impact, the reported p-values have been divided by two to reflect one-tailed tests.

Table7-1. Impact on average papers (continued and end)[66]

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
No $dHuawei_{it-1}$ x *Yes* $dCHINA_{it-1}$					**0.071******	**0.060*****
					(0.014)	(0.024)
Yes $dHuawei_{it-1}$ x *No* $dCHINA_{it-1}$					-0.034	**-0.053***
					(0.029)	(0.039)
Yes $dHuawei_{it-1}$ x *Yes* $dCHINA_{it-1}$					**0.102*****	-0.040
					(0.035)	(0.082)
No $dHuawei_{it-1}$ x *Yes* $dCHINA_{it-1}$ x $AvgInternatArt_{it-1}$						0.024
						(0.039)
Yes $dHuawei_{it-1}$ x *No* $dCHINA_{it-1}$ x $AvgInternatArt_{it-1}$						0.041
						(0.070)
Yes $dHuawei_{it-1}$ x *Yes* $dCHINA_{it-1}$ x $AvgInternatArt_{it-1}$						**0.243****
						(0.125)
Constant	**0.286*****	**0.285*****	**0.290*****	**0.288*****	**0.286*****	**0.287*****
	(0.094)	(0.094)	(0.094)	(0.094)	(0.094)	(0.094)
Nb observations	6,152	6,152	6,152	6,152	6,152	6,152
Nb groups	796	796	796	796	796	796
F	**61.3******	**59.7******	**59.8******	**58.2******	**59.8******	**55.4******
R2	0.293	0.294	0.294	0.294	0.294	0.294
Log likelihood	135.648	136.230	137.302	137.850	137.225	139.595
Log likelihood0	-933.038	-933.038	-933.038	-933.038	-933.038	-933.038

Notes: ****p≤0.001, ***p≤0.01, **p≤0.05, *p≤0.1 and Standard errors in parentheses; Dummy variables for discipline, program and province are included; *PropArtMiddle* is omitted.

Contrary to our hypothesis H1.2.a, collaboration with Chinese researchers does not moderate the relationship between international collaboration and the average number of publications. This indicates that while collaboration with Chinese researchers has a direct positive effect on productivity, it does not enhance the overall influence of international collaborations.

The impact of intersectoral collaboration on researcher productivity is positive and significant, hence supporting hypothesis H2.a. The results from Models 1 and 2 show that the direct effects of collaboration with Huawei are not significant. However, when adding its moderating effect on the relationship between international collaboration and the average number of publications, the direct effect of collaborating with Huawei becomes marginally significant and negatively impacts the average number of publications, contradicting hypothesis H2.1. This reduction in publications may be due to several factors. Corporate entities like Huawei may prioritize proprietary research and development, focusing on patents and trade secrets to maintain competitive edges. This emphasis

[66] The robustness check for the impact on productivity was ensured through the use of the regress command for non-panel data with clustered standard errors. The robustness for impact on usefulness was conducted using the ivregress command for non-panel data with clustered standard errors. This analysis is documented in Appendix C.

on protecting intellectual property and commercial interests rather than publishing open research may lead to fewer collaborative papers being submitted to academic journals. Additionally, the geopolitical tensions and suspicions surrounding collaborations with Huawei may diminish their effectiveness, as restrictions, security concerns, and administrative barriers associated with these tensions may contribute to the observed negative effect. Despite the direct negative effect, collaboration with Huawei has a positive moderating effect on the relationship between international collaboration and researcher productivity, supporting hypothesis H2.2. This suggests that the involvement of Huawei in international collaborations amplifies their influence on productivity, as illustrated in Figure 7-2.

As a multinational company with a significant presence in multiple countries, Huawei facilitates access for Canadian researchers to international collaborators. Through its extensive network and numerous partnerships, Huawei acts as an intermediary, fostering connections between Canadian and international researchers, thereby enhancing collaboration and publication opportunities. This synergy and complementarity between Canadian researchers, Chinese researchers, and Huawei boost the scientific output of Canadian researchers. Furthermore, a triple interaction involving collaboration with Huawei, Chinese researchers, and international collaboration also significantly enhances productivity. This combination of collaborations with Huawei and Chinese scientists optimizes international collaboration efforts and markedly increases researcher productivity, as demonstrated in Figure 7-3.

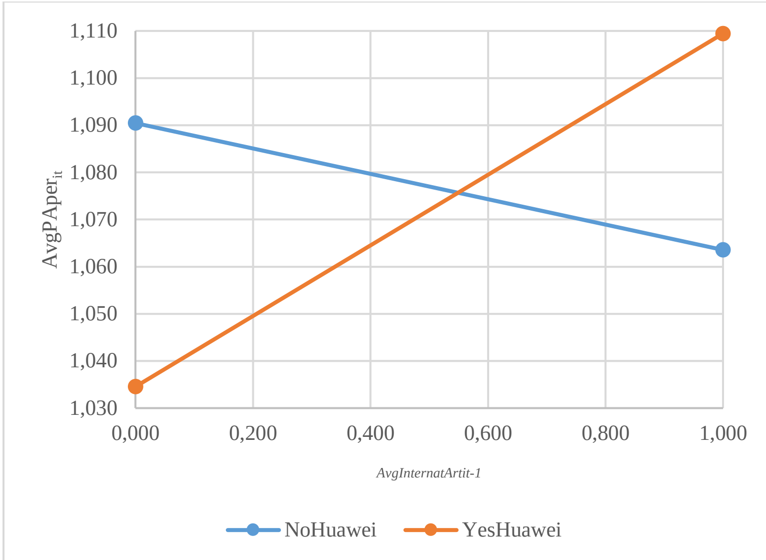

Figure 7-2. The moderating role of collaboration with Huawei on the relationship between international collaboration and researcher productivity.

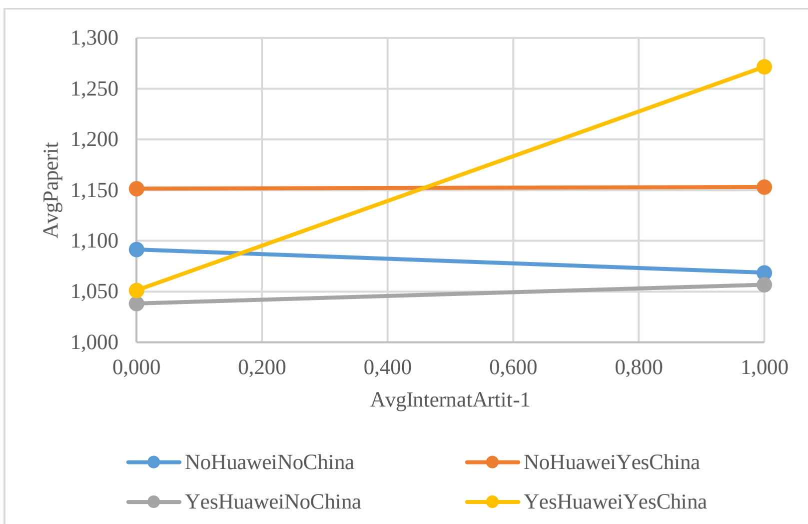

Figure 7-3. The moderating role of collaboration with Huawei and Chinese researchers on the relationship between international collaboration and researcher productivity.

Public funding exhibits a non-linear impact on the productivity of researchers. As illustrated in Table 7-1, the quadric terms of both collaborative funding (*AvgGovColGrant*) and individual funding (*AvgGovIndGrant*) are both significant. Our findings reveal that at higher levels of funding, the initial negative impact decreases, and the number of publications begins to increase, exhibiting an inverted-U relationship. These results underscore the significance of sufficient financial resources in providing researchers with access to the necessary infrastructure, equipment, and human resources required to execute projects that lead to publications.

Table 7-2 presents the results from the second stage of the 2SLS regression used to estimate the usefulness of articles (*Avgmnc*), while the first stage results are detailed in Appendix C.

Table 7-2. Impact on Average citations – Second Stage of regression results

Variables		**Model 1**	**Model 2**	**Model 3**	**Model 4**
ln($AvgGovColGrant_{it-1}$/10000+1)		**-0.128****	**-0.127****	**-0.127****	**-0.128****
		(0.052)	(0.052)	(0.052)	(0.052)
$dChair_{it-2}$		-0.061	-0.058	-0.057	-0.059
		(0.053)	(0.053)	(0.053)	(0.053)
ln($AvgPaper_{it-2}$ +1)		**0.083******	**0.082*****		
		(0.025)	(0.025)		
ln($Avgmnc_{it-2}$*10+1)				**0.075******	**0.076******
				(0.013)	(0.013)
ln($PropArtFirst_{it-1}$*100+1)		-0.002	-0.001	-0.001	-0.002
		(0.008)	(0.008)	(0.008)	(0.008)
ln($PropArtLast_{it-1}$*100+1)		**0.014****	**0.014****	**0.014****	**0.014****
		(0.007)	(0.007)	(0.007)	(0.007)
ln($AvgIntersectArt_{it-1}$*10+1)		-0.002	-0.001	0.0002	-0.001
		(0.016)	(0.016)	(0.016)	(0.016)
$AvgInternatArt_{it-1}$		**0.201******	**0.194******	**0.178******	**0.186******
		(0.036)	(0.043)	(0.043)	(0.036)
ln($CareerAge_{it-1}$/10+1)		**0.679****	**0.693****	**0.698****	**0.685****
		(0.300)	(0.300)	(0.298)	(0.297)
[ln($CareerAge_{it-1}$/10+1)]^2		**-1.415******	**-1.425******	**-1.387******	**-1.377******
		(0.249)	(0.249)	(0.248)	(0.248)
$dUSA_{it-1}$		0.029	0.060	**0.063***	0.031
		(0.021)	(0.038)	(0.038)	(0.021)
dUK_{it-1}		0.006	-0.069	-0.068	0.007
		(0.027)	(0.063)	(0.063)	(0.027)
$dINDIA_{it-1}$		**-0.080****	-0.137	-0.125	-0.064
		(0.040)	(0.098)	(0.097)	(0.040)
$dSKOREA_{it-1}$		**0.112*****	0.089	0.086	**0.116*****
		(0.038)		(0.094)	(0.038)
$dCHINA_{it-1}$		**0.054****	0.018	0.021	**0.061*****
		(0.026)	(0.047)	(0.047)	(0.026)
[$AvgInternatArt$ x $dUSA$]$_{it-1}$			-0.060	-0.064	
			(0.065)	(0.065)	
[$AvgInternatArt$ x dUK]$_{it-1}$			0.126	0.126	
			(0.098)	(0.098)	
[$AvgInternatArt$ x $dCHINA$]$_{it-1}$			0.072	0.079	
			(0.077)	(0.077)	
[$AvgInternatArt$ x $dINDIA$]$_{it-1}$			0.090	0.094	
			(0.147)	(0.147)	
[$AvgInternatArt$ x $dSKOREA$]$_{it-1}$			0.037	0.047	
			(0.142)	(0.142)	
Nb observations		6,152	6,152	6,152	6,152
Nb groups		796	796	796	796
F		**38.484******	**33.516******	**34.315******	**39.389******
R^2		0.181	0.182	0.186	0.185
Log likelihood		-4069.794	-4067.079	-4052.542	-4055.512
Sargan statistic (overidentification test of all instruments)	χ^2	1.004	0.893	0.867	0.981
Endogeneity test of endogenous regressors	χ^2	**9.659******	**9.586******	**9.510******	**9.587******

Notes: ****p≤0.001, ***p≤0.01, **p≤0.05, *p≤0.1 and Standard errors in parentheses; Dummy variables for discipline, program and province are included; *PropArtMiddle* is omitted.

The correlation between the two past performance variables, $AvgPaper_{it-2}$ and $Avgmnc_{it-2}$, forces us to include them in separate regressions (Models 1 and 4). Additionally, to test hypothesis H1.2b, we incorporated interaction terms between *AvgInternatArt* and countries dummy variables in subsequent models (Models 2 and 3).

In the first stage regression, the instruments used to address endogeneity show high statistical significance in explaining public collaborative funding (*AvgGovColGrant)*. Our findings reveal that having obtained higher average amounts of individual funding in the past (*AvgGovIndGrant*) is positively associated with raising more collaborative funding. This outcome exemplifies the Matthew effect within the context of research funding: the more funding a researcher has previously secured, the higher the likelihood of obtaining additional funding. Furthermore, participation in projects with leading companies such as Huawei and Ericsson is also associated with a significant increase in collaborative funding. This underscores the strategic advantages for researchers in partnering with industry leaders to access public funding. Collaborations with Huawei (*YesHuaweiNoEricsson*) in the field of 5G facilitate the acquisition of public funding. Similarly, collaborations with Ericsson (*NoHuaweiYesEricsson*) also significantly enhance access to public funding opportunities. Additionally, our results show that collaborating with both Huawei and Ericsson (*YesHuaweiYesEricsson)* further boosts the likelihood of obtaining public funding. In the context of geopolitical tensions surrounding Huawei, Ericsson offers a stable alternative for researchers seeking public funding within the 5G ecosystem.

In the second stage regressions, as detailed in Table 7-2, our results show that both collaboration with China and international collaboration individually enhance the average mean normalized citation score (*Avgmnc*), hence supporting hypotheses H1.b and H1.1b. The advanced expertise and state-of-the-art resources that Chinese researchers contribute to collaborations significantly enhance the usefulness of the research, resulting in higher citation rates for Canadian researchers. However, while collaboration with Chinese scientists directly affects citation rates, it does not moderate the effect of international collaboration on the usefulness of the research published, thus refuting hypothesis H1.2.b. The interaction between these two types of collaboration is not significant.

Moreover, the results indicate that collaborating with South Korea (d*SKOREA*) is positively associated with a better citation score, therefore presenting a viable alternative to collaborating with China for increasing the visibility and impact of Canadian 5G research. The results also show a decrease in average citations (*Avgmnc*) as collaborative funding (*AvgGovColGrant*) increases. This can be attributed to several factors. First, the majority of NSERC-funded 5G projects involve industry collaboration, which typically focuses on applied research aimed at addressing specific business challenges or developing practical solutions. Such projects often differ from theoretical research and tend to produce publications that are cited less frequently. Second, confidentiality agreements, which are common in industry collaborations, can restrict the publication and dissemination of research findings, reducing their visibility and citation count. Third, the administrative tasks associated with managing industry collaborations can consume a significant portion of researchers' time, limiting their capacity to engage in more visible research activities that might garner more citations.

In addition to the collaboration and funding variables, other factors also influence both dependent variables. The *CareerAge* of the researcher exhibits a non-linear quadratic relationship with *AvgPaper* and *Avgmnc*. The inverted-U shape pattern suggests that scientific productivity and usefulness peak at a certain point in a researcher's career. This observation is consistent with findings in the literature (Bonaccorsi & Daraio, 2003). This pattern may be due to the fact that as researchers advance in their careers, they often assume more administrative roles and serve on committees and advisory boards, reducing the time they can dedicate to research and potentially impacting their citation counts (Zuo & Zhao, 2021).

Researchers who frequently occupy the last author rank (*PropArtLast*) on papers tend to produce more publications and receive more citations on average. The last author position is often held by the leader of the laboratory or chair, or senior author who typically has a recognized expertise, and better performance in terms of publication and visibility (Peidu, 2019). This position is indicative of their productivity and citation impact. Furthermore, past performance indicators ($AvgPaper_{it-2}$ and $Avgmnc_{it-2}$) show that researchers who have published and been cited more frequently in the past continue to do so in the future, underscoring the cumulative advantage described by the Matthew effect in scientific research.

7.6 Discussion and conclusion

Geopolitical tensions between the USA and China have recently intensified, particularly around 5G technology. China, represented by its national company Huawei, is accused by the United States of exploiting international scientific collaborations and their 5G technology for espionage and intellectual property theft. Canada, also deeply involved in this dispute, is now critically examining all collaborations with Chinese researchers and Huawei. This particular context provides the rationale to evaluate the impact of these collaborations with China on the scientific performance of Canadian researchers. Our research provides valuable insights for policymakers, particularly in the context of international scientific collaboration and the challenges posed by geopolitical tensions.

Understanding the potential trade-offs between security measures and scientific performance is essential to ensuring that Canadian researchers can continue to benefit from international partnerships with China, as our results show, without compromising national security. In particular, our findings indicate collaboration with Chinese scientists is not only associated with greater productivity but also with more usefulness of Canadian researchers' publications. Given China's leadership in 5G research and development, its expertise provides a valuable resource for Canadian researchers to enhance their research outcomes. While such collaboration enhances research impact, policymakers must balance academic performance and openness with potential national security concerns. Several countries have begun taking steps to address the complexities of international scientific collaboration. For instance, Finland, in cooperation with its universities, issued "*Recommendations for academic cooperation with China*" (Ministry of Education and Culture, 2021). Similarly, Sweden released its "*Approach to matters relating to China*" (Government of Sweden, 2019), which outlines the challenges that come with such partnerships. In Canada, the government has developed two self-paced online courses aimed at researchers and university staff, titled "*Introduction to Research Security*" and "*Cyber Security for Researchers*". These 40-minute courses provide a broad overview of key information and engage participants with various educational techniques (Government of Canada, 2021a). Although these measures did not directly target China, they reflect broader protective actions being taken globally. These guidelines aim to address foreign interference, and future research should focus on examining the impact of these initiatives on international scientific collaboration and researcher performance to assess whether they strike a balance between open science and research security. As Johnson et al. (2022) mentioned, this balance is particularly challenging, as it requires regular analysis of scientific collaborations to identify which areas are essential for fostering open science and which may pose risks that necessitate stricter security measures.

Our findings also emphasize the importance for policymakers to consider the indirect impacts when developing guidelines addressing high-risk collaborations. For example, our analysis shows that collaborations with Huawei are associated with a negative impact on the overall productivity of Canadian researchers. However, collaboration with Huawei positively moderates the relationship between international collaboration and Canadian researchers' productivity. Huawei's global presence might broaden collaboration opportunities for Canadian scientists, enabling them to connect with more international researchers, which could enhance their productivity. Additionally, our findings show that collaborating with both Chinese researchers and Huawei amplifies the positive influence of international collaborations on scientific productivity. Advanced technological resources and expertise in 5G technology provided by Huawei and Chinese researchers show strong potential to significantly augment international collaborations, boosting their overall positive impact on Canadian research productivity.

Our study also shows that, while beneficial, collaborations with Chinese scientists are not irreplaceable. Partnerships with researchers from other countries leading in 5G technology could also enhance the performance of Canadian scientists. This highlights the importance for policymakers to prioritize diversifying international collaborations, particularly in the context of geopolitical tensions, to ensure that research productivity and citation impact are not overly reliant on collaborating with researchers from any single country. One practical approach could be diversifying funding for collaborative research projects across several key firms to ensure the resilience of Canada's scientific network in the face of geopolitical challenges. Our findings support this, as we observed that collaboration with Huawei facilitates access to public funding in the 5G sector. However, collaboration with Ericsson, Huawei's main competitor in 5G, also positively influences the securing of public collaborative funding. This suggests that while Huawei is significant for funding, viable alternatives like Ericsson offer similar benefits.

Another important approach highlighted in the OECD (2024) report is the recommendation for funding bodies to incorporate risk assessments within their grant application and evaluation processes. For example, in Canada, NSERC has integrated this practice into its Alliance Grants Program, requiring applicants to identify and devise strategies to manage potential risks. These risk mitigation plans, along with the initial risk assessments, are carefully scrutinized by the funding agency before final decisions on grant allocations are made (Government of Canada, 2021b).

Our research offers some insights for policymakers, particularly in strategic areas like 5G technology. As such, it suggests that policymakers should assess and address dependencies on specific countries in international scientific collaborations, especially in the context of geopolitical tensions. It also serves as a first step toward a deeper analysis of international science collaboration and innovation ecosystems. Furthermore, this research underscores the need for more directional and coordinated STI policies encouraging trusted international partnerships and the open exchange of ideas. Further research is needed to assess the impact of geopolitical tensions on international research collaboration and to evaluate public policies and initiatives that may threaten the openness of science and international cooperation in this context. This is particularly important as current global challenges require international collaboration to effectively address them.

Our study has some methodological limitations. First, the identification of 5G projects in the NSERC and MITACS databases relied solely on the keyword “5G”. Future studies could broaden this search strategy by incorporating additional keywords to capture a more extensive range of 5G projects. Another limitation of this study is the incomplete data within the OST database for the period prior to 2008. The absence of comprehensive records before this year may impact the calculation of researchers’ career ages. Specifically, for scientists who began publishing before 2008, their early career contributions might not be captured, leading to an underestimation of their actual career lengths. Another limitation is the exclusive reliance on funding data from NSERC. Including other sources of public funding in Canada could expand our sample of 5G authors and provide a more comprehensive overview of the funding landscape. Additionally, our analysis is based only on collaboration data involving Huawei from the NSERC database, which does not cover all possible collaborations between Canadian researchers and Huawei. Research contracts are not included in our study and are probably a non-negligible part of research funding. Future research could enhance our findings by utilizing additional databases or by conducting comparative analyses in other national contexts, which would offer a more robust understanding of the dynamics and impacts of such collaborations.

This study is confined to the Canadian context, which may limit the generalizability of the findings to other countries. Additionally, the Two-Stage Least Squares (2SLS) model used in our analysis involves instruments in the first stage to estimate the endogenous variable, public collaborative grant. While these instruments were the best available for our study, future research might benefit from identifying and employing more instruments. Furthermore, we used the number of publications and average mean normalized citation scores as proxies to measure researchers' productivity and the usefulness of their work. Although these indicators are widely recognized in the academic literature, other measures, such as journal impact factor, could also be examined. Future research could explore intangible indicators of the impact of collaboration, such as access to new networks, knowledge, and students, which may provide additional insights into the broader effects of scientific partnerships.

Despite these limitations, we believe that our results offer a valuable starting point for further investigation into the significance of scientific collaboration in contexts marked by geopolitical tensions. Also, future studies could incorporate other quantitative methods, such as surveys completed by researchers, to explore how collaborations with Huawei and Chinese researchers contribute to other aspects of research productivity and usefulness beyond publication and citation metrics.

CHAPTER 8 GENERAL DISCUSSION

This chapter is dedicated to discussing our findings, with a particular emphasis on how they align with the three initial research objectives.

8.1 Strategic mechanisms involved in the emergence of an innovation ecosystem

The first contribution of this study is the empirical examination of orchestration through a temporary structure formed by multiple organizations (Article 1). In contrast to much of the existing literature focuses on single organizations as central orchestrators, often termed keystones or hub firms (Iansiti & Levien, 2004; Dhanaraj & Parkhe, 2006; Nambisan & Sawhney, 2011; Azzam et al., 2017; Hurmelinna-Laukkanen & Nätti, 2018), our research empirically examines how a temporary, multi-organizational structure can influence the emergence of innovation ecosystems.

Our findings (Article 1) suggest that this temporary structure needs to establish legitimacy, especially in the early stages of the ecosystem's development. Thomas & Ritala (2022) emphasize that legitimacy is crucial for emerging ecosystems because they often face a "liability of newness". This challenge arises from a lack of information and proof of the ecosystem's viability, particularly regarding its value proposition. Bringing together several key players in the ecosystem can reinforce the project's legitimacy and attract a larger number of organizations, unlike an ecosystem launched by a single company, such as a hub firm. This shows the rest of the ecosystem that the participation of these key players, from different sectors such as companies, governments and NPOs, increases the credibility and scope of the project, which encourages other players to join in. This was particularly relevant in the case of 5G, where the technology was still new, and there was limited information available about its full potential and impact. In the case of INNOV5G, including key, influential players within the ecosystem, such as well-known multinational corporations, has significantly boosted its legitimacy and effectiveness. Our results indicate that the involvement of these prominent multinationals in establishing INNOV5G has been crucial in attracting and engaging other ecosystem members. This collaboration was intended to create a sense of urgency within the Canadian ecosystem, which was perceived as lagging behind countries like the US and China in 5G development. However, legitimacy is not based solely on the composition of the players within the temporary structure. Other factors also influence how ecosystem players perceive this legitimacy. For example, the continuity and stability offered by permanent players can be a central element of legitimacy, unlike temporary structures, which have a limited duration.

Bringing together key players within a temporary structure nevertheless presents certain challenges, especially when these players are also competitors in specific markets. The literature refers to this situation as coopetition (Moore, 1993; Iansiti & Levien, 2004; Basole et al., 2015; Yang et al., 2021; Xin et al., 2023). In this context, the formation of a temporary structure can facilitate coopetition. Indeed, when a temporary structure is set up around a specific project with well-defined objectives, coopetition becomes easier to manage. Competing companies can then see in this cooperation an opportunity to accelerate innovation while sharing the costs and risks associated with the initial phase of the project. This type of temporary collaboration encourages companies to work together to achieve beneficial short-term results, without compromising their long-term competitive position. Our study of the INNOV5G project, in which some multinationals were also competitors, clearly illustrates this point. These companies took advantage of this initiative to pool their skills and resources, over a limited period, to support the entire ecosystem, which was lagging behind other countries in 5G deployment. From the outset, the players agreed on each other’s roles, as well as the financial or technological contributions they were responsible for. Our results show that it was decided that each player would focus on his or her specific area of expertise. Thus, this case demonstrates that a temporary structure can effectively facilitate coopetition from the very beginning of the project. Conversely, in the case of a single, permanent orchestrator, the initiative might be perceived differently. It could give the impression that the orchestrating company is monopolizing the ecosystem’s critical resources, leading competitors to view this as an attempt to dominate the ecosystem, thereby hindering cooperation. To mitigate this risk and foster coopetition, the single orchestrator could adopt a neutral stance and promote open governance, ensuring that all players, including competitors, are able to participate on an equitable basis.

Our results show that temporary structures, as orchestrators, include mechanisms that actively support both the knowledge and business ecosystems, which are fundamental components of the broader innovation ecosystem. This aligns with Clarysse et al. (2014), who emphasize the importance of considering the interplay between these ecosystems. Our findings highlight the importance of attracting ecosystem members (Dedehayir et al., 2018; Cohendet, 2021; Faccin et al., 2022) by creating awareness throughout the entire ecosystem. INNOV5G has implemented mechanisms to attract key players in the knowledge ecosystem, such as universities, scientists, and students, as well as key actors from the business ecosystem, such as compagnies and SMEs. In this context, our study emphasizes the essential role of research innovation intermediaries within temporary orchestration structures. Our results align with Sultana & Turkina (2023), who highlight the importance of intermediaries in mobilizing the ecosystem. These intermediaries leverage their extensive networks and specialized outreach experience to facilitate the ecosystem's emergence. The creation of a temporary structure, integrating various innovation intermediaries from the outset, could facilitate the connection between knowledge ecosystems and business ecosystems. Because of their role as facilitators, these intermediaries potentially have networks and mobilization capacities that multinationals would not have. Conversely, for a permanent company playing the role of orchestrator, this task could become more complex, as mobilizing both knowledge and business ecosystems would require an approach better adapted to the specificities of these two types of ecosystems, an approach with which research intermediaries are more familiar.

In addition to mobilizing knowledge and business ecosystems, intermediaries could also play a key role in building and promoting cross-sector collaborations between stakeholders from these two ecosystems, particularly during the initial phases of innovation ecosystem emergence. The ability to orchestrate collaborations between stakeholders from different sectors is widely recognized in the literature on innovation ecosystems (Hurmelinna-Laukkanen et al., 2022; Sultana & Turkina, 2023). INNOV5G has facilitated collaborative projects that involve a diverse array of organizations from various sectors, including SMEs, museums, universities, and multinationals. This strategic facilitation of intersectoral collaboration is important for the emergence of innovation ecosystems, as noted by Dzhengiz & Patala (2024). It allows for the integration of a broad spectrum of expertise and resources from both the knowledge and business sides of the innovation ecosystem. For instance, our regression analysis (Article 4) confirms the importance of such intersectoral collaboration in increasing the productivity of Canadian researchers, as evidenced by the higher number of published papers. This enhanced productivity, in turn, significantly contributes to the foundational development of a vibrant knowledge ecosystem. A permanent orchestrator, usually a company, seeking to establish collaborations between the two ecosystems may encounter difficulties due to cultural differences and strategic priorities specific to each ecosystem. For example, companies and universities may have divergent expectations in terms of results, which could complicate collaboration if the company in charge of orchestration fails to effectively manage the expectations of the knowledge ecosystem.

Our study also examines the formation of another type of collaboration, namely international collaboration within innovation ecosystems. The results of our regressions (Article 4) indicate a positive impact of international collaborations on the usefulness of Canadian research, measured by the number of citations, which aligns with the findings of existing literature (Aldieri et al., 2019; Veretennik & Shakina, 2024). These collaborations involve scientists, industries, hospitals, and non-profit organizations, thereby broadening the scope and enhancing the impact of research, which could facilitate the emergence and global expansion of innovation ecosystems. In this context, the formation of a temporary structure integrating large multinationals, each with a client base across several sectors, could provide its members with a vast international network, fostering opportunities for global collaboration, beyond what a single orchestrator could offer. However, several conditions must be met for this to succeed, foremost being the commitment of these multinationals to open their networks and adopt a mindset that benefits the entire ecosystem. Additionally, other factors must be considered; for instance, INNOV5G's initial ambitions to foster wide international collaborations were not fully realized due to the disruption caused by the COVID-19 pandemic.

Moreover, in some cases, bringing together key players within a temporary structure, acting as the orchestrator, could facilitate the introduction of more diverse and tailored incentives, encouraging organizations to join the emerging innovation ecosystem (Autio & Thomas, 2014; Dedehayir et al., 2018). INNOV5G has successfully encouraged collaboration by offering funding for joint projects. Interviews reveal that this financial support was crucial in motivating participants, particularly SMEs, to engage as it reduces the financial risks associated with investing in new technologies. In the case of INNOV5G, this temporary structure brings together not only multinationals, but also three levels of government, thus diversifying and increasing the sources of funding from each of these players. This configuration offers a considerable financial advantage over what a single orchestrating firm could provide. This funding could facilitate the mobilization of players and the emergence of the ecosystem. Our regression analysis (Article 4) shows that funding significantly boosts the productivity of Canadian researchers in the ecosystem. Such enhanced productivity enriches the knowledge side of the innovation ecosystem, fostering its emergence.

However, our results from Article 1 show that funding alone could not be sufficient as an incentive. Technical and administrative support provided by the orchestrators is necessary for members to join and thrive within the ecosystem. Interviews with SME participants revealed that despite the financial support, the lack of human resources to manage and fill out necessary documentation, such as claims for funding, poses a significant barrier. Furthermore, the need for technical expertise in new technologies like 5G is critical, as many SMEs do not possess all the necessary knowledge and resources to effectively leverage these technologies. Offering a platform is another key incentive (Gawer & Cusumano, 2014). Our results indicate that during the early stages of emerging ecosystems, platforms should be open and accessible, particularly to resource-limited entities like SMEs. Providing free or low-cost access is important for maximizing participation in the nascent phase. The temporary structure's ability to bring together multiple players with diverse expertise and resources could facilitate the implementation of both technological and administrative incentives, something a single company acting as orchestrator might not be able to achieve.

Moreover, our findings emphasize the importance of fostering a culture of experimentation. Orchestrators should facilitate environments where members can freely develop and refine innovations through trial and error, which enhances innovation without the immediate pressure for results (Rinkinen & Harmaakorpi, 2019). Permanent organizations often prioritize long-term stability and risk management, which could potentially limit the development of a culture of experimentation. In contrast, temporary structures could be designed to encourage such a culture by offering a framework where the risks associated with experimentation might be shared and mitigated.

8.2 Ecosystems resilience to external disturbances

Currently, certain technologies, such as 5G, artificial intelligence, and quantum computing, are not only having a significant impact on geopolitics but are also being shaped by it. These technologies are fundamentally transforming industries and societies, pushing companies and countries into fierce competition to attain leadership in these areas in order to safeguard national security. This competition contributes to political tensions and instability, leading to shifts in public policy that heavily influence innovation ecosystems. In this context, the resilience of these ecosystems becomes an important aspect to consider. The existing literature does not empirically examine the resilience of innovation ecosystems in response to geopolitical tensions related to frontier technologies. While some studies investigate resilience (Floetgen et al., 2021; Liu et al., 2022; Chen & Cai, 2023; Wang et al., 2023; Abdi, et al., 2024; Zhang et al., 2024), they generally focus on social and economic indicators, without thoroughly examining the effects of geopolitical uncertainties.

In the current context, where frontier technologies both shape and are shaped by the emergence of innovation ecosystems, orchestration mechanisms must increasingly account for the geopolitical impacts that influence ecosystem development and incorporate strategies for resilience. One of the key strategies that innovation ecosystem orchestrators can adopt to strengthen their resilience in the face of geopolitical uncertainties is to encourage and promote local innovation. Indeed, in order to reduce dependence on a country or company with which there are geopolitical tensions and suspicions concerning national security, orchestrators can use their leverage position to encourage national organizations to step up their research efforts in cutting-edge technologies and foster the development of innovations. The example of INNOV5G illustrates this well: although respondents did not explicitly acknowledge that this initiative was intended to counterbalance Huawei's influence, it can be situated in a context of growing tensions with Huawei. Led by one of Huawei's competitors, with whom Canada has no geopolitical conflict, and supported by the government, this initiative fostered the development of local innovations by raising awareness and encouraging companies in two Canadian provinces to develop 5G solutions. The aim was for Canada to be able to compete with other prolific countries in this field without depending on Huawei or China.

However, such initiatives are likely to incur high costs. In this context, organizations playing an orchestrating role must continually advocate financial incentives to encourage and promote local innovation, while protecting the ecosystem from external disruption. For example, in the case of INNOV5G, the initiative was launched by multinationals, who approached the government to set up funding programs aimed at facilitating local innovation and reducing the ecosystem's dependence on a company or country with which geopolitical tensions exist.

Another action orchestrators can take to strengthen resilience in an emerging innovation ecosystem, particularly within an uncertain geopolitical context, is to stay continuously informed of geopolitical developments that could impact the ecosystem. By regularly assessing the effects of these tensions on collaborations within the ecosystem, they can adjust their strategies and adapt their approaches to minimize potential disruptions. In our study, we applied this approach by examining the potential impact of geopolitical tensions on international scientific collaborations in the field of 5G (Article 2). Our findings underscore the importance for orchestrators to initially assess the extent of the impact that potential disturbances, such as geopolitical tensions in our case, could have on the emergence of the ecosystem. For example, our bibliometric analysis results (Article 2) show a shift in collaborative patterns at the international research level between China and countries such as the USA, UK, and Canada, during the period of geopolitical tensions. Additionally, our findings indicate a decrease in network centralization, suggesting that recent geopolitical tensions between China and the USA have influenced the international network of 5G researchers. Despite these shifts, the small-world structure of the network was preserved, ensuring effective knowledge diffusion within the network even if collaboration tendencies with China shifted.

Furthermore, orchestrators could run simulations to anticipate and mitigate potential disturbances, such as geopolitical tensions, ensuring the resilience of the ecosystem. This proactive approach allows them to assess the potential impacts in scenarios like the exclusion of key players. For instance, in the Canadian context, we conducted simulations to evaluate the robustness of the academic-industry collaboration in the absence of Huawei (Article 3). Our results demonstrate that the ban on Huawei does not significantly affect the structural properties of the 5G network. Specifically, the impact on the largest connected component is minimal, and the network retains its small-world properties, effectively maintaining knowledge transfer despite Huawei's absence. Furthermore, the elimination of Huawei does not significantly influence the centralization of the network or alter the trend observed over time.

However, assessing the impact of geopolitics on the ecosystem can prove difficult for orchestrators, as geopolitical conditions can change rapidly, making the assessment complex. Furthermore, it is difficult to anticipate the evolution of geopolitical conflicts and their impact on the ecosystem, as tensions can arise unpredictably.

Another way for orchestrators to strengthen the resilience of an innovation ecosystem is to diversify collaborative relationships to avoid dependence on a single player. Our results (Article 4) show the importance of this approach and having alternatives in collaboration strategies within the ecosystem, particularly in scenarios where certain actors, such as countries or organizations, are implicated in geopolitical contexts like China and Huawei in our study. For example, our results (Article 4) indicated that while collaborations with China and Huawei significantly enhance the performance of 5G scientists and positively moderate the relationship between international collaboration and productivity, Canadian researchers possess viable alternatives. These alternatives, involving partnerships with researchers from other countries, can similarly boost their performance and contribute to the robustness of the ecosystem.

While diversifying collaborations is recognized as a key strategy for building resilient innovation ecosystems, it's important to note that simply increasing the number of partners does not guarantee true diversification. To foster the emergence of a resilient ecosystem, orchestrators must also take into account the diversity of what each collaboration can offer. If all partners bring similar knowledge or focus on the same technological areas, the ecosystem remains vulnerable to external shocks, despite the multiplication of collaborations. This approach was adopted in our study by assessing the thematic resilience of the 5G ecosystem in Canada. Our results (Article 3) show that the collaborative and thematic network remains robust, indicating that Canadian contributions to research in these areas are strong, despite Huawei's absence. This study shows that, although Huawei is an important player, its role is neither unique nor irreplaceable within the academic network. Therefore, it is proposed that orchestrators consider these dynamics before making decisions to privilege or ban collaborations with other countries or organizations.

8.3 The roles of public policies and government interventions emerging innovation ecosystems

Throughout our articles, we highlight the critical role of government actions and public policies in the orchestration process during the emergence of innovation ecosystems. This emphasis on the importance of public policies aligns with the literature (Rinkinen & Harmaakorpi, 2019; Neto et al., 2024), which underscores the role of funding, political, and economic reforms in facilitating the development of these ecosystems.

Our results show that political rhetoric could play a significant role in influencing the innovation ecosystem. Official statements and media coverage could shape the perceptions of ecosystem participants. Our results show how the governmental discourse on scrutinizing collaborations with Chinese institutions may have impacted the ecosystem. Our bibliometric study (Article 2) reveals how the atmosphere of hostility towards China, fueled by the Trump administration's threats to other countries if they do not align with U.S. policies, may have altered the tendency to collaborate with China. This shift may reflect the potential influence of political rhetoric and governmental actions on international research collaborations within the 5G ecosystem.. In Canada, unlike in the USA where formal decisions were quickly enacted, the dialogue was dominated by rhetoric without the formulation of new laws that clarified the expected actions for ecosystem members. This prolonged period of uncertainty and the lack of clear directives have led to a nebulous operational environment, as evidenced by our findings of a decrease in collaboration with China even before any formal government decision was made. Moreover, this uncertain climate made universities and researchers uncomfortable and feeling unsafe about collaborating with Chinese researchers or Huawei (Davies, 2019; Perper, 2019). Even without explicit legal prohibitions, the press pressure and incidents of arrests of scientists in U.S. universities due to their collaborations with Chinese entities may have made Canadian scientists hesitant.

The government could also play a role in supporting innovation ecosystems by offering incentives. Our results (Article 1) indicate that funding provided by the federal government and two provincial governments was instrumental in founding INNOV5G, marking a significant starting point for the emergence of the 5G ecosystem. A portion of the government funding was allocated to support the attraction of a broad range of organizations to benefit from INNOV5G programs, thereby contributing to the mobilization of the ecosystem. Public funding can facilitate the emergence of the ecosystem by fostering various types of collaborations. Our results (Article 3) show that the funding network of academic-industries maintains a small-world network structure, which means there is an optimal diffusion of knowledge. However, public funding bodies must carefully balance promoting international collaborations with addressing national security concerns.This need for balance is evident in assessments like the one conducted in Article 4, where we evaluated whether collaboration with China is truly beneficial for the performance of Canadian scientists and whether alternative partnerships with other countries facing geopolitical issues could provide similar advantages. Our results indicate that collaboration with China is indeed beneficial for scientists' performance, enhancing their performance. However, the findings also reveal that there are other viable and beneficial alternatives, suggesting that these collaborations are not necessarily interdependent. Such assessments are crucial for policymakers and funding bodies to make informed decisions that foster scientific performance while navigating complex geopolitical landscapes.

Several reports and recommendations underscore the importance of evaluating national security risks before awarding funding. In the United States, the National Science Foundation (NSF) has established a policy prohibiting its employees from participating in foreign government-sponsored talent recruitment programs to safeguard national security (National Science Foundation, 2020). Similarly, in Canada, NSERC has incorporated risk management mechanisms into its Alliance Grants program, requiring applicants to identify potential risks and propose mitigation strategies. These plans are thoroughly reviewed before funding decisions are made (Government of Canada, 2021). The OECD report (2024) further supports this approach, recommending that funding agencies include risk assessments in their processes, particularly for projects involving international collaborations.

Third, our findings indicate another important role the government plays in the orchestration process: ensuring alignment between government actions and the ecosystem's needs and objectives. In the case of INNOV5G, the project was initiated as a pre-commercial testbed, attracting various members of the ecosystem with the promise of developing new technologies and solutions. However, at the project's conclusion, some of the bands essential for the technologies developed were not even available in the government's spectrum auction. This misalignment can severely impact the ecosystem's emergence, as the products and services tested in the pre-commercial phase may lack real-life commercialization opportunities, rendering the efforts of ecosystem members potentially futile. Several members who joined INNOV5G encountered limited market opportunities because there was insufficient customer demand for 5G technology at the time. This might have been because the full potential of 5G technology had not yet been realized, as the federal government had not yet auctioned the necessary frequency bands for these projects. This misalignment between the ecosystem's output and market demand, exacerbated by regulatory delays, can hinder the effective emergence of the ecosystem.

Another way governments can help ensure the resilience of innovation ecosystems is by providing well-defined guidelines. These guidelines are important for striking a balance between encouraging open scientific collaboration and safeguarding research security, both of which are essential for maintaining and enhancing the resilience of these ecosystems. In Canada, the government has introduced two online courses for researchers and university staff, titled “*Introduction to Research Security*” and “*Cyber Security for Researchers*”, which provide a comprehensive overview of key security information using various educational techniques (Government of Canada, 2021). While these measures are not explicitly directed at China, they represent broader efforts to address research security concerns. Other nations have also taken steps in this direction. Finland, for example, in collaboration with its universities, issued the “*Recommendations for Academic Cooperation with China*” (Ministry of Education and Culture, 2021), and Sweden developed its “*Approach to Matters Relating to China*” (Government of Sweden, 2019), both of which outline the complexities and risks involved in international partnerships.

The methodologies employed in our study for assessing and simulating ecosystem robustness (Article 2 and Article 3) could serve as a guide for policymakers. By integrating impact assessments and simulations that focus on collaboration dependencies, public policies can be better tailored to the strategic needs of innovation ecosystems.

CHAPTER 9 CONCLUSION

The general research question that structured this thesis is: How do key actors orchestrate strategic interactions within an emerging innovation ecosystem to navigate uncertainties in international, technological, and political contexts? This question has guided the development of four articles, each examining different perspectives and data sets. To address this question, we adopted a multi-method approach, combining qualitative methods including semi-structured interviews with quantitative methods such as social network analysis, regressions, and text mining.

In this concluding chapter, we will highlight the most important takeaway messages from each article, discuss the limitations of our research, propose directions for future studies, and conclude with a final note on the intertwined nature of technology, economics, and geopolitics, and their collective influence on innovation ecosystems in today's world.

9.1 Summary of chapters

In the first article, we explored how temporary structures formed by key organizations can orchestrate emerging innovation ecosystems. This investigation was conducted through a qualitative study involving 53 semi-structured interviews, centered around the case study of INNOV5G. Our results highlight the necessary conditions for forming such temporary structures dedicated to orchestrating ecosystems. Actors within these structures must capitalize on new opportunities for collaboration. In our case, this involved 5G technology, an area where Canadian organizations were lagging compared to other countries. The study also revealed that these actors need to align their visions, adopt specific roles, and establish effective governance within these temporary structures. Moreover, our interview results show the mechanisms of attraction and awareness for engaging ecosystem members. By using multiple communication tools, a clear message was communicated to the ecosystem about the opportunity to develop 5G products and services before it's too late. This study also shows the importance of fostering a culture of experimentation by providing an open platform free of charge, which allows for trial and error without the pressure for immediate results, necessary for testing new ideas. The study underscored the necessity for orchestrators to offer financial, administrative, and technical support to lower entry barriers and facilitate broader participation. Additionally, it was evident that orchestrators need to forge diverse collaborations and create market opportunities to sustain the ecosystem's vibrancy. In this context, INNOV5G implemented programs that facilitated collaboration and introduced mechanisms to showcase member work, attracting clients and fostering potential collaborations. Finally, our research addressed the need for orchestrators to adapt to external disturbances by modifying internal processes and responding to issues affecting ecosystem members caused by external disruptions. Each dimension of our findings not only shed light on the multifaceted role of orchestrators but also highlighted the potential challenges they may face during the emergence of innovation ecosystems.

Our observations at various 5G events and during interviews with ecosystem members revealed a tension around collaborations involving the global leader in 5G technology and Chinese scientists. This atmosphere was largely influenced by the news at the time, centered on the Trump administration's accusations of espionage against China and Huawei. Such allegations led to significant actions including the arrest of scientists by the FBI and the exclusion of Huawei from the U.S. market. These developments contributed to an environment of mistrust and caution in Canada, potentially affecting collaborative efforts and the emergence of an innovation ecosystem. This backdrop of geopolitical tension sets the stage for exploring the deeper impacts of such external factors on the emergence of 5G innovation ecosystem across the three remaining articles.

The second article of this thesis begins by exploring the knowledge ecosystem of innovation, investigating the potential effects of geopolitical tensions on the structural properties of the 5G co-authorship network and international collaboration patterns. Through a bibliometric analysis of 5G research, we noted potential shifts in collaboration patterns between China and countries such as the US, UK, and Canada, which coincide with the period of geopolitical tensions. This observed shift also suggested a trend towards less centralized network structures, although the network consistently retained its small-world properties. These findings highlight the possible influence that recent geopolitical tensions between China and the U.S., along with its allies, might have on the international co-authorship network in the 5G domain.

Following the findings of the second article, which focused on scientists, we expanded our scope in the third article to include a broader range of actors, such as industry players, universities, and non-profits, within the Canadian context. This study, utilizing data from NSERC, examined Huawei's role and assessed its impact on network robustness and research themes. Our results show that the removal of Huawei did not significantly affect the network's structural properties or the robustness of key research topics. Canada's contributions in these areas remained strong, even without Huawei's involvement. These findings suggest that while Huawei is a significant player, its role within the Canadian academic network is neither singular nor irreplaceable.

The fourth article broadens the analysis to include international collaborations between Canadian researchers and Chinese scientists. This study examines the nuanced effects of these collaborations on the productivity of Canadian 5G researchers and their research usefulness. Using regression analysis, our findings reveal that while collaborations with Chinese researchers positively influence research outcomes, partnerships with Huawei present a more complex scenario, where direct impacts on productivity may be negative, yet these collaborations still enhance the benefits of broader international partnerships. Despite the significance of these collaborations, our analysis indicates that Canadian researchers can still achieve high performance through partnerships with researchers from other countries.

9.2 Research limitations

Generalizability and contextual specificity

One of the main limitations of this study is the generalizability of the results. For the qualitative study, as the analysis is mainly based on a single case study with integrated units of analysis, the results obtained cannot be directly applicable to other contexts or types of innovation ecosystems. More specifically, the effectiveness of the temporary structures observed in INNOV5G is strongly influenced by specific contextual factors, such as the involvement of large technology companies and substantial government support. This specificity could limit the applicability of the results to temporary structures with different characteristics. Additionally, the focus on 5G technology in all our articles may also restrict the scope of the results, as focusing on a specific technology may influence the types of collaborations and innovations that emerge, which could differ in ecosystems centered around other technologies.

Data limitations

A significant limitation of our articles concerns the nature of the data used, which is limited to qualitative data, bibliometric data from Web of Science, and funding data from NSERC. These sources do not cover all the players and all their interactions within the innovation ecosystem. Excluding certain players and their interactions could influence the results obtained concerning the emerging innovation ecosystem in a context of geopolitical disruptions. Moreover, our quantitative assessment of the network relied on NSERC as the single public available funding source. While ecosystem members may have access to other funding sources, data from these were not accessible. As a result, our analysis might not fully capture the broader network dynamics, as it excludes the influence of other potential funding sources that could play a role in shaping the network and the ecosystem's emergence and development. Furthermore, using data such as the number of publications and citations as a proxy for collaboration is also a limitation.

In Article 4, a limitation lies in the inability to restrict the analysis to publications specifically related to 5G. Although researchers were selected based on projects explicitly focused on 5G, the metadata extracted from the OST database includes all publications and collaborations of the researchers, without providing a filter to isolate those exclusively related to 5G.

Methodological constraints

The pandemic context limited our ability to carry out a longitudinal study and field observations throughout the INNOV5G project. This constraint prevented us from analyzing in real time the evolution of roles and emergence mechanisms within the temporary structure. From a methodological point of view, although social network analysis offers some answers about network robustness, it does not capture the qualitative aspects of network interactions, and the strategies implemented to mitigate the risks associated with geopolitical tensions and improve or deteriorate ecosystem resilience. For example, in the second article we observe that political decisions could have influenced changes in collaboration trends in international research. Although we note a temporal coincidence between certain political events and these changes, our analysis does not attempt to empirically establish direct causality in a quantitative way.

9.3 Future research

Comparative and cross-sectoral studies

Comparative studies between different countries, regions, or sectors could significantly enhance our understanding of the orchestration of innovation ecosystems. By comparing temporary structures and orchestration dynamics in different types of innovation ecosystems, future research could validate the generalizability of the results obtained. Longitudinal studies on the evolution of roles within ecosystems would allow for tracking changes in contributions from different structures and players over time. For example, using Eisenhardt's method (Eisenhardt, 1989) to conduct a multi-case study on various temporary structures could enable the development of a theory on the emergence of innovation ecosystems. Moreover, extending the investigation to the impacts of geopolitical contexts on a variety of technology sectors beyond 5G would help discern sectoral differences and refine our understanding of resilience across different innovation ecosystems.

Future research could deepen the literature on the resilience of innovation ecosystems to geopolitical tensions by adopting a comparative approach between different countries. Such an approach would help identify best practices and effective strategies for maintaining ecosystem stability despite geopolitical disruptions. In addition, empirical analyses could be conducted to assess the impact of policy decisions on the emergence of ecosystems, using more diversified indicators than those employed in the current thesis. These studies would aim to identify the best public policies for fostering the emergence of these ecosystems during geopolitical tensions.

Development and validation of new metrics and indicators

Future research could focus on developing new, more comprehensive metrics to measure the emergence and resilience of innovation ecosystems. The use of quantitative models based on these indicators would enable policymakers and ecosystem members to quantify and respond effectively to geopolitical disruptions. This would contribute to the literature by providing quantifiable tools for assessing emergence processes. The validation of these indicators would also enable ecosystem players to adapt their practices, and the mechanisms deployed, thereby better orchestrating the emergence of new ecosystems.

The effect of government guidelines on 5G collaborations and the protection of national security

Future research could evaluate the impact of government directives aimed at managing the risks associated with international collaborations in 5G and other frontier technologies. Such studies would help determine whether these measures have successfully promoted international collaborations while safeguarding national security. Additionally, it would be valuable to explore whether these guidelines have contributed to strengthening the resilience of ecosystems in the face of external geopolitical disruptions. For example, future studies could incorporate temporal analyses and causal inference methods—such as difference-in-differences designs—around well-defined geopolitical events, thereby more effectively isolating and quantifying their influence on specific dimensions of the 5G research collaboration network.

Integrating geopolitical and power dynamics

While the current study provides structural insights into the influence of geopolitical tensions on the global 5G research landscape, future investigations could deepen the theoretical grounding by engaging with scholarship that examines how technologies both reflect and reinforce existing power structures. Integrating concepts such as “smart power” (Nye, 2011) would offer a more nuanced understanding of the orchestrator’s role, highlighting the delicate balance between strategic authority and collaborative influence. Similarly, drawing on the broader literature on the geopolitics of technological innovation and the state’s role in shaping innovation systems (Taylor, 2016; Breznitz, 2007) could elucidate how political frameworks, cultural norms, and national priorities interact to shape innovation ecosystems. By connecting these perspectives to the patterns identified in this thesis, future research could move beyond structural analysis to illuminate the underlying power relations, strategic considerations, and policy interventions that guide the formation, resilience, and evolution of international research collaborations in the 5G domain.

Accounting for global supply chains and multinational corporate influences

In addition to strengthening the theoretical foundation through geopolitical and power-oriented frameworks, future research could more explicitly consider the roles of global supply chains, multinational corporations, and international collaborations in shaping the orchestration process. Incorporating insights from innovation management literature (e.g., Dodgson & Gann, 2018) would help clarify how value distribution, resource flows, and strategic alliances affect not only the structure and resilience of research networks but also the creation and diffusion of new technologies. Examining the interplay between corporate strategies, cross-border partnerships, and policy interventions could provide a richer understanding of how orchestrators navigate complex, interdependent innovation ecosystems, adapt to shifting power dynamics, and influence the trajectory of technological development

9.4 Final words

As we move forward, the concept of global techno-politics, where technological advancements are deeply intertwined with geopolitics strategies, will likely become increasingly relevant. This will demand that ecosystem orchestrators, including policymakers, researchers, and industrials, remain vigilant in their strategies to foster resilient innovation ecosystems. Technological advancements such as 5G, quantum computing, artificial intelligence, and other transformative technologies are examples of how technological, geopolitical, and economic forces shape the emergence of these ecosystems. We believe that our study paves the way for future research and practical applications in this field, highlighting the need for continued exploration of the complex relationships between technology, politics, and economics in the context of innovation ecosystems.

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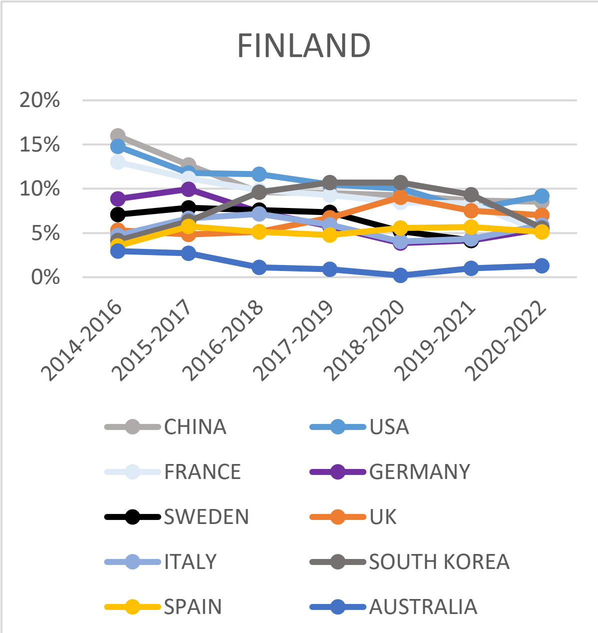
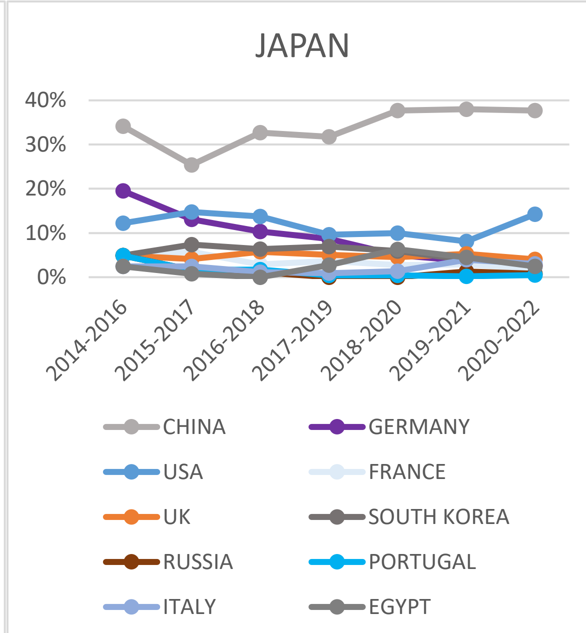
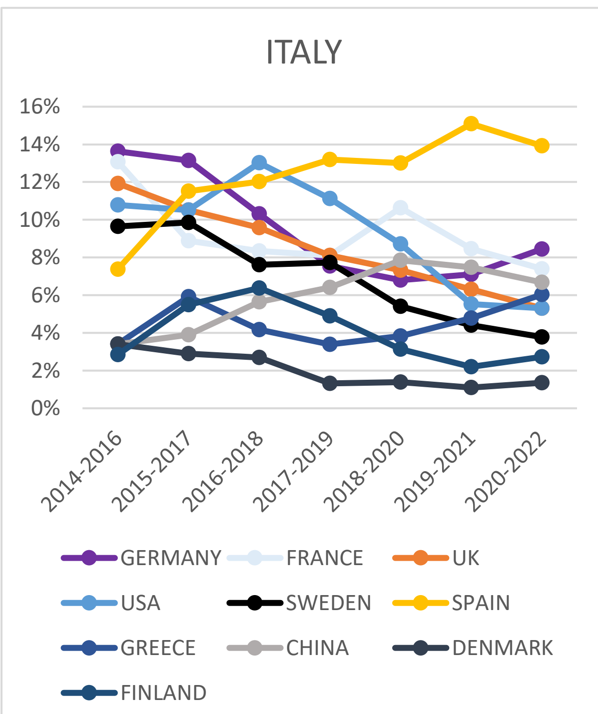
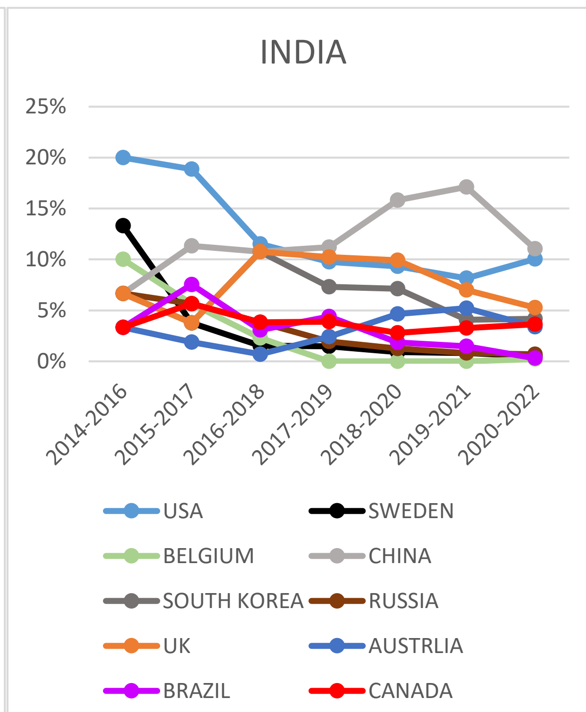
APPENDIX A – SUPPLEMENTARY MATERIALS ARTICLE 2









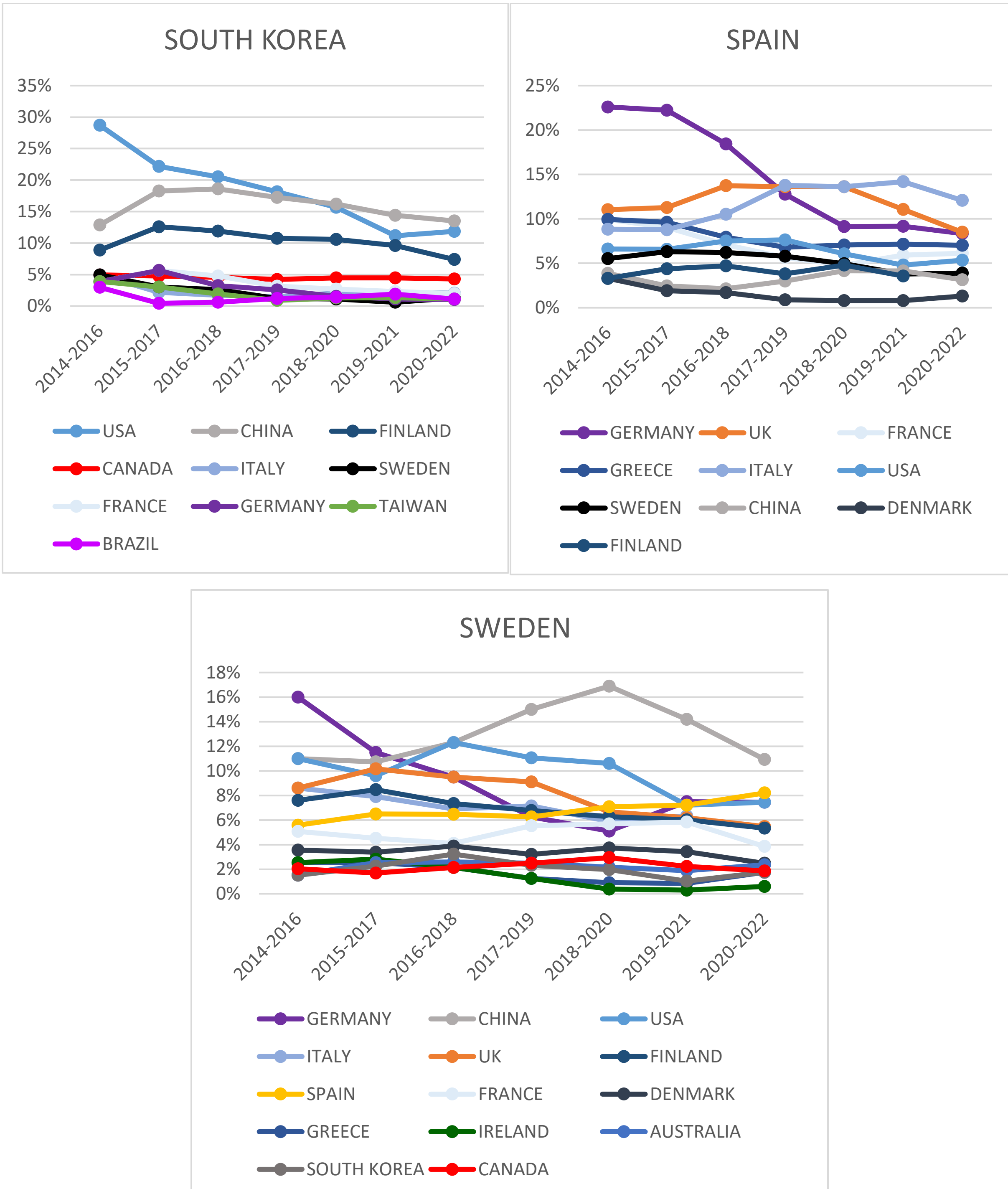


Figure A- 1. Scientific international collaboration in 5G technology

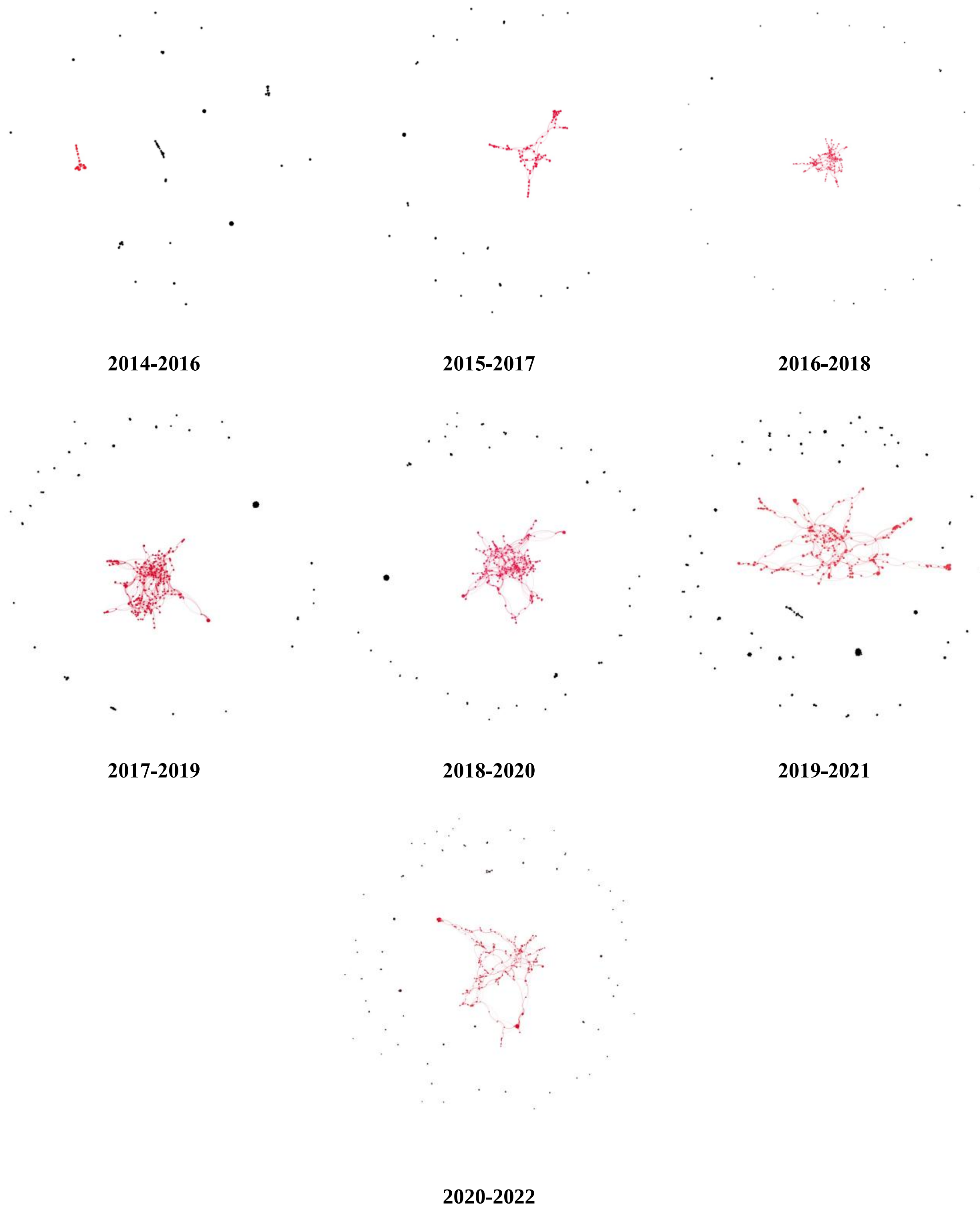


Figure A- 2. Evolution of the main component for the co-authorship network between CHINA and UK

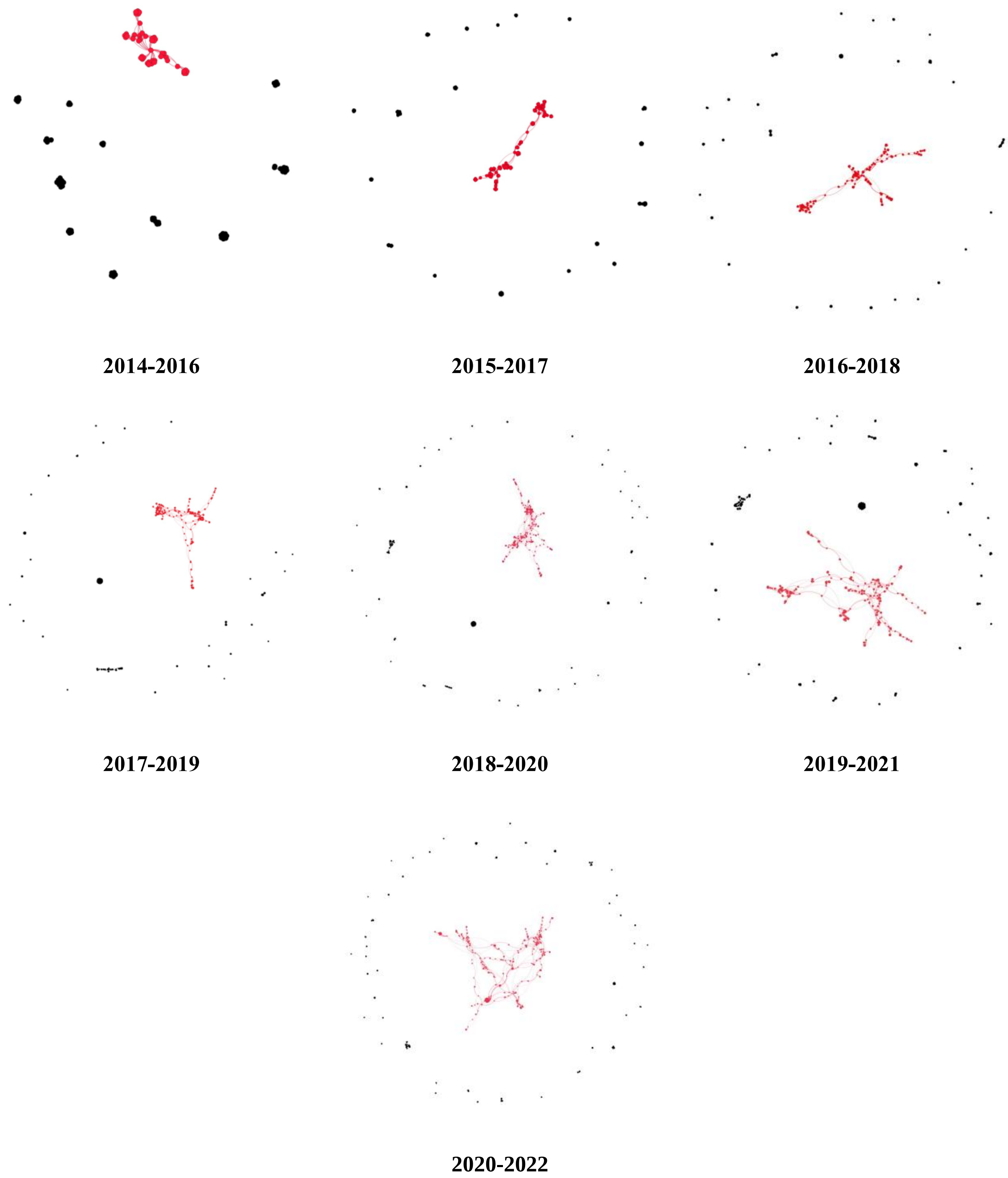


Figure A- 3. Evolution of the main component for the co-authorship network between CHINA and Canada

APPENDIX B – SUPPLEMENTARY MATERIALS ARTICLE 3

Table B- 1. Hierarchical clustering results (topics)

Main theme	Clusters number	Clusters title	Clusters size
Location-based technologies	66	Advanced localization and tracking technologies in various environments	13
	65	Enhanced navigation and positioning through sensor integration in various environments	8
	47	Innovative technologies and strategies for enhanced indoor and outdoor wireless communication and contact tracing.	8
	64	Optimizing and analyzing Wi-Fi networks and technologies	6
	52	Wireless communication and control in residential and acoustic environments.	14
Millimeter-wave technologies	7	Millimeter-wave technology applications and developments in 5G and wireless communications	41
	2	Advancements and challenges in mm wave technologies for 5G and imaging application	20
Energy management and efficiency	60	Data-driven electric vehicle emission reduction and energy management.	21
	20	Smart grid technologies and energy management	41
	9	Energy-efficient resource allocation in advanced wireless networks	30
	4	Power management and energy efficiency in 5G wireless communication technologies	72

Table B- 2. Hierarchical clustering results (topics) (continued)

Main theme	Clusters number	Clusters title	Clusters size
Iot and sensor networks	58	Wireless object monitoring, earthquake analysis, and motion sensing technologies for IoT and disaster mitigation	9
	45	Wireless sensor technologies for health and operational management in mining and oil industries.	21
	39	Agent-based decision making in stochastic game theoretical systems.	11
	38	Multi-agent scheduling and resource allocation in various industries, including healthcare, for enhanced efficiency and performance	8
	36	Wireless sensor networks in various applications and technologies	39
	25	Smart home and smart city technologies	18
	24	IoT communication and infrastructure research	17
Communication technologies and coding	44	Optimizing cable technologies for data transmission and grid monitoring	7
	42	Exploring coding theories and 3D technologies in network and multimedia applications	9
	41	Advancements and applications of coding and information theory in communication networks	11
	11	Implementation and application of polar and LDPC codes in 5G wireless communication systems	11
Edge and cloud computing	27	Mobile edge computing and mobile cloud applications	28
	26	Edge computing and deep learning for IoT and 5G networks	13
	21	Cloud computing, resource management, and privacy in fog networks	30

Table B- 1. Hierarchical clustering results (topics) (continued)

Main theme	Clusters number	Clusters title	Clusters size
Electromagnetic technologies	6	Advancements and applications of electromagnetic metamaterials in communication and processing technologies	58
	3	Advancements and challenges in electromagnetic metasurface-enhanced antenna arrays for communication systems.	63
Multimedia and content delivery	28	Multimodal media and communication technologies	37
	23	Multimedia content and video technology advancements	21
Network management and optimization	63	Optimizing 5G connectivity and network management through artificial intelligence.	6
	62	Optimizing network traffic management and operations in cellular networks	11
	61	Modeling and optimization in real-time software systems	48
	33	Quality of service and quality of experience in next-generation networks and service architectures	36
	32	Wireless mesh network performance and multicast optimization	11
	30	Resource management for next-generation wireless networks	31
	29	Data center networking and optimization	7
	14	Optimization of machine communications and node management in network layers	19
	13	Innovative strategies for massive data traffic and low latency in 5G networks	34
	12	Optimization and management in next-generation small cell cellular networks	35
	10	Optimizing cooperative diversity in wireless relay networks	41
	8	Access and management of dynamic spectrum in cognitive radio networks	21
	40	Technological approaches to sound and noise management in various applications and environments.	18

Table B- 1. Hierarchical clustering results (topics) (continued)

Main theme	Clusters number	Clusters title	Clusters size
Professional development and skills	50	Professional skill development and training programs in emerging technologies.	5
Safety, security, and privacy	59	Enhancing cybersecurity through advanced messaging verification and low-latency communication infrastructure optimization	3
	51	Enhancing safety and reliability through technological solutions in various environments	16
	34	Blockchain security and IoT privacy in emerging networks	44
	22	Vehicular communication and safety technologies	34
	19	Quantum information science and technologies for enhanced secure communication and computation.	17
Silicon and optical technologies	5	Innovations and applications of silicon circuits and chips in communication and diagnostics.	24
	1	Advancements in silicon photonics and optical communication systems.	101

Table B- 1. Hierarchical clustering results (topics) (continued)

Main theme	**Clusters number**	**Clusters title**	**Clusters size**
Advanced wireless communication technologies	67	Advanced radio channel modeling and remote communication technologies.	22
	57	Advanced wireless communication technologies and protocols for 5G, IoT, and beyond, including VLC, MMW, and RFID applications, and hardware development for DSP, 5G, and AI systems	11
	18	Synchronization and estimation in wireless communication systems	7
	15	Adaptive transmission techniques and channel management in wireless communications.	17
	54	Advanced wireless communication and networking technologies with a focus on interface, database, and platform development.	14
	43	Innovative approaches to RFID and wireless communication identification and management	15
	46	Digital innovations and paradigm shift in wireless communications and technology applications	7

Table B- 1. Hierarchical clustering results (topics) (continued and end)

Main theme	Clusters number	Clusters title	Clusters size
Interdisciplinary research	56	Advanced technologies converging in aerospace, healthcare, and entertainment domains	5
	55	Advanced technology applications for testing and monitoring in diverse industries	8
	53	Interdisciplinary research in hardware, software, and sensing applications	10
	35	Medical imaging and healthcare technology advancements	42
	31	Optimizing game server performance and latency in cloud-based multiplayer online gaming.	10
	37	Building construction and management technologies and methods	13
	48	Human-interactive robotic systems and applications	9
	49	Electrical and thermal management in various technological applications	15
Mimo	16	Advancing 5G technologies: SDN, massive MIMO and full duplexing collaboration	54
	17	5G innovations: massive MIMO, mm wave communication, and wireless backhaul solutions	22

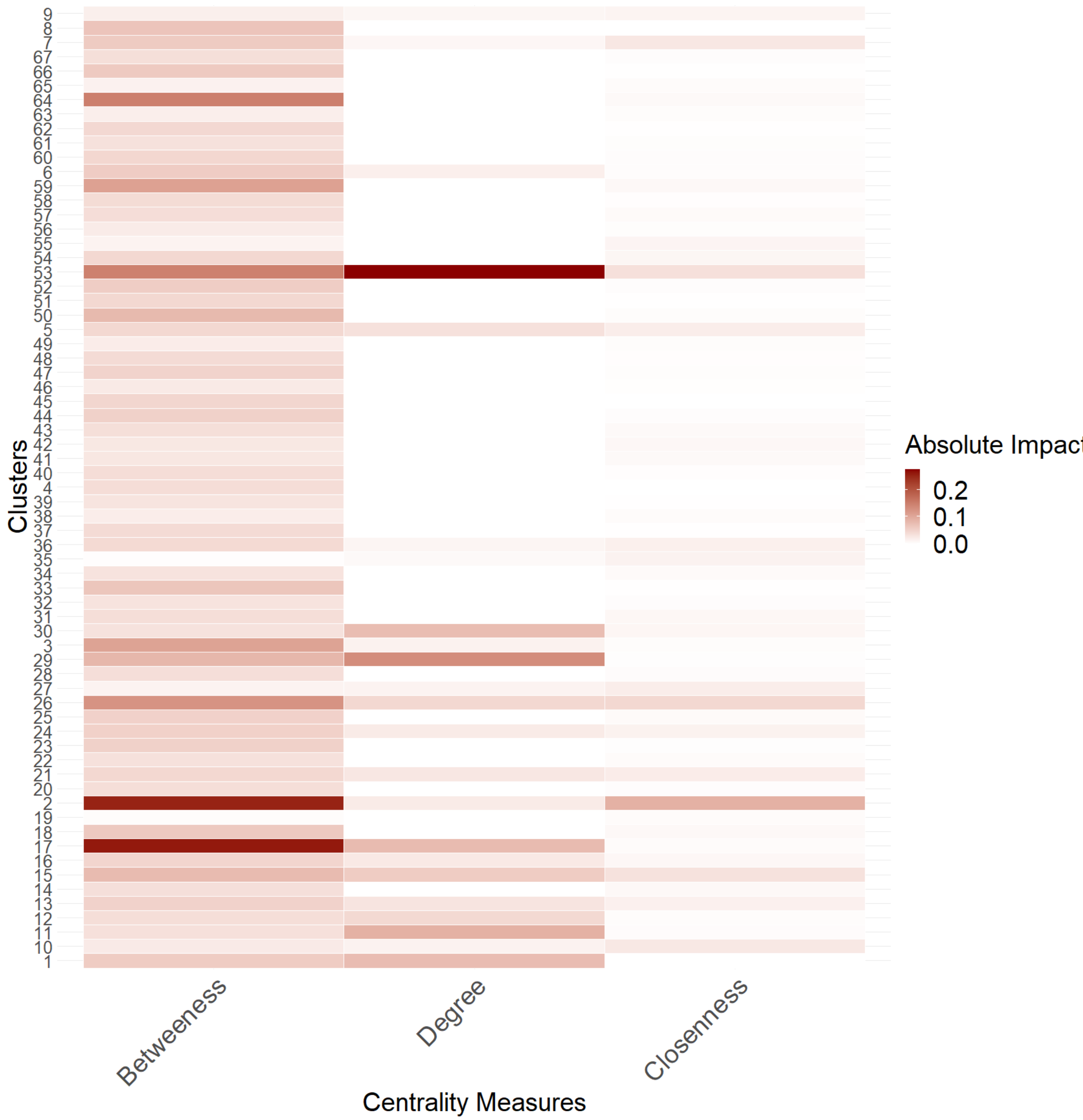


Figure B- 1. Impact of Huawei's removal on clusters centrality measures

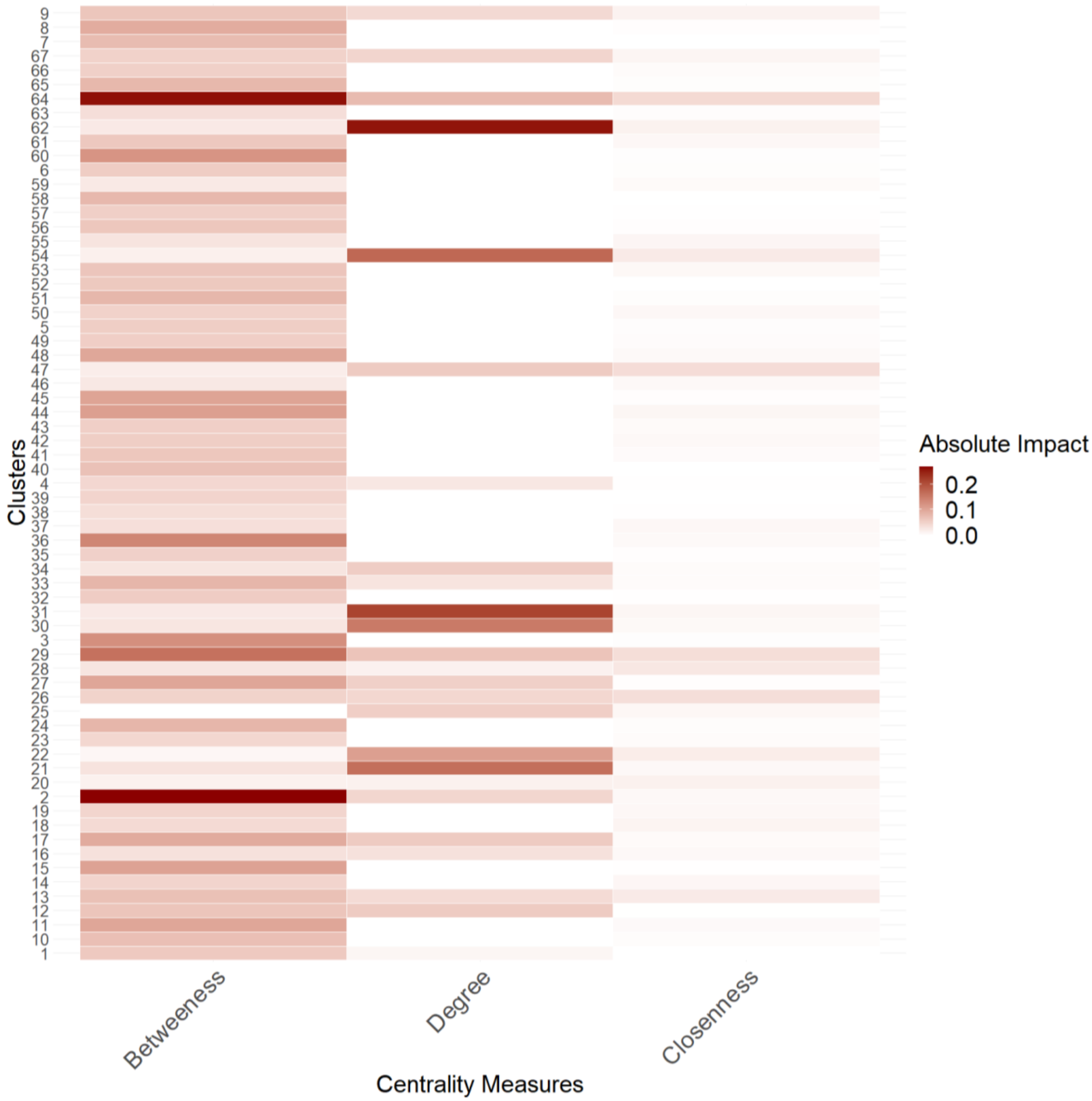


Figure B- 2. Impact of Ericsson’s removal on clusters centrality measures

APPENDIX C – SUPPLEMENTARY MATERIALS ARTICLE 4

Table C- 1. NSERC program groups

Program Group	NSERC Programs
Research and partnership	Alliance Grants
	Automotive Partnership Canada Project
	Applied Research and Development Grants-Level 1
	Applied Research and Development Grants-Level 2
	Applied Research and Development Grants-Level 3
	College and Community Innovation Program
	Industrial Research Chairs for Colleges Grants
	Collaborative Research and development Grants
	Engage Grant Program
	Engage Plus Grants Program
	Department of National Defence\ NSERC Research Partnership
	Idea to Innovation
	Industrial Research Chairs
	Research Network
	Quantum Works Innovation Platform
	Special Research Opportunity Program -Project
	Strategic Projects-Group
	Synergy Awards
	Connect Grants level 1
	Connect Grants level 2
	Interaction Grants Program
	Strategic Research Networks Program Letters of Intent
	Regional Office Discretionary Funds
	Chairs for Women in Science and Engineering - Project

Table C-1. NSERC program groups (continued and end)

Program Group	**NSERC Programs**
Discovery	Collaborative Health Research Projects
	Research Tools and Instruments - Category 1 (<$150,000)
	Research Tools and Instruments
	Special Research Opportunity Program - Project
	Canada Research Chairs
	Technology Access Centre
	Discovery Development Grant
	DND/NSERC Discovery Grant Supplement
	Discovery Launch Supplement
	Parental Leave - Research Grants
	PromoScience
	Discovery Grants Program - Accelerator Supplements
	Discovery Frontiers - Digging into Data
	Discovery Grants Program - Individual
	EWR Steacie Fellowships - Salary
	EWR Steacie Fellowships - Supplement
	Unique Initiatives Fund
Training	Postdoctoral Fellowships
	Collaborative Research and Training Experience

Table C- 2. First stage regression results

Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**
$AvgInternatArt_{it-1}$	-0.023	-0.044	-0.047	-0.026
	(0.029)	(0.035)	(0.035)	(0.029)
ln($AvgIntersectArt_{it-1}$*10+1)	**0.036*****	**0.037*****	**0.037*****	**0.036*****
	(0.013)	(0.013)	(0.013)	(0.013)
ln($PropArtFirst_{it-1}$*100+1)	-0.009	-0.009	-0.009	-0.009
	(0.006)	(0.006)	(0.006)	(0.006)
ln($PropArtLast_{it-1}$*100+1)	0.005	0.006	0.006	0.005
	(0.005)	(0.006)	(0.005)	(0.005)
$dChair_{it-2}$	**0.111*****	**0.109****	**0.110****	**0.111*****
	(0.043)	(0.043)	(0.043)	(0.043)
ln($AvgPaper_{it-2}$+1)	0.018	0.018		
	(0.020)	(0.020)		
ln($Avgmnc_{it-2}$*10+1)			0.014	0.014
			(0.010)	(0.010)
$dUSA_{it-1}$	-0.007	-0.040	-0.039	-0.007
	(0.017)	(0.031)	(0.031)	(0.017)
dUK_{it-1}	**0.044****	0.025	0.025	**0.044****
	(0.022)	(0.051)	(0.051)	(0.022)
$dINDIA_{it-1}$	**0.064****	-0.082	-0.079	**0.067****
	(0.032)	(0.079)	(0.079)	(0.032)
$dSKOREA_{it-1}$	**0.072****	**0.170****	**0.169****	**0.073****
	(0.031)	(0.076)	(0.076)	(0.031)
$dCHINA_{it-1}$	0.032	0.047	0.047	0.034
	(0.021)	(0.039)	(0.039)	(0.021)
[$AvgInternatArt$ x $dUSA$]$_{it-1}$		0.068	0.067	
		(0.053)	(0.053)	
[$AvgInternatArt$ x dUK]$_{it-1}$		0.024	0.024	
		(0.080)	(0.080)	
[$AvgInternatArt$ x $dINDIA$]$_{it-1}$		-0.028	-0.026	
		(0.063)	(0.063)	
[$AvgInternatArt$ x $dSKOREA$]$_{it-1}$		**0.235***	**0.236****	
		(0.120)	(0.120)	
[$AvgInternatArt$ x $dUSA$]$_{it-1}$		-0.163	-0.161	
		(0.116)	(0.116)	
ln($AvgGovIndGrant_{it-2}$+1)	**0.027******	**0.026******	**0.027******	**0.027******
	(0.005)	(0.005)	(0.005)	(0.005)
ln($CareerAge_{it-1}$/10+1)	**0.751*****	**0.759*****	**0.764*****	**0.755*****
	(0.242)	(0.242)	(0.241)	(0.240)
[ln($CareerAge_{it-1}$/10+1)]^2	**-0.343***	**-0.353***	**-0.348***	**-0.337***
	(0.202)	(0.203)	(0.202)	(0.202)
$NoHuaweiYesEricsson_{it-1}$	**0.617******	**0.616******	**0.616******	**0.616******
	(0.037)	(0.037)	(0.037)	(0.037)
$YesHuaweiNoEricsson_{it-1}$	**0.681******	**0.683******	**0.684******	**0.681******
	(0.040)	(0.040)	(0.040)	(0.040)
$YesHuaweiYesEricsson_{it-1}$	**0.711******	**0.718******	**0.717******	**0.711******
	(0.088)	(0.088)	(0.088)	(0.088)

Table C-2. First stage regression results (continued and end)

Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**
Constant	**-0.276***	**-0.271***	**-0.286***	**-0.291***
	(0.151)	(0.151)	(0.152)	(0.152)
Nb observations	6,152	6,152	6,152	6,152
Nb groups	796	796	796	796
F	**112.086********	**98.671********	**98.722********	**112.147********
R^2	0.431	0.432	0.432	0.431
Log likelihood	-2777.878	-2773.210	-2772.524	-2777.158
Log likelihood$_0$	-4514.119	-4514.119	-4514.119	-4514.119

Notes: ****p≤0.001, ***p≤0.01, **p≤0.05, *p≤0.1 and Standard errors in parenthesis; Dummy variables for discipline, program and province are included; *PropArtMiddle* is omitted.

Table C-3. Descriptive statistics

Variables	N	Mean	Standard deviation	min	max
Avgmnc	6,152	1.060	1.815	0	58.274
AvgPaper	6,152	4.160	5.681	0	66.333
PropArtFirst	6,152	0.061	0.173	0	1
PropArtLast	6,152	0.432	0.325	0	1
AvgGovColGrant	6,152	23,032	50,285	0	878,700
AvgGovIndGrant	6,152	14,336	42,158	0	41,8577
CareerAge	6,152	10.213	4.650	0	36
AvgInternatArt	6,152	0.418	0.330	0	1
AvgIntersectArt	6,152	0.120	0.215	0	1

Table C- 4. Correlation matrix

Variable		1	2	3	4	5	6	7	8	9	10
ln(*Avgmnc**10+1)	**1**	1									
ln(*AvgPaper*+1)	**2**	0.618	1								
ln(*PropArtFirst**100+1)	**3**	0.131	0.018	1							
ln(*PropArtLast**100+1)	**4**	0.386	0.523	-0.222	1						
ln(*AvgGovColGrant*/10^5+1)	**5**	0.102	0.261	-0.105	0.180	1					
ln(*AvgGovIndGrant*+1)	**6**	0.105	0.272	-0.115	0.188	0.903	1				
ln(*CareerAge*/10+1)	**7**	0.141	0.320	-0.005	0.173	0.470	0.468	1			
AvgInternatArt	**8**	0.314	0.402	-0.098	0.429	0.054	0.074	0.110	1		
ln(*AvgIntersectArt**10+1)	**9**	0.374	0.347	0.122	0.174	0.009	0.007	0.079	0.254	1	
ln(*Avgmnc**10+1)	**10**	0.125	0.163	-0.020	0.126	0.051	0.059	-0.052	0.150	-0.057	1

Table C- 5. Impact on average papers

Variables	Model 1	Model 2	Model 3	Model 4
ln(*AvgGovColGrant*$_{it-1}$/10000+1)	-0.100	-0.100	-0.041	-0.042
	(0.092)	(0.093)	(0.056)	(0.056)
dChair$_{it-2}$	0.080	0.081	0.051	0.048
	(0.061)	(0.062)	(0.035)	(0.034)
ln(*AvgPaper*$_{it-2}$ +1)	**0.272******	**0.276******		
	(0.038)	(0.037)		
ln(*Avgmnc*$_{it-2}$*10+1)			**0.522******	**0.523******
			(0.021)	(0.021)
ln(*PropArtFirst*$_{it-1}$*100+1)	**0.033*****	**0.034*****	0.013	0.013
	(0.012)	(0.012)	(0.008)	(0.008)
ln(*PropArtLast*$_{it-1}$*100+1)	**0.033*****	**0.034*****	0.013	0.013
	(0.012)	(0.012)	(0.008)	(0.008)
ln(*AvgIntersectArt*$_{it-1}$*10+1)	0.025	0.028	0.020	0.019
	(0.023)	(0.023)	(0.016)	(0.016)
AvgInternatArt$_{it-1}$	**0.373******	**0.322******	**0.144*****	**0.167******
	(0.065)	(0.079)	(0.054)	(0.042)
ln(*CareerAge*$_{it-1}$/10+1)	**1.485******	**1.490******	**0.308****	**0.304****
	(0.218)	(0.217)	(0.146)	(0.146)
[ln(*CareerAge*$_{it-1}$/10+1)]^2	**-0.896******	**-0.899******	-0.187	-0.185
	(0.205)	(0.204)	(0.123)	(0.123)
dUSA$_{it-1}$	**0.135******	**0.171*****	**0.109****	**0.076*****
	(0.037)	(0.063)	(0.043)	(0.024)
dUK$_{it-1}$	0.049	-0.082	-0.021	**0.057****
	(0.046)	(0.092)	(0.060)	(0.028)
dINDIA$_{it-1}$	-0.093	-0.035	-0.084	-0.039
	(0.065)	(0.163)	(0.109)	(0.038)
dSKOREA$_{it-1}$	**0.153****	**0.258***	0.153	**0.135******
	(0.062)	(0.150)	(0.095)	(0.037)
dCHINA$_{it-1}$	**0.081****	-0.068	-0.005	**0.067*****
	(0.040)	(0.074)	(0.048)	(0.024)
[*AvgInternatArt* x *dUSA*]$_{it-1}$		-0.059	-0.057	
		(0.118)	(0.079)	
[*AvgInternatArt* x *dUK*]$_{it-1}$		0.213	0.127	
		(0.162)	(0.103)	
[*AvgInternatArt* x *dCHINA*]$_{it-1}$		**0.277****	**0.135***	
		(0.133)	(0.083)	
[*AvgInternatArt* x *dINDIA*]$_{it-1}$		-0.112	0.067	
		(0.256)	(0.175)	
[*AvgInternatArt* x *dSKOREA*]$_{it-1}$		-0.187	-0.038	
		(0.236)	(0.149)	

Table C-5. Impact on average papers (continued and end)

Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**
Nb observations	6,152	6,152	6,152	6,152
Nb groups	796	796	796	796
Wald χ^2	**5356.43*******	**5388.78*******	**990.21*******	**9881.7*******
R^2	0.4639	0.4653	0.6166	0.6161

Notes: ****p≤0.001, ***p≤0.01, **p≤0.05, *p≤0.1 and Standard errors in parentheses; Dummy variables for discipline, program and province are included; *PropArtMiddle* is omitted.

Table C- 6. Impact on average citations

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
ln($AvgGovColGrant_{it-2}$/10^5+1)	**-0.054***	**-0.053***	**-0.053***	**-0.053***	-0.048	-0.049
	(0.031)	(0.031)	(0.031)	(0.031)	(0.031)	(0.031)
[ln($AvgGovColGrant_{it-2}$/10^5+1)]^2	**0.044*****	**0.043*****	**0.043*****	**0.043*****	**0.039*****	**0.04*****
	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)
ln($AvgGovIndGrant_{it-2}$+1)	-0.039	-0.039	-0.038	-0.038	-0.035	-0.036
	(0.032)	(0.032)	(0.032)	(0.032)	(0.032)	(0.032)
[ln($AvgGovIndGrant_{it-2}$+1)]^2	**0.005***	**0.005***	**0.005***	**0.005***	**0.005***	**0.005***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$dChair_{it-2}$	**0.174******	**0.174******	**0.178******	**0.177******	**0.177******	**0.181******
	(0.051)	(0.051)	(0.051)	(0.051)	(0.051)	(0.051)
ln($PropArtFirst_{it-1}$*100+1)	**0.016****	**0.016****	**0.016****	**0.016****	**0.015***	**0.015***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
ln($PropArtLast_{it-1}$*100+1)	**0.074******	**0.074******	**0.074******	**0.074******	**0.074******	**0.073******
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
$AvgInternatArt_{it-1}$	-0.034	-0.026	-0.046	-0.036	-0.033	-0.02
	(0.039)	(0.042)	(0.039)	(0.043)	(0.039)	(0.043)
ln($AvgIntersectArt_{it-1}$*10+1)	**0.068******	**0.067******	**0.068******	**0.067******	**0.068******	**0.067******
	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)
ln($CareerAge_{it-1}$/10+1)	**0.384******	**0.381******	**0.373******	**0.368******	**0.378******	**0.375******
	(0.100)	(0.100)	(0.099)	(0.099)	(0.099)	(0.098)
[ln($CareerAge_{it-1}$/10+1)]^2	-0.143	-0.141	-0.135	-0.132	-0.143	-0.14
	(0.096)	(0.096)	(0.096)	(0.095)	(0.095)	(0.094)
$dUSA_{it-1}$	**0.263******	**0.262******	**0.262******	**0.261******	**0.265******	**0.264******
	(0.025)	(0.025)	(0.025)	(0.025)	(0.025)	(0.025)
dUK_{it-1}	**0.292******	**0.291******	**0.292******	**0.292******	**0.286******	**0.287******
	(0.037)	(0.037)	(0.037)	(0.037)	(0.036)	(0.036)
$dINDIA_{it-1}$	**0.178******	**0.179******	**0.177******	**0.179******	**0.184******	**0.183******
	(0.049)	(0.049)	(0.049)	(0.049)	(0.049)	(0.049)
$dSKOREA_{it-1}$	**0.292******	**0.293******	**0.287******	**0.289******	**0.286******	**0.284******
	(0.052)	(0.051)	(0.051)	(0.051)	(0.051)	(0.050)
$dCHINA_{it-1}$	**0.310******	**0.332******	**0.309******	**0.336******		
	(0.029)	(0.053)	(0.029)	(0.053)		
$dHuawei_{it-1}$	0.014	0.014	**-0.101***	**-0.103***		
	(0.055)	(0.055)	(0.066)	(0.066)		
$dHuawei_{it-1}$ x $AvgInternatArt_{it-1}$			**0.258***	**0.263***		
			(0.164)	(0.162)		
$dCHINA_{it-1}$ x $AvgInternatArt_{it-1}$		-0.041		-0.05		
		(0.091)		(0.089)		
No $dHuawei_{it-1}$ x *Yes* $dCHINA_{it-1}$					**0.291******	**0.339******
					(0.029)	(0.053)
Yes $dHuawei_{it-1}$ x *No* $dCHINA_{it-1}$					**-0.111****	**-0.087***
					(0.049)	(0.057)
Yes $dHuawei_{it-1}$ x *Yes* $dCHINA_{it-1}$					**0.487******	0.23
					(0.097)	(0.212)
No $dHuawei_{it-1}$ x *yes* $dCHINA_{it-1}$ x $AvgInternatArt_{it-1}$						-0.087
						(0.087)
Yes $dHuawei_{it-1}$ x *No* $dCHINA_{it-1}$ x $AvgInternatArt_{it-1}$						-0.07
						(0.117)
Yes $dHuawei_{it-1}$ x *Yes* $dCHINA_{it-1}$ x $AvgInternatArt_{it-1}$						0.432
						(0.407)
Constant	**-0.138******	**-0.138******	**-0.131******	**-0.13******	**-0.13******	**-0.131******
	(0.028)	(0.028)	(0.028)	(0.028)	(0.028)	(0.028)

Table C-6. Impact on average citations (continued and end)

Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**
Nb observations	6,152	6,152	6,152	6,152	6,152	6,152
Nb groups	796	796	796	796	796	796
F	**161.07******	**158.71******	**158.17******	**155.46******	**160.34******	**150.78******
R^2	0.696	0.696	0.696	0.697	0.698	0.698
Log likelihood	-3828.460	-3828.118	-3823.232	-3822.720	-3810.444	-3804.715
Log likelihood$_0$	-7490.650	-7490.650	-7490.650	-7490.650	-7490.650	-7490.650

Notes: ****p≤0.001, ***p≤0.01, **p≤0.05, *p≤0.1 and Standard errors in parentheses; Dummy variables for discipline, program and province are included; *PropArtMiddle* is omitted.