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For Renata, Erika and Lexa

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Summary

General introduction

In real-world economies and societies, it is usual to observe the existence of formal or informal arrangements between actors (individuals and/or organizations) aimed at achieving both common and individual objectives. Shaped by pairwise (dyadic) interactions, these forms of collective action generate hybrid organizational forms or "institutional structures of production" (Menard, 2013) which situate themselves half-way between the micro and macro level and are more than the sum of their parts – i.e., they become "higher-order" (supra-dyadic) entities (Battiston *et al.*, 2020). Such structures play an essential role in transforming interacting micro behaviour into aggregate (macro) outcomes. As their boundaries are often loosely-defined and unstable, however, these hybrid organizations still remain poorly understood and under-researched in economics to date.

Going into these "mesoscopic" structures with suited methodological tools is thus an important challenge and the aim of this thesis. Its contribution is twofold. On the one hand, we propose new methodologies from social network analysis (the "place-based methodology" and the "chain-based methodology") that allow overcoming the pitfalls of traditional, dyad-based analytical tools. On the other hand, we perform two concrete applications of these methodologies to two different domains (respectively, innovation studies and financial economics). In doing that, we show their distinct advantages in capturing the structural properties of hybrid organizations and in bringing renewed interpretations of many economic phenomena for which the structure of interactions and the very nature of spillovers between actors matter.

Our starting point is to argue that it is convenient to represent hybrid organizations as networks, and to develop network methodologies that allow scaling up the traditional analysis of pairwise interactions and dyadic operators to a structural network analysis. We then distinguish between two discrete types of hybrid organizations: "horizontal" organizations (regrouping individuals with close functions and shared objectives) and "vertical" organizations (regrouping individuals with different objectives and properties).

"Horizontal" hybrid organizations focus on common properties of actors arising from collective action – viz. groups, or (more formally) *sets*. Indeed, group membership implies common properties such as shared objectives, resources, outcomes, behaviours, beliefs, identity, and so on. Collaborative research projects, technological clusters, firms' directorate boards, co-authored publications, lobbies, joint-ventures, and social clubs are just some common examples of these "mesoscopic" structures. The intersections or overlaps among groups – actors that are involved in several groups – are particularly relevant both for groups and actors. For groups, overlaps represent "bridges" through which "fluids" are allowed to circulate (Owen-Smith and Powell, 2004), and imply ways to exchange, coordinate, influence, or control. For actors, overlaps imply shared properties – those from the groups to which they belong – but some "bridging" or "broking" capacities. "Horizontal" hybrid organizations can be conveniently seen as affiliation networks (Faust, 1997), but classical methodologies – viz. the analysis of individuals' one-mode projected networks – miss the accurate identification of these unique combinations of affiliations, and generate an artificial clustering or cliquishness (Newman *et al*., 2001; Uzzi and Spiro, 2005) that can lead to misinterpretations. To overcome these problems, we propose a simple and little-know alternative approach – the "place-based methodology" (Pizarro, 2007).

"Vertical" hybrid organizations focus on the structure – the roles played by actors and the links between them – and the unity of collective action. Aggregations of pairwise interactions make sense and achieve their objectives when they form indissociable structures, where actors take roles that regulate the interactions with the others. Supply chains, transport networks, brokerage, or financial intermediation are just some simple examples of these "mesoscopic" structures. In these forms of organization, the structure formed by actors and links is relevant, but also its unity, since the loss or removal of any actor or link implies the collapse of the organization. In this thesis, we highlight the convenience of seeing these hybrid organizations as supra-dyadic interaction network (also known as "higher-order" interaction networks), and we focus on one form of supra-dyadic interaction unit: relational chains. Classical and more recent approaches – single-layer single-relational and multi-layer multi-relational networks, respectively – fail to consider the structures of hybrid organizations as units, generating some biases that can lead to misinterpretations. In recent times, a multidisciplinary stream of research consecrated to the study of supra-dyadic interaction networks has emerged (Battiston *et al*., 2020). While scholars have mostly focused on the question of unity and how to preserve it in the analysis (mainly using hypergraphs: Bonacich *et al*., 2004, Estrada and Rodríguez-Velázquez, 2006), the proposed approaches still go by the internal interaction structure of "higher-order" structures. To overcome this limitation, we suggest to use hyperstructures (Criado *et al*., 2010), which preserve both the unity and the internal structure of supra-dyadic interaction organization: this leads us to formulate our "chain-based methodology" for the study of relational chains. The formulation of this original analytical tool, as well as its introduction into economics as a way to preserve the unity of sequential relational chains, are another major methodological contribution of this thesis.

This thesis is organized as follows. Chapter 1, "*Chasing "Strange Animals": Network Analysis Tools for the Study of Hybrid Organizations*" (co-authored with Stefano Ugolini and Jérôme Vicente), introduces the theoretical framework and research opportunities for the study of hybrid organizations, and argues for the need to develop adequate empirical methodologies in order to analyse them. On the one hand, the use of classical tools for affiliation networks ("horizontal" organizations) is discussed, highlighting the methodological and interpretative problems generated by the popular one-mode projection approach. Based on the concept of structural equivalence (Lorrain and White, 1971), the "place-based methodology" is proposed for the study of affiliation networks. Structural equivalence stipulates that every two actors occupy a structurally equivalent position if they connect in the very same way to the network, i.e. if they have the same structural properties (the same relational resources and constraints). Grouping structurally equivalent positions together as single nodes allows reducing the network to its "skeleton" (Breiger *et al*., 1975; Doreian, 2009). The proposed methodology identifies structurally equivalent positions of actors in affiliation networks – viz. places – as very unique combinations of affiliation to sets, which can be projected as a network of places. This allows overcoming the biases and misinterpretations associated to classical one-mode projection analyses. On the other hand, the use of hyperstructures – a novel methodological approach based on the use of hypergraphs – is proposed for the study of "vertical" organizations. We focus on a particular kind of supra-dyadic interactions – viz. sequential interaction (or, "relational") chains – where positions and links are ordered (e.g. a buyer-broker-seller triad) and removal of any of the roles or links results in the collapse of the entire supra-dyadic unit. Both the classical approach via single-layer single-relational networks and the more recent approach via multi-layer networks are discussed: since they do not preserve the unity of relational chains, these approaches present serious analytical shortcomings. To overcome these deficiencies, the "chain-based methodology" – based on the hyperstructure approach – is proposed, since it preserves both the unity and the substructure of supra-dyadic interactions within the relational chain.

In the remainder of the thesis, these methodological insights are put to work in two different domains. In Chapters 2 and 3, the "place-based methodology" is applied in the context of innovation economics, in order to study the structural properties of one particular type of "horizontal" hybrid organization: viz., collaborative R&D projects. Innovation studies are a not a field chosen "at random", since economists (Acemoglu *et al*., 2016), sociologists (Owen-Smith and

Powell, 2004) as well as economic geographers (Giuliani, 2007; Ter Wal and Boschma, 2009) have early captured the fact that innovation processes are better understood through the mechanisms of network formation and dynamics than through pure market interactions and competitive pressures. Nevertheless, one of the challenges remains to explore new ways to deal with network data on R&D collaborations in order to capture higher-order structures of interaction which may provide new interpretations of innovation networks dynamics, such as resilience and diversification, both being nowadays at the core of the design of innovation policies.

Chapter 2, "*The visible hand of cluster policy makers: An analysis of Aerospace Valley (2006-2015) using a place-based network methodology*" (co-authored with Jérôme Vicente), suggests capturing particular hybrid organizations in two related topics of innovations studies these last years: the structuring of innovation networks and clusters, with a focus on the effects of networks incentives in the organization of innovations activities and the macro-structure of knowledge spillovers. More precisely, we focus on the effects of cluster R&D policies on collaborative knowledge networks. Using an original hand-collected dataset of publicly-funded collaborative projects from the French *Aerospace Valley* cluster (from 2006 to 2015), we build 4-cohort knowledge networks that enable us evidencing the evolving structural properties of the cluster over time. We analyse networks combining both places and cohesive blocks methodologies (Moody and White, 2003) in order to extract the community structure. This allows us to evidence the meso structure of the network, and to study both its micro and macro properties. Concretely, highly cohesive and influential groups – which we call "elites" – are identified, and their composition – viz. the organizations and research projects involved – are studied. We discuss the results of the community structure analyses on the degree of convergence between the structural properties of the cluster selected by the Program and policy makers' objectives. Finally, we identify the actors of the structural and technological changes observed through the period. In particular, we observe a growing role of SMEs, which move from the periphery to central positions thanks to their research diversification – viz. cross-sectoral projects.

Chapter 3, "Do R&D diversification policies change the cognitive structure of knowledge networks? Evidence from France using a meso-structural approach", goes beyond the regional level of cluster to invest the structure of innovation networks at the national scale, still stressing on the relevance of the "places" methodology as regard previous works on innovation network based on public-funded R&D projects based on pure dyadic network methodologies. We examine the effects of diversification R&D policies on sectoral collaborative knowledge networks. Diversification R&D policies – mainly through cross-sectoral project funding – try to raise new research topics and technologies in order to develop new markets, thus increasing the competitiveness and resilience of R&D systems (Porter, 1998; Boschma and Frenken, 2012; Lämmer-Gamp et al., 2014). However, the probability of successful emergence of new topics – diversified topics – is higher when they are related to more cohesive/core parts of the technology/knowledge network (Boschma et al., 2014; Crespo et al., 2014; Essletzbichler, 2015; Crespo et al., 2016) – viz., when they are well-integrated. Using data on publicly-funded collaborative projects from the French FUI program for the period 2006-2015 (18 calls for tender), we build 31 knowledge networks by cohort and sector of activity. We combine both places and cohesive blocks methodologies, and define "peaks" as highly cohesive communities at the local level. This allows studying the micro and macro structural properties of the networks at the meso-level. Additionally, we use a conceptual framework of proximity (based on collective action – e.g. shared objectives, contributions, and outcomes – rather than on individual attributes) to identify both the micro-dynamics of actors and the cognitive macro-structure of the networks. Through a qualitative analysis, we confirm that "peaks" can be identified as main research topics of the networks. Consequently, the study of "peaks" – their number and composition – allows us obtaining the research topics portfolio and identifying the topics that come from cross-sectoral projects – viz., diversified topics. As this methodology provides information about cognitive structures using simple affiliation data (viz., organization-projects), we can quantitatively examine the effect of funded cross-sectoral projects on sectors' research portfolios. The results point to the existence of a positive effect of diversification R&D policy incentives on the emergence of well-integrated diversified topics. However, there is no evidence that these policies have a positive effect on the broadening of knowledge networks' topics portfolios. Additionally, the effect of diversification policies on the emergence of diversified topics is unequal across sectors. The need for more "surgical" measures regarding the nature and cycle-life of sectors is discussed.

In Chapters 4 and 5 of the thesis, we apply the "chain-based methodology" in the context of financial economics, in order to study the structural properties of one particular type of "vertical" hybrid organization: viz., financial intermediation chains. Since the collapse of Lehman Brothers (a relatively small, but highly connected bank) in 2008, network analysis and simulation methodologies have been become overwhelmingly popular in financial economics as tools to evaluate the resilience of financial systems (Glasserman and Young, 2016; Battiston and Martinez-Jaramillo, 2018; Caccioli *et al.*, 2018; Iori and Mantegna, 2018). This abundant literature has been marked by a strict dyadic approach, as it has almost constantly seen financial networks as the sum of the bilateral credit relations existing between similar institutions (i.e., interbank loans). However, real-world financial networks go beyond the simple interbank networks that constitute their backbone (Lux, 2016). Recent research has highlighted the existence of long intermediation chains (Adrian and Shin, 2010), that play a crucial role in overcoming information asymmetries in credit markets (Glode and Opp, 2016). To the best of our knowledge, our contribution is the first one to consider these chains as hybrid organizations, as well as the first one to apply novel network analysis tools that consider the unity and substructure of these "mesoscopic" entities. To do so, we collect an original database featuring entire intermediation chains connecting borrowing firms to lending institutions. This database covers the global financial network not as it is today, but in a previously unexplored period – i.e., the so-called first globalization of 1880-1914. It is therefore of special interest as we compare it to today: as a matter of fact, such a comparison reveals to what extent a different organization of "mesoscopic" entities may entail huge differences in terms of macroscopic outcomes (in particular, in terms of the system's resilience to shocks).

Chapter 4, "*The Origination and Distribution of Money Market Instruments: Sterling Bills of Exchange during the First Globalisation*" (co-authored with Olivier Accominotti and Stefano Ugolini), presents our database and looks at the determinants of the observed structure of our "mesoscopic" entities – i.e. the origination and distribution chains of the staple money market instruments of the time (sterling bills of exchange). Our hand-collected data set comes from a unique archival source – the Bank of England's *Discount Ledgers* – which report systematic micro-level information of bills circulating on the London money market and on all agents involved in their origination and distribution. For this work, we exploit all individual bills re-discounted by the Bank of England during the year 1906 (23,493 bills). Bills of exchange always involved a drawer (a borrower located anywhere in the world), and acceptor (a London-based actor who guaranteed the bill's payment in pounds sterling at maturity), and a discounter (a wholesale lender). In other words, a bill is an origination-distribution chain involving three ordered roles by two ordered links. This chain which must be considered as a supra-dyadic unit, since the removal of any of the roles or the links results in the collapse of the entire chain. The data set is reduced by the removal of all redundant drawer-acceptor-discounter triads, obtaining 8,888 non-identical bills. Then, we build a static network of 4,970 agents. Among these, we find that the drawer role is played by 3,554 nodes, the acceptor role by 1,439 nodes, and the discounter by 145 nodes (note that some nodes played more than one role). Thus, we analyse the sterling money market preserving the unity of bills, so as supra-dyadic units. Our analysis reveals a globalized market, and underscores the crucial role played by acceptors and discounters in overcoming information asymmetries between borrowers and final lenders. Indeed, at origination, one first guarantee of the bill's payment is provided by the acceptor, thus reducing credit risk before distribution to a discounter. Next, as the bill is distributed to a final investor (a re-discounter or "retail" lender), the discounter adds a secondary guarantee by endorsing the bill. Thus, discounters played two distinct functions on the money market: not only they distributed bills, but also enhanced their creditworthiness. This complex market organization ensured that risky private debts could be transformed into extremely liquid and safe monetary instruments traded throughout the global financial system.

Chapter 5, "Bank substitutability and financial network resilience: insights from the first globalization" (co-authored with Olivier Accominotti and Stefano Ugolini), investigates how the meso structure of our "vertical" hybrid organizations (intermediation chains) impacted the macro properties of the global financial network (its resilience to shocks). We focus on one particular aspect of resilience: the degree of substitutability of banks. While a recent wave of research on financial network resilience has largely focused on the interconnectedness dimension and the identification of "too-interconnected-to-fail" actors (Freixas et al., 2000; Glasserman and Young, 2016; Battiston and Martinez-Jaramillo, 2018; Caccioli et al., 2018; Iori and Mantegna, 2018), we remark that the substitutability dimension (yet one of the five dimensions of systemicness put forward by the Basel Committee on Banking Supervision) has received considerably less attention. Using the dataset introduced in Chapter 4, we study the resilience of the international financial network during the first globalization by focusing on the substitutability of banks (acceptors and discounters). With this purpose, we apply simple node-removal techniques to simulate the upper-bound effects of bank defaults on firms' access to credit. As argued above, intermediation chains are supra-dyadic units, so the removal of any of its actors involves the collapse of the entire chain. Then, in our framework substitutability refers to the existence for borrowing firms of alternative paths to access the market through other the relational chains when their bank is removed. Consequently, the network is defined as a hyperstructure in order to preserve both the unity and the internal relational substructure of chains. Compared to nowadays' interbank networks – characterized by highly hierarchical structures and few very highly systemic, unsubstitutable actors (Pröpper et al., 2008; Craig and Von Peter, 2014; Fricke and Lux, 2015) – our results show a resilient financial network, where even individuals or groups of actors with relatively high market share exhibit low levels of systemicness and high substitutability (both at an absolute, local, or geographic level). This means that, in stark contrast with the findings of the literature on current-day systems, a financial network deprived of systemic actors can exist and did actually exist at one of the highest times of international economic development. This conclusion has important implications for regulators, as it shows that providing banks with incentives to produce private information (rather than merely relying on publicly-available information) can considerably enhance the resilience of the financial system to shocks. From the general viewpoint of this thesis, Chapters 4 and 5 confirm that the way hybrid organizations structure themselves may have far-reaching effects on the macro properties of economic systems.

References of the introduction

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Chapter 1 – Chasing "Strange Animals": Network Analysis Tools for the Study of Hybrid Organizations

Abstract:

Real-life economies feature a number of hybrid organizations laying between the micro and macro level. Aimed at dealing with spillovers, these mesoscopic structures are coordination mechanisms with unclear and unstable boundaries. We argue that network analysis tools based on supra-dyadic relationships can greatly improve our understanding of the structural properties of these "strange animals". We illustrate this by focusing on two innovative tools: the "place-based methodology" (allowing to assess agents' substitutability in horizontal affiliation networks), and the "chain-based methodology" (allowing to assess agents' substitutability in vertical interaction networks). We provide some example of how the application of such methodologies can concretely improve our understanding of the resilience properties of widespread real-world hybrid organizations.

Keywords: *Hybrid organizations; mesoscopic structures; affiliation networks; supra-dyadic interaction units; place-based methodology; hyperstructures; chain-based methodology*

JEL codes: B41, D85, E14, L14.

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1.1. Introduction

Between micro behaviour and decision on one side and macro aggregates on the other side, many rich and complex processes happen to develop. To date, understanding such processes and their role in many social and non-social phenomena remains one of the biggest challenges for social sciences (Schelling, 1978; Kirman, 1992) as for physics (Newman, 2003; Battiston *et al.*, 2020). The tools developed by network science have proven to be particularly appropriate in dealing with such a challenge (Barabasi, 2002; Watts, 2004). In the recent decades, they have been introduced in many social sciences, in order to disentangle grey areas between different branches of each discipline: for instance, in sociology (Granovetter, 1985; Burt, 2000), to better understand social capital and its role in determining access to resources like jobs or recognition; in management and innovation studies (Kogut, 2000; Owen-Smith and Powell, 2004), to better capture the drivers of firm creation and innovative performances; or in economic theory (Jackson, 2008), to better understand the role of networks in determining individual strategies and the outcomes of coordination games.

Nevertheless, this huge wave of research, which has been applying network theories and tools to disentangle micro-macro phenomena, has largely occulted the intermediated level of analysis. Indeed, in this literature macro structures or aggregates are depicted as directly emerging from pairwise (dyadic) interactions in networks, without paying particular attention to the "strange animals" (Ménard, 2013) that do exist between the two scales and irrigate economic life. We refer here to the concepts of *meso-structure* and *hybrid organization*, both typifying "higher-order" structures (Battiston *et al*., 2020) that emerge from dyadic interactions but, in a sense, escape from actors' intention while influencing aggregate outcomes. Such structures have however been identified by scholars since long. Think for example of industrial districts, originally defined by Marshall (1919) as "organic wholes", in which ideas and knowledge are exchanged and improved through channels which develop beyond entrepreneurs' intentions, and affect national growth. Another classical example is interlocking directorates (Schoorman *et al.*, 1981), in which large communities of inter-linked corporate directors give rise to elite circles influencing industrial strategy (but also policymaking) without any legal status or formal institutional frontiers.

These meso-structures are "strange" in that they have no formal existence and boundaries as organizations typically have, making it much harder for scholars to deal with them with respect to clearly identified micro units of analysis. Nonetheless, hybrid organizations are a fact of economic life (Thorelli, 1986; Powell, 1990; Holmstrom and Roberts, 1998; Baker *et al.*, 2002; Dopfer *et al.*, 2004; Ménard, 2013, 2014), and constitute relational matrixes and networks through which many "fluids" such as information, knowledge, or other economic assets can circulate (Owen-Smith and Powell, 2004). These matrixes and networks display different topological and structural forms, and these offer great opportunities to analyse how *spillovers* matter and affect aggregate outcomes.[1] Such opportunities have only very partially started to be seized to date.

Going into these hybrid organizations with suited methodological tools is thus an important challenge, and the aim of this contribution. We argue that it is convenient to represent hybrid organizations as networks, and to develop network methodologies that allow scaling up the traditional analysis of pairwise interactions and dyadic operators to a truly structural network analysis – whose aims are identifying meso-structures, detecting their structural properties, and undercovering their role in macro-dynamics. We focus on two types of hybrid organizations in which agents are involved, produce or benefit from spillovers. First, we consider "horizontal" organizations, which can be conveniently seen as affiliation networks (Faust, 1997). Second, we consider "vertical" organizations, which can be conveniently seen as supra-dyadic interaction networks (Bonacich *et al*., 2004).

In recent decades, different branches of the social science literature have consistently shown that applying network analysis to both affiliation and interaction networks can yield valuable insights about the properties of such networks, especially for what concerns their resilience to shocks – the substitutability of the individuals composing the network, their position or role, as well as the statistical properties of the network (May *et al*., 2008; Crespo *et al*., 2014). However, applying inappropriate structural analysis tools may be conducive to some errors in the modelling of social and economic phenomena, as well as in the interpretation of empirical results. Under this respect, we provide two distinctive contributions, as we propose the adoption of two innovative tools, one for affiliation networks (the "place-based methodology") and one for supra-dyadic interaction networks (the "chain-based methodology"). Both contributions converge in their ability to overpass the respective biases of the traditional methodologies used for each type of hybrid organization, which may occult what is structurally going on between agents and macro-structures.

The remainder of the paper is organized as follows. Section 1.2 invests the research opportunities that lie in treating hybrid organizations as networks, and underlines the need to develop suited analytic tools for that purpose. Section 1.3 argues that the traditional analysis of affiliation networks as one-mode projections of bipartite networks can be conveniently replaced by the "place-based

[1] The concept of "spillover" is often rather loosely defined in the literature. In this paper, we consider as spillovers both *marginal externalities* (i.e., "classical" external effects) and *inframarginal externalities* (i.e., complementarities). For a discussion, see Liebowitz and Margolis (1994) and Hogendorn (2012).

methodology". This methodology introduces the concept of structural equivalence, and allows overpassing well-known biases related to artificial cliquishness – leading to misinterpretations in the degree of substitutability of individuals belonging to horizontal hybrid organizations. Section 1.4 argues that the now common analysis of supra-dyadic interaction networks as multi-layer networks can be conveniently replaced by the "chain-based methodology". This methodology introduces the concept of *hyperstructure*, and allows overpassing well-known biases related to the lack of consideration for extra-dyadic structures – leading to misinterpretations in the degree of substitutability of individuals belonging to vertical hybrid organizations. In both sections, we provide some concrete examples of application of these two new methodologies, and show why they bring added value to the analysis of real-world phenomena in many topics and subfields of social sciences. Finally, Section 1.5 concludes that properly applying the correct structural analysis tools may potentially yield substantial improvements in our understanding of the structural properties of meso-economic organizations.

1.2. Hybrid organizations and network analysis: conceptual framework

1.2.1. The missing piece of coordination structures in micro-macro dynamics

Economic life involves a complex combination of entities, from individuals to states (including firms or other intermediate bodies in between), which interact at different scales and through which many "fluids" circulate. Therefore, an approach defining the micro-foundations of macroeconomic phenomena only considering individuals as units of analysis (and thus, thinking about micro/macro loops in terms of how aggregates influence directly individuals and vice versa) early appeared too simplistic to social scientists, as it occulted important intermediate scales of coordination. Together with sociology (Weber, 1947) and management (Mintzberg, 1979), economics has not remained on the fringes of research on organizations, esp. with the contribution of Williamson (1985) and the development of the New Institutional Economics (NIE) School, both inspired by the seminal intuitions of Coase (1937, 1960). According to this view, uncertainty about the behaviour of other agents or the very nature of exchanged goods, and the resulting transaction costs in coordination dynamics, provide for the existence of different types of organizations in different economic contexts. The result is a continuum of organizational forms from pure market interaction to pure authority and hierarchy, with a large spectrum of "strange animals" in between. Such "hybrid" organizations are characterized by unclear institutional and legal frontiers (Ménard, 2013), so that it is difficult to identify where power and authority actually occur (Perrucci and Pilisuk, 1970). Moreover, these “strange animals” appear to be aimed at dealing with spillovers otherwise than through the classical internalization process (via the acquisition of property rights) that Coase (1937, 1960) and Williamson (1985) famously focused on.

One good example of this problem (and one that has been highly disputed in economic geography and innovation economics since the 1990s) is provided by the case of *knowledge spillovers* (Feldman, 1994). This concept dates back to the intuitions of Marshall (1919), who famously pointed to the role of “districts” in fostering industrial development at the end of the 19th century. According to mainstream economics, unintended knowledge spillovers decrease incentives to innovation, while knowledge accumulation favours economic growth (Arrow, 1972): the resulting “knowledge dilemma” can be efficiently solved, in a second order optimum, through the establishment of patents as property rights allowing knowledge to become a tradable good (Antonelli, 2005). However, other scholars have shown that incentives to innovation and knowledge accumulation mostly originated from *intended* knowledge spillovers: such spillovers flow through communities, sometimes called “clusters” (Owen-Smith and Powell, 2004), which are identified as a main source of economic growth (Vicente, 2018). The same occurs in other fields and contexts, for instance in industrial strategy and economic policy, with the role of elite circles in the industry (interlocking directorates), or in the interactions between “captains of industry” and policymakers – i.e., communities of people having different institutional affiliations, roles and positions, but sharing common interests and having close social capital built over time and traced back to their first interactions in the top administration and business schools (Mizruchi, 1996; Van Apeldoorn and De Graaff, 2014; Comet, 2019).Yet another example is that of clans or kinship systems, which are loosely-defined organizations that can have far-reaching consequences in terms of economic development (Azariadis and Stachurski, 2005).

Clusters, elite circles, clans, among others, are part of these “strange animals” for economists, i.e. objects with no clear and stable institutional frontiers that can hardly be considered as “agents”, but whose influence on macro-aggregates and economic dynamics remains strong. These hybrid organizations cannot be analytically and empirically highlighted in Williamson’s (1985) framework: even if they are intermediate structures between markets and hierarchies (Ménard, 2013), they lack formal institutional arrangements such as contracts, franchising, or so. To the contrary, these meso-structures precisely emerge without any formal rule, through social interactions and relational chains that overpass, and sometimes escape, the intentions of individual agents in their own pairwise interactions. Detecting these communities and better considering these hybrid organizations as higher-order actors involved in coordination dynamics remains an important challenge. It would allow studying macro-dynamics and changes in a different (and complementary) way with respect to traditional micro-macro causation, thus avoiding the biases and misinterpretations stemming from mere pairwise (dyadic) interactions.

Such biases have been early identified in sociological research on the organizational foundations of community power. Early contributions by Freeman (1968) and Perrucci and Pilisuk (1970) have shown that power and influence are diluted through unstable interest groups, whose border variability cannot be directly linked to common-sense classifications of formal categories of organizations – thus revealing that the reality of power cannot be searched only in objective organizational categories. Other structures, often broader and not directly linked to the aggregation of formal categories of organizations (and therefore, more difficult to portray), do actually matter. These structures allow for the circulation of different "fluids" that are essential to the determination of many economic aggregates – which makes some of these "strange animals" even more influential than visible, formal organizations. Economic sociology recognized this issue very early on, but was limited at the time by the availability of suited empirical tools and methodologies. Recent developments in social sciences based on network theory (from mathematics and physics) now make it possible to overcome these limits and identify richer structural facts, thus opening scope for a better understanding of the role of these higher-order actors (Battiston *et al*., 2020).

1.2.2. Studying hybrid organizations through network analysis tools: issues

Network theories have been often used in social sciences with two alternative goals: either 1) to assess individual performance according to individual network strategy and position (Powell *et al.*, 1999), or 2) to relate some aggregates and collective behaviours to network properties and dynamics, themselves emerging from individual behaviour (Watts, 2004; Ahuja *et al*., 2012). If the question of how hybrid organizations can be identified and studied is not relevant to the first approach, it is nonetheless central to the second approach.

So far, network properties and dynamics have been understood as the result of a set of dyadic relations. In the case of affiliation matrixes in bipartite networks, higher-order structures are treated as exogenous and infused top-down onto the network: think, for instance, of granted R&D consortia in which firms are considered to be involved regardless of the actual way they participate into the project. In the case of interaction matrixes, higher-order structures are identified through exogenously-determined criteria: think, for instance, of acquaintance networks in which individuals are considered to be involved regardless of the actual way they interact with each other.

Therefore, the analysis of the aggregate properties of these networks (such as their link-formation behaviour or their resilience to shocks) has been performed through the application of tools exclusively based on dyadic connections. Such tools do not allow considering higher-order groups (these "strange animals") as "mesoscopic nodes" that escape both the intention of microscopic nodes and the boundaries of clear-cut institutional frontiers (do firms provide similar contributions to R&D projects in similar ways regardless of their formal affiliation? do people play similar social roles regardless of the way they are positioned within a web of bilateral interaction links?). Network scientists have early developed these tools to detect parts of "mesoscopic" structures, without however going to the point of considering them as higher-order nodes of "higher-order networks" that can emerge independently of the direct bilateral interaction between their lower-order nodes (Battiston *et al.*, 2020).

For instance, think of the community detection tools for the identification of several types of cohesive structures such as cliques (Everett and Borgatti, 1998) and blocks (Moody and White, 2003), which have been largely applied in the literature in order to explore both network dynamics and structural properties. They have been used to analyse the outcomes of network formation and growth mechanisms (Snijders, 2001; Barabasi, 2002) as well as the macro-structural properties of networks, from small worlds and connectedness to assortativity and core-periphery structures (Watts and Strogatz, 1998; Borgatti and Everett, 2000; Newman, 2002). These methodologies have vastly contributed to improving our understanding of the way spillovers occur through complex and evolving social structures. Yet, they do not allow identifying and studying more invisible hybrid structures, as none of them allows dissociating the notion of group from that of the bilateral links observed between their microscopic nodes. Mesoscopic nodes do not however necessarily originate from formal affiliation or bilateral interaction links across microscopic nodes, but rather from properties related to their position and their relational behaviour. This confers on mesoscopic actors a hardly perceptible autonomy, but an unquestionable influence on many economic facts. Therefore, the challenge is to design new methodologies to capture these higher-order nodes (Battiston *et al.*, 2020) and to study if their structural properties and dynamics affect aggregated outcomes in a different way than predicted by methodologies based on pure pairwise interactions between initial lower-order nodes.

1.2.3. Beyond pairwise relations: new tools for studying hybrid organizations

In the remainder of this paper, we propose to adopt new network analysis tools going beyond pairwise relations in order to identify and analyse hybrid organizations. Following the classical conceptual framework in industrial economics (see e.g. Williamson, 1985), we distinguish between "horizontal" organizations (regrouping individuals with similar functions or specializations) and "vertical" organizations (regrouping individuals with different functions or specializations).

We then focus on two types of horizontal and vertical hybrid organizations. First, we consider *horizontal hybrid organizations* allowing for coordination through affiliation, as for instance firms engaged in large R&D collaborative projects or standardization process in a particular industry. Second, we consider *vertical hybrid organizations* allowing for coordination through sequential interactions, as for instance producers of different intermediate goods in a supply chain or shipping lines in the international shipping network.

Our distinction between *affiliation* and *interaction* networks is in line with the seminal contributions in sociology of Nadel (1957) and Breiger (1974), according to whom these are the two main kinds of relations. Affiliation relations consider the participation of individuals to groups or events (where all the individuals of a group or event interact with others but not necessarily with all others), while interaction relations consider that actors carry out actions with other actors and are defined by their position in the sequence of the reciprocal interaction.

We then illustrate the network analysis tools that have been generally applied to the study of horizontal affiliation networks and vertical interaction networks, and we expose their limits. To circumvent these limitations, we propose to adopt new methodologies that go beyond traditional dyadic-based tools: the "place-based methodology" for horizontal affiliation networks (Section 3), and the "chain-based methodology" for vertical interaction networks (Section 4).

1.3. Horizontal hybrid organizations as affiliation networks

1.3.1. Introduction: Affiliation networks

Affiliation networks are a way to study affiliation relationships using a structural approach – i.e., focused on *position*. This means that the social features of individuals and/or sets (groups or events) are defined by their position with respect to all the other individuals/sets, as well as by the relations existing among them. An interesting property of affiliation relationships (and thus of affiliation networks) is the so-called *duality*. Introduced by Simmel and formalized by Breiger (1974), the concept of duality establishes that the features of individuals are determined by their affiliation (participation) to sets, and the features of sets are determined by the individuals that are affiliated to them.

Suppose a population of individuals that are members of a population of different groups. If an individual is member of several groups, we can assume that she will be favourable to decisions that benefit all groups in which she is a member, so she will try to influence the strategies of each of the groups. Thus, membership influences both individuals' and groups' behaviour, and the behaviour of individuals will differ according to their membership patterns (i.e., the individuals' position). Likewise, the behaviour of groups will be different according to the co-membership patterns of their members (i.e., the groups' position). As a result, if individuals' membership patterns become more extensive, it is legitimate to expect that the level of coordination across groups will also increase.

This is the general idea in the works of Hobson (1906), which are considered the earliest studies in Social Network Analysis focusing on affiliation networks (Freeman, 2004). Since then, the analysis of position, which is the core of structural analysis, has been developed both methodologically and conceptually. One main development has been the introduction of the concept of *structural equivalence* (Lorrain and White, 1971; Breiger *et al.*, 1975). The general idea is quite simple: if individual features in a network are determined by how individuals are connected among them (i.e. their position), every two individuals connecting in the very same way to the rest of the network (i.e., having the same position) will have similar features since they share the same relational environment. In this case we say that these individuals are structurally equivalent, or that they occupy a structurally equivalent position. Following the previous example, individuals belonging to the very same groups will be expected to have the same behaviour (i.e., to be favourable to the same strategic decisions). Likewise, groups featuring the very same members will be expected to have the same strategic behaviour. The great advantage of resorting to this structural perspective consists of the fact that it is a systemic approach, taking into account how phenomena happening in one part of the network have an impact on the other parts.

1.3.2. Analytical tools: bipartite networks and their one-mode projections

One basic tool used in the analysis of affiliation networks consists of drawing *bipartite networks* (also known as two-mode networks). Bipartite networks are defined here as networks where a population of individuals are linked to a population of sets by an affiliation relationship. Formally, elements of one population (individuals or sets) are related by binary links to elements of the other population, but no links exists between elements of the same population (Wasserman and Faust, 1994). Mathematically, we define a bipartite network as $G = (V, S, E)$ where V is a population of individuals, S is a population of sets, and E is the set of edges that relies individuals to sets by an affiliation relationship.

Figure 1.1: Affiliation, bipartite network and one-mode projection

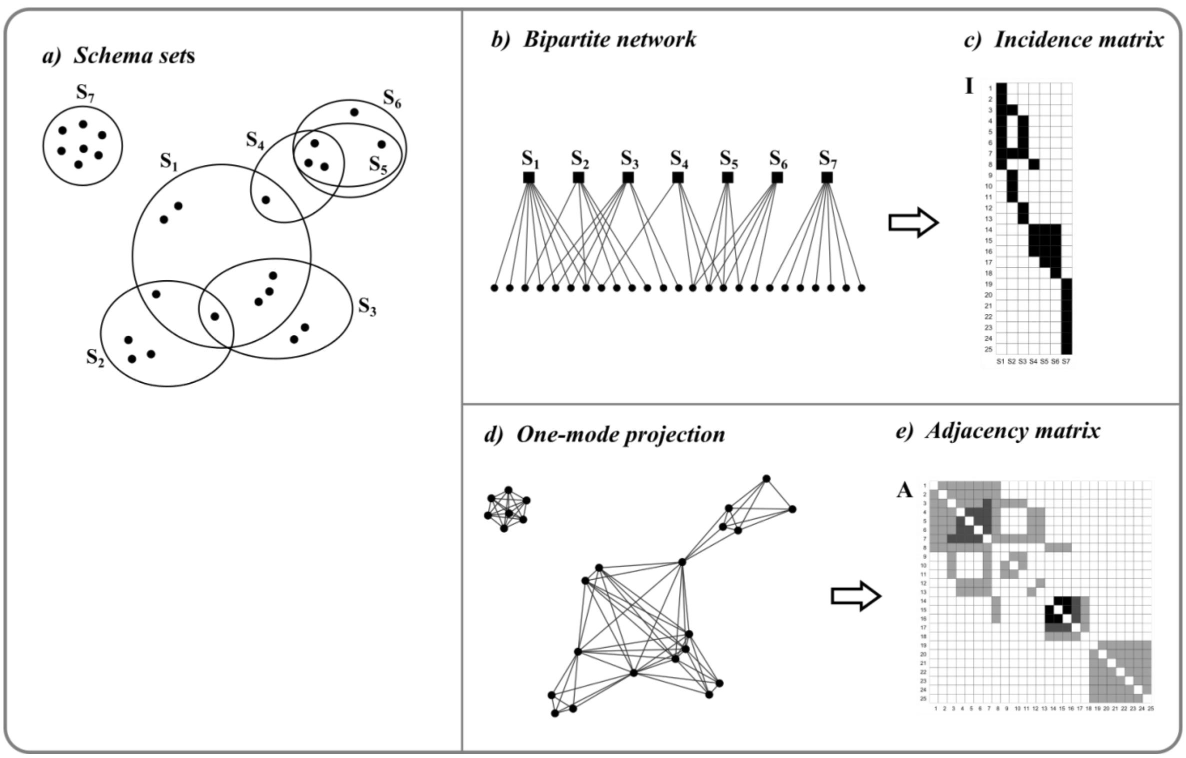

Figure 1.1a represents a situation in which 25 individuals are involved in 7 different sets. Some individuals are involved in just one set (see esp. the case of all individuals involved in set S_7), while others are involved in several sets (i.e., they are located at the intersection of two or more sets). Figure 1.1b is a representation of this situation as a *bipartite network*. Each individual (represented as a dot) is linked to the set(s) (represented as squares) in which it is involved. Note that no link exists between elements of the same population (individuals or sets). Figure 1.1c is the *incidence matrix* of the bipartite network, where individuals are put in rows and sets in columns (an affiliation link of an individual to a set is represented as a black square): for example, individuals from 1 to 8 are all linked to S_1, and individual 3 is also linked to S_2.Figure 1.1d is the

one-mode projection of the bipartite network. In this projection, nodes represent individuals, and individual are links if they belong to the same set. The clustering phenomenon is clearly observable in the case of the subgraph on the upper left, which corresponds to the set S_7: here all actors involved in the set are linked together, thus forming a clique. In this kind of projections, the degree of a node (i.e., the number of ties reaching the node) is equal to the number of all other individuals involved in the same set. Finally, the *adjacency matrix* of the one-mode projection is in Figure 1.1e, in which individuals are both in rows and in columns, and a link between two individuals is represented as a coloured square; the intensity of the colour informs about the value of the link (a darker square represents a more intense relationship). Since the relationship is not oriented, the matrix is symmetric. The clustering phenomenon is also observable in this matrix.

Usually, scholars do not directly analyze bipartite networks, but rather their projections. Breiger (1974) formalized the Simmelian concept of duality by using matrices. He proposed to project bipartite networks as two *one-mode networks*, where all nodes are of the same type (or "mode"). This result in two one-mode projections for each bipartite network: 1) one network of individuals that are linked if they belong to the same sets, and 2) one network of sets that are linked if they share the same individuals. Figure 1.1c represents the one-mode projection (for individuals) of the bipartite network represented in Figure 1.1b. In this one-mode network, two nodes are linked if they belong to at least one same set: consequently, each member of a set is directly linked to all the other members of the same set.

1.3.3. One-mode projections of bipartite networks: analytical problems

One major problem associated to one-mode projections of bipartite networks is the clustering effect that is artificially generated (Newman *et al.*, 2001; Uzzi and Spiro, 2005). We call *clustering* the situation where a subset of individuals fully connected with one another, usually forming a *clique* (i.e., a situation in which every two actors within the subset are linked with each other). Since in a projection as the one shown in Figure 1.1d all the individuals affiliated to a set are directly linked between them, this generates an artificial clustering effect that can perturb classical network metrics, especially in the case of measures based on degree or on community detection – thus leading to misinterpretations. This problem is magnified as the range of sets' size (in terms of number of elements) becomes very wide.

In our example in Figures 1.1a-c, the individual at the intersection of sets S_1, S_2, and S_3 has the highest degree in Figures 1.1d-e (viz., 12). The individual at the intersection of sets S_1 and S_2 has a degree of 10, which is also the case for the individual at the intersection of sets S_1 and S_4. All the individuals belonging to set S_7 have a degree of 6 because the set has 7 members. Now, suppose that the size of S_7 is bigger (say, 20): then the degree for each individual belonging to S_7 will be equal to 19, which is the highest degree value of the one-mode network. Therefore, the degree of each individual is directly proportional to the size of the sets to which she belongs. This means that an individual involved in a few big sets will have a higher degree than an actor involved in more but smaller sets. Note that bipartite networks, by construction, are not informative about how individuals interact within a set. Consequently, the degree and other measures in one-mode projections of bipartite networks must be interpreted according the signification of the sets. In Figures 1.1d-e, the degree of a node corresponds to the number of other individuals with whom the individual shares one or more sets, but this does not tell us anything about the actual way in which individuals interact within those sets.

1.3.4. Solutions: place networks

To overcome these problems, we can mobilize the "place-based methodology" (Pizarro, 2007), which allows obtaining a network of structurally equivalent positions within the bipartite network. In short, a *place* is the lieu of all the individuals who are structurally equivalent, viz. who belong to the very same sets (Borgatti and Everett, 1992; Pizarro, 2007). The methodology consists of drawing a different kind of bipartite network with the respect to the "classical" one: viz., a bipartite network connecting sets to places (rather than individuals), in which places are groups of structurally equivalent individuals represented as single nodes (see Figure 1.2a). More formally, a bipartite network of places and sets is a network of structurally equivalent positions, where each node represents a unique combination of affiliations to the set mode. As shown in Figure 1.2a, all individuals belonging to the same combination of sets are grouped in the same place, as they are all structurally equivalent

Figure 1.2: Places' network

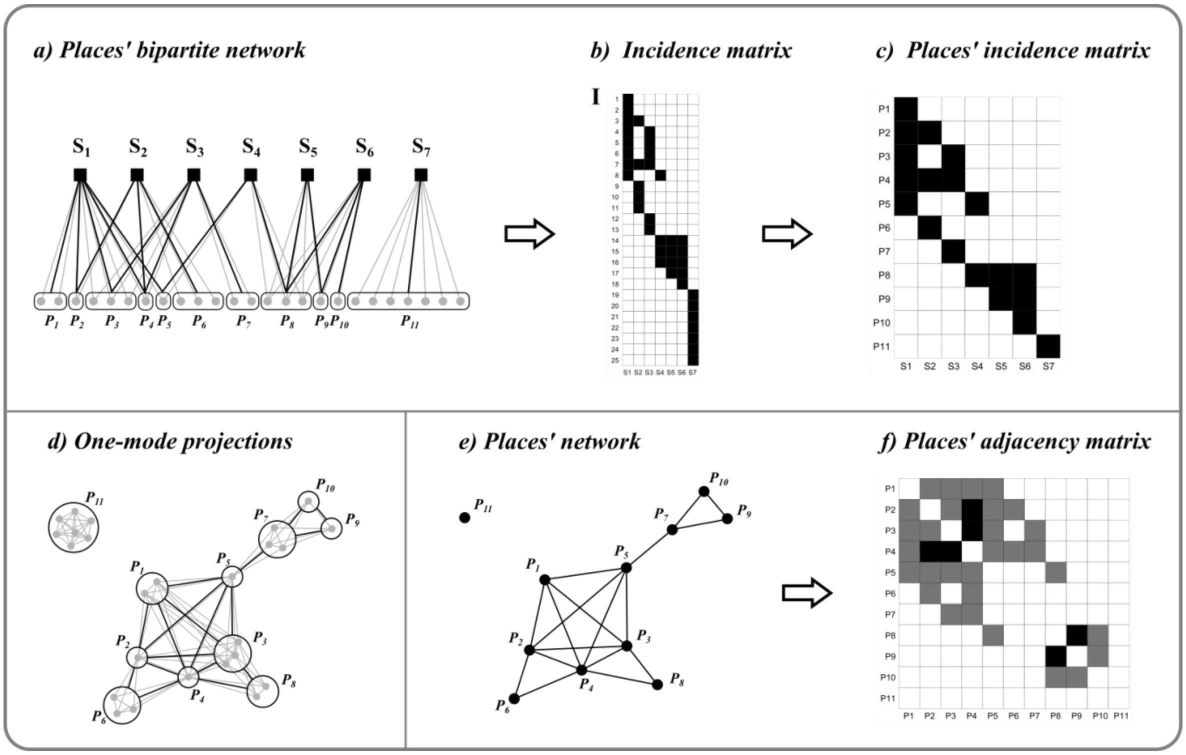

Figure 1.2a represents the *places' bipartite network*. For illustrative purposes, this network is superimposed onto the original bipartite network (greyed out). As we can see, each place P_i corresponds to a unique combination of affiliations to sets (no two places can be linked to exactly to the same set(s)), and all the individuals grouped together in a place P_i all belong to exactly the same set(s). Figure 1.2b is the incidence matrix of Figure 1.1c, and Figure 1.2c is the *places' incidence matrix* – rows are places, columns are sets, and black squares represent links between places and sets. Note that places are observable in Figure 1.2c as identical rows (same links to sets, so structurally equivalent positions): all "redundant" rows are merged into one single row in Figure 1.2c. In Figure 1.2d the places' network is superimposed onto the one-mode projection of individuals (greyed out) presented in Figure 1.1d. As we can see, structurally equivalent individuals are grouped into one same place (represented as a circle in this graph), and the way they are linked to the rest of the network is exactly the same. Figure 1.2e represents the *places' network* obtained from the bipartite network, where nodes consist of places of structurally equivalent individuals and links between nodes represent the fact that structurally equivalent individuals share the same sets. Here the degree is related to the number of unique combination of affiliation to set(s), so the degree is a measure of the relational diversity. Figure 1.2f is the *places' adjacency matrix*, where both rows and columns are places. A link between two places is represented as a coloured square; the intensity of the colour informs about the value of the link (a darker square represents a more intense relationship).

Since a network of places is a bipartite network, we can draw its one-mode projection and thus obtain two networks: 1) a network of places, in which nodes are linked when they belong to the same sets, and 2) a network of sets, in which nodes are linked when they include the same places.

The first one, i.e. the network of places (see Figures 1.2d-e), can be interpreted as a summary of the individuals' projection network (i.e. Figure 1.1d), i.e. the "skeleton" of the relationships across individuals, in which all redundant information (viz., individuals' membership to the same set) is removed. Its advantage is that the artificial clustering problem referred above is now solved. As a matter of fact, in a network of places the projection of a single set does *not* form a clique, because all structurally equivalent individuals are grouped into one single place. This allows overcoming the analytical problems associated with artificial clustering.

A comparison of the network of places (Figure 1.2e) with the traditional one-mode projection of the same network of individuals (Figure 1.1d) highlights the analytical advantages of the "place-based methodology". In general, the degree value of nodes drops as it is now no longer associated to the numbers of individuals in shared sets, but to the number of combinations of membership in the shared sets. For example, the highest degree in Figure 1.1d is 12 because each individual belonging to set S_1 is connected to 7 other actors that are also in set S_1, the 3 of set S_2 (the actor at the intersection of S_1 and S_2 is counted in set S_1 memberships), and the two of set S_3 (the 3 actors at the intersection of sets S_1 and S_3 are also counted in set S_1). In the network of places this actor occupies alone the place P_4, which has a degree of 6 because share sets with the combinations of sets S_1 (place P_1), S_1-S_2 (P_2), S_1-S_3 (P_3), S_1-S_4 (P_5), S_2 (P_6), and S_3 (P_8). This actor has in both networks the highest degree, even if the value is different, but the position in the rank regarding the others can change dramatically between both networks. Good examples are the members of the set S_7, which have a degree value of 6 in the one-mode network and 0 in the places' network.

The metrics based on geodesics are also impacted by the use of place-based methodology. A *geodesic* is defined as the shortest path existing between two nodes in a network. Since in the network of places structurally equivalent individuals are grouped, the number of geodesics that include these nodes are reduced, and this has an effect on geodesic-based metrics of centrality as the betweenness.[2] For example, the three individuals occupying the place P_7 are the second more central ones in the network of places, but they are in the fourth position in the one-mode network. Similarly, the individual occupying the place P_4 has the third position in the betweenness rank of the network of places, but the second one in the "classical" one-mode network.

Therefore, performing structural analysis through the "place-based methodology" improves the assessment of the properties of affiliation networks. First, it allows purging structurally redundant

[2] Formally, the *betweenness* of a node is the number of shortest paths (geodesics) that pass through the node regarding all the geodesics of the network. The betweenness is usually interpreted as the capacity of an individual to control the flows (e.g. information) of the network.

information, thus allowing for the emergence of the “skeleton” of the network. As a consequence, the clustering problem is overcome, and metrics (degree and geodesic-based) can be interpreted more easily since the number of ties reaching a node is unambiguous (in the sense that only ties originating from unique combinations of sets are taken into account). Second, this methodology provides information about structurally equivalent positions: where they are located, how they are composed (i.e., who are the individuals involved in a same position), and how they are defined (i.e., what is the combination of sets defining the position). This informs us about which individuals share the same relational resources and constraints, with who are connected, and so on.

1.3.5. Studying horizontal hybrid organization through places: some applications

The analysis of affiliation networks through the “place-based methodology” can help us improving considerably our understanding of many real-world socio-economic phenomena. In what follows, we provide three simple examples of possible applications: political elites (i.e., the intersection/amalgam of political, economic, and governmental elites), interlocking directorates in business, and collaborative projects in innovation. Each of these three examples concern one different type of horizontal hybrid organization, in which individuals choose to collaborate in order to reap the gains from cooperation at the local level.

1) *Political elites* are a classical object of study in Social Network Analysis (Knoke, 1990). Since power is relational and positional (Weber, 1974), political systems and elites have been studied as social networks, where the focus is on the social structure rather than on individuals and their attributes. In this general approach to power, some scholars have proposed a definition of social structure as a *stable* order or pattern of social relations among positions (Nadel, 1957; Laumman and Pappi, 1976): this means that power can be “measured” by focusing on structural roles (Breiger, 1979, Knoke, 1990) that go beyond individual characteristics. Furthermore, political elites have been analysed through affiliation networks (Knoke, 1990), where affiliations have often been extracted from biographical data (Mintz, 1975). Elites have therefore been defined as those groups of individuals who situate themselves at the overlap between political, economic, and social organizations (Domhoff, 1975; Freitag, 1975; Domhoff, 2006). As a result, the concept of “place” early emerged in this literature as a convenient analytical tool for both issues. Baena and Pizarro (1985) (to our best knowledge, the very first application of the “place-based methodology”) used it to study the Spanish political elite during the Franco era (1939-1975), identifying a *superelite* of actors situated at the overlap of three

central groups. Similarly, Villena-Oliver (2014a, 2014b) compared the structure of two Spanish governments (2004-PSOE and 2012-PP governments) using professional background affiliations in order to unveil the "revolving doors" between the government and other public and private organizations. The introduction of a "structural" approach to the study of affiliation networks by these works has considerably improved our understanding of political elites. As a matter of fact, the concept of "place" provides a rigorous definition for such a nebulous entity as "power" is, and thus allows identifying power structures that would not emerge from a traditional pure network approach.

2) *Interlocking directorates* are another classical object of study in SNA. It has been widely observed that shareholders tend to nominate to the boards of directors of joint-stock companies individuals who already sit in the boards of other companies. It is understood that shareholders nominate individuals who cumulate many mandates in order for the company to reap the benefits of control, coordination and social cohesion in terms of a reduction of uncertainty (Jeidels, 1905; Schoorman *et al.*, 1981; Knoke, 1990; Mizruchi, 1996; Davis *et al.*, 2003). Since these studies were mainly concerned with organizational aspects, most of them focused on the analysis of set one-mode projections (i.e., the network of companies linked by shared directors) and studied quantitatively the actors at the interlocks – e.g. the distribution of the number of directors in interlocks or the inclusion of individual variables (background, age, other affiliations, …) in order to explain the interlocks composition. (Palmer *et al.*, 1986; Chu and Davis, 2016; Cronin, 2011). As in the case of political elites, also in the case of interlocks places have naturally emerged as a convenient tool of analysis. In her study of a selection of 149 big global multinationals, the application of the "place-based methodology" allows Herrero-Lopez (2015) to show that the control of companies is actually exercised through interlocking shareholdings rather than through interlocking directorates. Concretely, in a globalised world, interlocks shareholdings can control a larger number of geographically dispersed companies, while interlocks directorates operate on a more national scale. This study allows appreciating the advantages of the methodology. First, it allows reducing significantly the size of networks (a big advantage when dealing with networks made of thousands of individuals), as all structurally equivalent positions are merged into single places.. Second, it allows identifying mesoscopic entities – communities – that derive from the structure of overlaps (the focus of the place-based analyses) and not only on the structure of companies (the focus of traditional analysis based on dyadic relations), and that would not emerge otherwise.

Indeed, she overcomes the clustering problem by the "place-based methodology" in her community analysis, but she does not explicit this advantage of the methodology.

3) In innovation economics and policy, network analysis has often been used to typify mesoeconomic structures of R&D. Since innovation is rarely the fruit of an isolated inventor but the result of a collective process subjected to strong knowledge spillovers (Audretsch and Feldman, 2004), *innovation networks* are one of those strange animals that position themselves between the innovative behaviour of actors, from which they result, and the aggregates of innovation productivity, which result from them. Much research has been carried out, at the geographical level, with the popularization of research on clusters (Owen-Smith and Powell, 2004; Giuliani, 2007; Vicente *et al.*, 2011) or at the level of industries and technological fields (Roijakkers and Hagedoorn, 2006; Rosenkopf and Schilling, 2007). The same occurs in research on innovation policies, whose public incentives have shifted from market failures to network failures (Woolthuis *et al.*, 2005), thus leading to the design of public incentives for collaboration and the strengthening of networks and large R&D consortia. This innovation policy pattern has led to a growing attention on the effects of such policies on technological renewal and the emergence of new markets (Vonortas, 2013), as well as the resilience of regional innovation systems (Crespo *et al.*, 2016). This wave of investigation is based on an analysis of the structural properties built from dyadic relationships, with the risk of bias generated by the problem of artificial clustering linked to the size of the co-patent cliques and research consortium that weakens the empirical results, while at the same time preventing us from capturing how circles of actors emerge beyond formal alliances. In this area, as recently demonstrated by Lucena-Piquero and Vicente (Chapter 2), the use of the "place-methodology" based on the identification of blocks of structural equivalence and the way with which these blocks interact enables circumventing these risks. In particular, this methodology allows detecting, beyond formal cliques, different groups of actors according to their explorative or conformist relational behaviour, and then better identifying the constituting factors of the evolution and resilience of innovation networks.

1.4. Vertical hybrid organizations as sequential interaction networks

1.4.1. Introduction: sequential interaction networks

Together with affiliation relationships, interaction relationships are one of the two main families of relationships commonly present in any social or economic phenomena. In this kind of relationships, individuals carry out actions which involve or impact other individuals, and this defines their position and more largely their roles. One of the most common examples of interaction relationships are, for instance, bilateral exchange relationships: according to the position of each individual with respect to the exchange flow, one individual will take the role of seller and the other one the role of buyer. Traditionally, scholars have used *dyads* (bilateral relationships, or "low-order interactions") as elementary units of interaction networks, so that "classical" interaction networks have been built as aggregation of all the dyadic links existing among a population of individuals. See for instance Krackhardt and Hanson (1993) work about the informal organization of a company. They study three interaction relationships (advice, trust and communication) to evidence the informal network behind the chart. Similarly, Coleman *et al.* (1957) analyse interpersonal networks among physicians to study the diffusion processes of a new drug. More recently, Kim *et al*. (2011) study of three automotive supply networks in terms of materials flows and contractual relationship. They compare the structure of the networks for the three firms and identify key central actors.

Formally, a network G is defined as $\mathrm{G} = (\mathrm{V}, \mathrm{E})$ where V is the set of individuals of the population and E is the set of links (arcs or edges, depending if the relationship is oriented or symmetric) between dyads (i.e., pairs of individuals).

As it is the case for structural equivalence in affiliation networks, a structural approach can also be applied in interaction networks. Recall that according to the structural approach, the position of each individual is defined by taking into account the overall structure of the network − viz., the position of an individual depends not only on all the links that she has with other individuals, but also to all the links the other individuals have with one another. This implies that local substructures within the network are considered as relevant to define the position of each individual beyond the direct dyadic links that the individual actually has. Simmel (1950) was the first scholar to underline that supra-dyadic structures (sometimes called "higher-order interactions" (Battiston *et al*,. 2020) − in his case, triads) reveal social phenomena that go beyond the individuals' bilateral interactions, thus being a germinal element of group phenomena − in which the group is more than the addition of its parts. According to Simmel, in a triad of individuals *A*, *B*, *C* the link between any couple of individuals is influenced or determined by the presence (or absence) of links among the others. The conceptualization of triads and other supra-dyadic structures are at the base of many important contributions, as Heider's balance theory about cognitive consistency[3], and more largely all works about modularity[4] and communities. Simmel and his followers have highlighted that supra-dyadic substructures are common in social and economic life, and are often integrated into common cultural conceptualizations having a name. For example, many family roles (e.g. grandparenthood) are roles defined by supra-dyadic kindship relations (being the parent of a parent).

Sequential interactions are special cases of supra-dyadic substructures where the positions and links are ordered. An elemental form of sequence is an open triad of elements *A*, *B* and *C* where *A* is linked to *B* by a directed tie (relation R_1) and *B* is linked to *C* by a directed tie (relation R_2), thus generating one sequence of individuals (*A, B, C*) from the sequence of links (R_1, R_2). According to the structural approach, the properties of any dyad will thus be dependent on the other dyads belonging to the sequence. One simple example of sequential interaction is a buyer-broker-seller triad, in which each individual's action is defined by the position she occupies within the sequence.

An important feature of sequences is the existence of an indirect link between actors that are not directly linked. In a buyer-broker-seller triad, an indirect link exists between the buyer and the seller even though the two never directly interact with each other: this link is fundamental, because it defines the triad and the economic phenomena it represents (in the example, the exchange occurring between the buyer and the seller). Social Network Analysis has picked up the importance of indirect links between actors by formalising them as *compound relations*: in a sequence of individuals (*A, B, C*), it exists a compound relation ($A \circ C$) indirectly linking the individuals who belong to the sequence without being directly linked to each other. Traditionally, compound relations have been identified *ex-post* (i.e., as the "artificial" sum of dyadic substructures) in order to investigate some structural features of interaction networks: for instance, the general formulation of structural equivalence provided by Lorrain and White (1971) is based on the ex-post construction of compound relations. This way of proceeding is appropriate for those types of compound relations that do not exist as *ex-ante* phenomena. For example, in the case of an indirect acquaintance

[3] The social psychologist Heider (1958) theorized that perceptions about actors (or objects) and relations (sentiments) of an ego involved in a triad require a *cognitive consistency* provided by the existence of balance in the triad. Thus, a balanced triad (e.g. my two friends are friends, or my friend also dislikes this food) represents a cognitive consistency for ego. An imbalanced triad (e.g. my two friends are enemies, or my friend likes this food that I hate) creates a tension or cognitive dissonance that the ego would try to solve.

[4] *Modularity* refers to the study of subgraphs in networks regarding their relative density or connectivity. There exist several methods to identify modules (i.e. groups, clusters, or communities) and their community structure.

relationship (e.g. being a friend's friend), the dyadic directed relationships between individual 1 and 2 and between individuals 2 and 3 can exist even though the compound relation between individuals 1 and 3 (i.e., their awareness of having one friend in common) does not actually exist. Consequently, the removal of any of the dyadic relationships belonging to the sequence does not necessarily imply the non-existence of all the other dyadic relationships belonging to the same sequence. However, in many real-world social and economic processes, supra-dyadic substructures *do* exist as *ex-ante* phenomena: differently said, in order to take place, some processes require the existence of a given sequence of several individuals bilaterally linked to each other. For example, in the case of an intermediated transaction (the buyer-broker-seller substructure), the dyadic directed relationships between the buyer and the broker and between the broker and the seller can *not* exist if the compound relation between the buyer and the seller (i.e. the transaction itself) does not exist. Consequently, the removal of any of the dyadic relationships belonging to the sequence *does* necessarily imply the non-existence of all the other dyadic relationships belonging to the same sequence.

In view of this fact, some scholars (see e.g. Bonacich *et al.*, 2004) have argued that some supra-dyadic substructures must be conceptualized as supra-dyadic *units*: since the underlying real-world social or economic process is more than the addition of its parts (i.e. the dyads), the supra-dyadic must be considered as an elementary component of the structure (i.e. as a unit). Consequently, the analysis of these processes must be adapted in order to take into account the supra-dyadic unit condition. This is what we propose to do through the study of "relational chains".

1.4.2. Analytical tools: relational chains

We define a *relational chain* as a supra-dyadic unit composed by an ordered sequence of individuals (connected by directed links) who participate into the same process. In order to better understand this concept, let us consider the following toy example: a network in which 12 individuals are involved in 6 different transfer processes (see Figure 1.3a). This example is based on two assumptions. The first one is that the order of appearance of each individual within the chain is relevant but not binding, which means that although not all nodes might occupy any of the positions of the chain ("roles" might not be played interchangeably), such positions are not exogenously fixed. The second assumption is that chains may have a variable length, which means that there does not exist an exogenously fixed constraint on the form of the chain. Note that these assumptions may not necessarily apply for any kind of relational chain: in some cases, constraints might exist both on the positions occupied by nodes within the chain and on the size of the chain. However, the fact of adopting less restrictive assumptions allows keeping the level of analysis as general as possible: in fact, more restrictive situations could be treated as special sub-cases of the present analytical framework.

Figure 1.3: Chains and single-relational network

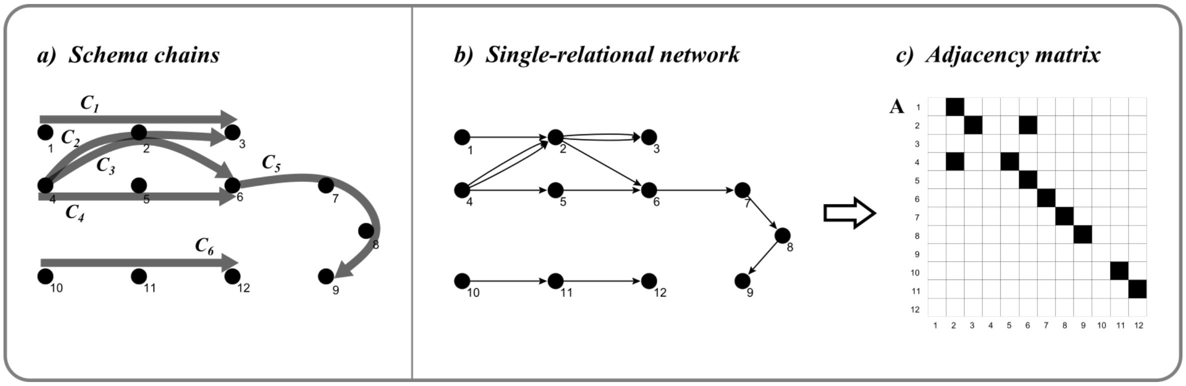

Figure 1.3a shows a situation where 12 individuals (black points) involved in 6 transfer processes or chains (gray arrows). Observe that some nodes are involved in more than one process, occupying different positions in each sequence, and that all chains involve 3 individuals (two steps) except the chain C_5, which involves 4. Figures 1.3bc is a single-relational or single-layer network representation – the graph and its associated adjacency matrix A – of the situation seen in Figure 1.3a: here arrows (directed ties) link pairs of nodes (dyads) following the sequence observed in the transfer process. In Figure 1.3b, pairs of nodes involved in more than one sequence are linked by more than one arrow, but the position occupied by each node in each sequence (and therefore, the unity of each process) is lost in the representation.

Usually these situations are analyzed as (single-layer single-relational) directed networks, and a simple way is to consider that the individuals are linked by a directed relation R. More formally, suppose a set of n individuals $V=\{v_1,v_2,v_3, \ldots,v_n\}$ and a relation R (also called the set of ordered pairs or links between individuals), which defines the graph $G=(V, R) \;/\; \{i,j\} \in V \wedge (i,j) \in R$. Then, the network is a collection of pairs of individuals, represented as arrows between nodes. Figure 1.3b is a traditional network representation of the situation depicted in Figure 1.3a, where actors are linked following the chains. This network might be simplified removing or merging multiple lines, as in the case of the pair of actors $(2, 3)$ or the pair $(4, 2)$.

1.4.3. Relational chains: analytical problems

The analysis of the traditional (single-layer single-relational) network representation as the one illustrated in Figure 1.3b can lead to some interpretative difficulties or misinterpretations, due the lack of information about chains and the position occupied by nodes within them. For example, a commonly used network metrics is the *betweenness centrality* of nodes, which is calculated as the number of geodesics (i.e., of shortest paths) that pass through a node: this metrics is typically associated to the individual's capacity to access or control fluxes between other individuals (a very crucial property in the context of transfer processes). If we compute the betweenness centrality of the nodes in Figure 1.3b, actor 6 results to be the most central actor in terms of betweenness. However, the betweenness centrality of actor 6 is artificially boosted by the fact of being situated at the end of chains C_3 and C_4 and at the beginning of chain C_5. This means that the validity of this metrics needs to be discussed in view of the actual properties of chains. If chains are not interdependent (meaning that the different transfer processes have nothing to do with one another), then it doesn't make much sense to consider that actor 6 plays any important role in terms of flux control, because in reality she does not play any actual "bridging" role between the individuals involved in chains C_3 and C_4 and those involved in chain C_5: as a result, her betweenness centrality becomes difficult to interpret in the traditional way.

Another popular network metrics that may be artificially impacted by the existence of relational chains is the node's *degree*, defined as the number of adjacent nodes directly connected to it. In networks where links are directed, we call *input degree* the number of nodes from whom the node receives an arrow, and *output degree* the number of nodes to whom the node sends an arrow. Although its meaning depends on the kind of relationship, usually the degree is associated to the importance of a node in terms of relational resources, as power, influence or social capital. In the type of network illustrated in Figure 13b, nodes that are located at the beginning or at the end of a chain have a lower degree than those located at the middle of the chain (except in case they are involved in other chains). More precisely, a node located at the beginning of one chain has degree 1, input degree 0, and output degree 1; whereas a node located at the end of one chain has degree 1, input degree 1, and output degree 0. However, all other nodes located along the same chain have, by construction, at least degree 2, and input and output degrees 1. Since the degree is commonly interpreted as an estimate of the importance of a node, the role played by nodes located at the beginning and at the end of chains will be underestimated, while that played by nodes located at the middle of the chain will be overestimated.

One possible way to overcome these problems consists of considering each step of a chain as a different type of relation. More precisely, we consider that all the individuals who are located at beginning of a chain are linked to the individuals in the second position of the same chain by a relation R_1; in turn, these individuals located in the second position are linked to those located in the third position by a relation R_2; and so on and so forth. More formally, the network is defined by a set of *n* individuals $V=\{v_1,v_2,v_3, \ldots,v_n\}$ and an ordered set of *x* relations between pairs of individuals $R=\{R_1, R_2, \ldots, R_x\}$, where we can build an ordered set of *x* directed networks G_i such that $G_1(ij) = (V_{ij},R_1) / (i, j) \in R_1; G_2(jk) = (V_{jk}, R_2) / (j, k) \in R_2; \ldots ; G_x(pq) = (V_{pq}, R_x) / (p, q) \in R_x$. Then, we can build a network *G* as the union of all the networks G_i. We can define this network as $G=(V,R,D)$ where *D* is the set of relations $R_r \in R$, so the network is the collection of the pairs $(v_i,v_j)_r$ that are the directed links between actor v_i and actor v_j on the r_n relation.

We can call this type of network a *multi-layer multi-relational network*. The idea of considering various types of relationships to understand the real-world complexity has been present since early SNA works: Freeman (2004) provides some examples of classical studies with a multi-layer approach, such as Moreno's contributions on 1930s (e.g. 1934), Bott's works on 1950s (e.g. 1957) , or Roethlisberger's and Dickson's (1939) study on the Bank Wiring Room. In this tradition, networks with several relations have been analyzed separately or merged: see for example Wasserman and Faust (1994), Dickinson *et al.* (2016), or Bianconi (2018). Since these strategies lose the real-world complexity several disciplines have been developed a corpus of methods and techniques for the study of multi-relational networks. In recent decades, one methodology has gained considerable popularity in the study of multi-relational networks: their representation as *multi-layer networks* – i.e., as the superposition of different layers of networks, in which each layer only includes relations of the very same type (Dickinson *et al.*, 2016).

Figure 1.4: Multi-relational network

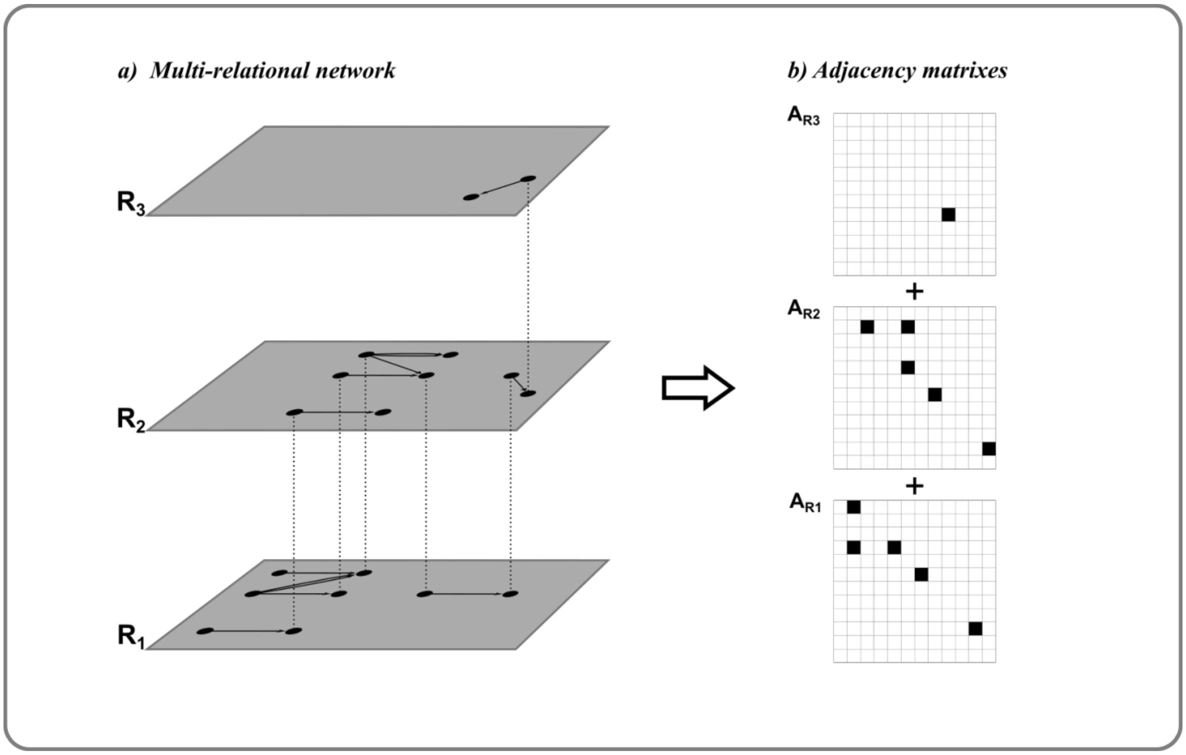

Figure 1.4a-b is the multi-layer multi-relational representation – graphs and matrixes – of the situation seen in Figure 1.3a. Each relation (and node pairs in relation) is stored in a layer and matrix according to the position it occupies in the sequence in the underlying processes (chains). Dotted lines link the very same individual across layers (e.g. node 2 is in layers R_1 and R_2, so a dotted line link both points representing this actor). With respect to the single-layer representation (Figure 1.3b), the multi-layer representation (Figure 1.4a) has the advantage of keeping track of the position occupied by each node in the sequence; however, the unity of each process is still lost in the representation.

As a result of its fast and multidisciplinary development, the corpus of terms and methods used in the domain of multilayer networks is very diverse and lacks consensus (Kivela *et al.*, 2014; Bianconi, 2018). For our purposes, we define a multi-layer network $G=(V, R, D)$ where *V* is the set of nodes, *R* is the set of links between pairs of nodes, and *D* is the set of layers of the network. In our example (see Figure 1.4a), the network has 3 layers, as there is at least one chain with a length 3. Following Bianconi (2018), this network can be considered as a multi-layer network without interlinks (links among layers), in which corresponding nodes in different layers indicate the same identity (e.g. the individual 2 is in layers 1 and 2, and the individual 8 is in layers 2 and 3). In this kind of multi-layer network, the degree is computed for each layer (e.g. node 2 has degree 1 in layer 1 and degree 1 in layer 2. In-degree and out-degree are computed on the same way), and the overall degree of the node is the sum of all layers' degree. The betweenness can be computed intra-layer or inter-layer (namely cross-betweenness centrality, where nodes in several layers are considered). However, as in single-layer networks, these betweenness algorithms (or other algorithms based on shortest paths) do *not* consider supra-dyadic structures as units, falling into similar problems as single-relational networks. As a result, while the development of multi-layer networks has provided many useful conceptual frames and metrics, the main shortcoming of this approach consists of ignoring the continuity (or interdependency) of relational chains. However, it is important to consider chains as *units*, in which the presence of all individuals and of the links existing between them is indispensable to the existence of the chain.[5] For example, the removal of node 3 should imply a failure in all the transfer processes in which it is involved (C_1 and C_2). Consequently, node 1 would be isolated from the network since the process C_1 is interrupted. Node 4 is also impacted, because of is involved in process C_2, but it is still connected to the network due its participation in the process C_3, so we said that it has an alternative access to the system. However, the removal of node 3 has no impact in the other dyads both in single-layer and multi-layer networks. In other words, the unity or interdependency of processes transfers is not preserved in these kinds of networks.

1.4.4. Solutions: sequential multi-relational hyperstructures

We propose to *not* separate relational chains across different layers, but to keep them together. In fact, chains are an (*ex-ante*) "input" of the network, in the sense that they represent indivisible units where one part of a chain cannot exist without the rest, and should therefore be taken into account while analysing the structure of interaction (Bonacich *et al.*, 2004; Estrada and Rodríquez-Velázquez, 2006). In order to do so, we propose to resort to hypergraphs. A *hypergraph* is a generalization of a graph in which one or several individuals are linked to one or several edges. In other words, a hypergraph is a bipartite network in which a set of individuals are linked to a set of edges. More formally, a hypergraph H is a bipartite network $\mathrm{H} = (\mathrm{V}, \mathrm{E})$ where V is a set of individuals and E is a set of no-empty subsets of V called edges or hyperedges. Consequently, a situation in which chains are considered as supra-dyadic units can be represented as a hypergraph where each chain C_i is a set of actors of V linked to an edge or a hyperedge of E. Hypergraphs

[5] A possible solution for this problem is introduced by Rodriguez and Shinavier (2010) who suggest the use of "filters" to ensure particular paths on multilayer networks. However, for networks as chains' networks filters are not useful since each chain should be associated to a filter (e.g. the database employed by Accominotti *et al*. (Chapters 4 and 5) has 8,888 transfer processes, so this solution would require the formulation of 8,888 filters).

provide a simple way to represents and analyse complex situations keeping the unity of the supra-dyadic input data. As showed by Bonacich *et al.* (2004), some network measures can be easily implemented using hypergraphs. Specifically, they use the formulation of eigenvector for bipartite graphs as a way to measure the eigenvector of individuals on the hypergraph. Similarly, Battiston *et al.* (2020) provides some possibilities for the measure of the nodes' degree in hypergraphs, showing the flexibility provided by this approach to complex systems. However, classic hypergraph approaches do not preserve the internal structure of supra-dyadic data (that is, the links and positions within the individuals, and in our case the sequence and links of chains). Feng *et al.* (2018) have observed this problem in situations in which the order of the actors is relevant, and they propose the concept of partial-order hypergraph to overcome this limit. In their solution, a partial-order hypergraph includes hyperedges which provide the order of the individuals in structural units (supra-dyadic units in our language). Unfortunately, partial-order hypergraphs are not a solution for chains, since they do not keep the sequence or continuity of individuals. In other words, as in multilayer networks, the measures are unable to recognize the ordering of paths within a chain.

A more interesting solution has been provided by Criado *et al.* (2010) who define *hyperstructures* as hypergraph networks in which hyperedges represent substructures. In their work, they use a subway network as an example of hypergraph in which the substructures (the subway lines) are preserved. While their definition of hyperstructures is restricted to non-oriented substructures (symmetric relations), nothing precludes extending it to oriented substructures (asymmetric relations).

Then, in order to preserve the unity of chains we can define a "network of chains" as a hypergraph in which edges or hyperedges correspond to relational chains. So, we define a chain C_i as a non-empty set of individuals $(v_i, v_j, v_k, \ldots, v_q) \in V$ where every pair is linked by a ordered sequence of relations $(R_1, R_2, \ldots, R_y)$ such that $\exists\ v_j \ / \ \forall\ (v_i,v_j)R_x \wedge (v_j,v_k)R_{x+1}$. Or in other words, a chain is a set of ordered pairs of actors where every two sequential pairs share the second and the first individual respectively. Additionally, we define a network of chains as a hyperlink $H = (V, E) \ / \ \forall\ C_i \ \exists\ E_i$. Thus, every chain C_i corresponds to an edge or hyperedge E_i. This way, every chain is considered as a unit (see Figure 1.5a-b).

Figure 1.5: Hyperstructure graph

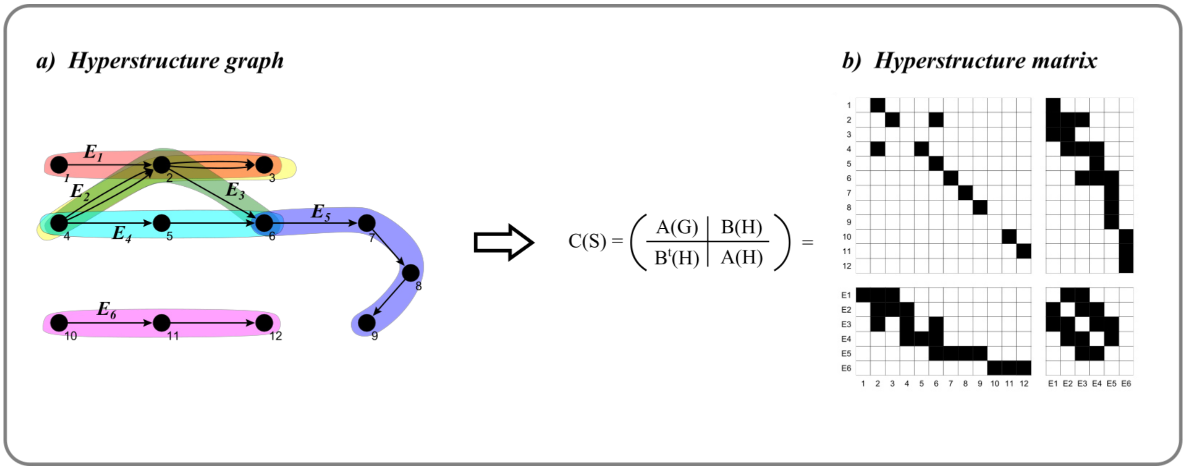

Figure 1.5a-b provides a representation of the transfer processes seen in Figure 1.3a as a hyperstructure. The *hyperstructure graph* represents the hyper-edges over the substructures (nodes and links) concerning the chains or transfer processes. The *hyperstructure matrix C(S)* is composed by: a) The adjacency matrix of individuals *A(G)* which contains all dyadic links between; b) The incidence matrixes *B(H)* and $B^t(H)$ which links groups of individuals and links (substructures) to hyper-edges. Note that $B^t(H)$ is the transposed matrix *B(H)* so it provides the same information; and c) the adjacency matrix *A(H)*, which informs about the overlaps among hyper-edges. The lecture of the hyperstructure matrix, as all matrixes, is from rows to columns. For example, the dyad (1, 2) is represented in the *A(G)* matrix – row 1, column 2 – by a black square. The incidence matrix *B(H)* informs that the node 1 is related to the hyper-edge E_1, and the incidence matrix $B^t(H)$ that the node 2 is related to hyper-edges E_1, E_2, and E_3. Since the common hyper-edge is E_1, the dyad is related to this hyper-edge, so the transfer process C_1. Similarly, there is two dyads (2, 3) which are represented in the *A(G)* matrix by a unique black square (remember that this matrix is binary). The matrix *B(H)* shows that the node 2 is related to hyper-edges E_1, E_2 and E_3, and the matrix $B^t(H)$ that the node 3 is related to E_1 and E_2, so one dyad *(2, 3)* is related to E_1 and the other to E_2.

Two main consequences derive from this definition of chains and network of chains as a hypergraph. The first, is that every chain is defined by its individuals and relations. So, any suppression of individual or links in the chain implies the failure of the entire chain. Following the example used above, the removal of node 3 involves the failure of the hyper-edge E_1, so all the dyads associated, and the node 1 would be isolated, thus respecting the unity of the process.

The second consequence is that structural positions of individuals are defined both by the internal structure of the chain (through the adjacency matrix *A(G)* and the hyper-edges (through the incidence matrixes *B(H)* and $B^t(H)$). This implies that we can easily formulate flexible network metrics that do keep into account the significance of chains, their internal structure, and their unity. For example, following Battiston *et al.* (2020), the degree of an individual is traditionally conceptualized as the number of other adjacent individuals. Following this conception, since all the individuals in a chain are interdependent and are linked by both direct and indirect-dependent links, we can define the degree of an individual as the number of other individuals involved in the chains in which she is involved. So, supposing that a chain composed by 4 individuals, the degree of every individual belonging to the chain is 3. If one of them is involved in another 4-node chain, then her degree is 6. Alternatively, we can define the degree of an individual as the number of chains in which she is involved, regardless the number of individuals by chain. So, an individual involved in one chain has a degree of 1, and an individual involved in 4 chains has a degree of 4.

Following our example, the network of chains shown in Figure 1.5a should be defined as a hyperlink network of chains $H = (V, E)$ where $E_1 = C_1 = (1, 2, 3)$; $E_2 = C_2 = (4, ,2, 3)$; $E3 = C3 = (4, 2, 6)$; and so on. Using our first definition of the degree, individual 1 has a degree of 2 (it is "adjacent" to individuals 2 and 3), and individual 2 a degree of 4 (it is "adjacent" to individuals 1, 3, 4, 6). And using the second definition of degree, individual has a degree of 1 (it is involved in chain C_1), and individual 2 a degree of 3 (it is involved in chains C_1, C_2 and C_3).

1.4.5. Studying vertical hybrid organization through chains: some applications

The analysis of sequential interaction networks through the "chain-based methodology" can help us improving considerably our understanding of many real-world socio-economic phenomena. In what follows, we provide three simple examples of possible applications: shipping networks in logistics, supply chains in trade, and origination and distribution chains in finance. Each of these three examples concern one different type of vertical hybrid organization, in which individuals choose to situate themselves within a chain in order to reap the gains from cooperation at the local level.

1) The analysis of shipping networks has gained much popularity in the logistics literature (Tran and Haasis, 2015; Ducruet, 2020). People or goods moving from a given point in space to another one often cannot be transported directly, but they have to pass through "third" points ("hubs") in order to be transferred to different means of transport. Shipping networks can therefore be seen as organizations that coordinate different actors in the transportation sector in order to maximize the efficiency of the system. Studying shipping networks through the "chain-based methodology" has some distinctive advantages with respect to "classical" multi-layer methodologies. This illustrated by the case of Calatayud *et al*. (2017), who study the Americas' merchant shipping networks as an eighty-layer network, where each layer is the network of

countries and shipping lines of a big liner shipping company. In order to study the vulnerability of this trade network, authors simulate attacks (node removal) over seven strategic nodes, and conclude that the impact of attacks over shipping lines varies according the country of origin of trade flows and the role of the nodes in the merchant network. While this study provides a useful knowledge about shipping networks, under our perspective, the impact of attacks is underestimated. For example, in their networks the USA is mainly a final destination of many goods, so if its suppression will impact all flows of goods from their origin and including the transit countries, and not only the countries directly connected to the USA by shipping lines. So, a chain approach should provide a more accurate assessment of the weakness of merchant shipping networks. Obviously, the possibility to apply a chain approach is dependent of the data available. It requires detailed information about shipping lines (where they start and where they end, as well as the ports they stop at) in order to well identify the chains.

2) The analysis of supply chains has gained much popularity in the trade literature (Hearnshaw and Wilson, 2013; Perera *et al*., 2017). Goods or services are extremely seldom produced in a single production round: much more often, final consumer goods are only the final outcome of many different stages of transformation of intermediate goods. Supply chains can therefore be seen as organizations that coordinate different actors in the industrial sector in order to maximize the efficiency of production. Studying supply chains networks through the “chain-based methodology” has some distinctive advantages with respect to “classical” multi-layer methodologies. This is illustrated by the case of Lee and Goh (2016). They use a multilayer (two-layer) analysis for the study of the global trade network of countries by primary and secondary sectors, focusing on the interdependency between both sectors (operations of the primary sectors are dependent to the demand from the secondary sector). In order to assess the vulnerability of the network, they perform a cascade failure simulation, and shows that impact is highly related to the interdependence between the two sectors (interlayer links). So, one of their main conclusion is that the multilayer approach provides a more accurate analysis than single-layer networks because the interdependence between layers (sectors) is included. Even if, as the authors point out, their model is an oversimplification of reality, we think it is correct to consider the interdependence between sectors in the analysis of trade networks. However, this oversimplification does not address the complexity of productive systems, or how a final product involves a chain of sub-products and primary goods around the world. Suppose the case of the automobile industry, which requires components manufactured in several countries, with primary goods from other several countries, and assemblies in third countries. That means that

the interdependency is not only inter-layers, but also intra-layers, and it depends of product-dependency chains. Applying the chain-based methodology here would well-identify the interdependencies and provides useful information about the vulnerability and resilience of the system. Another interesting illustration is provided by Inoue and Todo (2019), who analyse the impact and propagation of natural disasters (earthquake) in Japan's supply chains, and build a model (based on empirical data from the 2011 Great East Japan earthquake) to assess the economic impact of future natural disasters. We highlight several contributions of this work. First, they use empirical data to assess impact and build their model. Second, they address the question of the substitutability of individual actors, i.e. the presence of suppliers who can substitute the ones impacted by disaster and thus ensure the continuity of supply chains. Third, they include both direct and indirect effects of shocks on supply chains, highlighting that the effect of disaster has observable economic effects not only on directly-connected actors, but also on indirectly-connected ones, thus underlining the role of non-separable supply chains in the production system. While this study provides evidence of the importance of chains as an analytical unit, the direct and indirect effects of failures, and the role of substitutability in the resilience of the system, the study does not use chains as an elementary input data. Applying the chain-based methodology here would complete the analysis, providing a more detailed view of all interdependencies and a better assessment of the impact of the loss of actors in supply chains. This might potentially help putting in place management strategies or industrial development policies aimed at minimizing the vulnerability of chains.

3) The analysis of intermediation networks has gained much popularity in the finance literature (Adrian and Shin, 2010; Glode and Opp, 2016). Financial assets are seldom sold directly by the "producer" (the borrower) to the "final consumer" (the investor): much more often, they are originated and distributed through complex processes that involve several different intermediaries. Intermediation chains can therefore be seen as organizations that coordinate different actors in the financial sector in order to maximize the efficiency of the origination and distribution process. Studying intermediation networks through the "chain-based methodology" has some distinctive advantages with respect to "classical" multi-layer methodologies. This illustrated by the case of Accominotti *et al*. (Chapters 4 and 5) in their study of the London bill market during the First Globalisation. More specifically, these works describe and analyse a money market instrument – the sterling bills of exchange – which involves three actors or roles: a borrower (drawer), a guarantor (acceptor), and a lender (discounter). They consider each bill as a chain, which is treated as a supra-dyadic unit, where analyses respect the interdependence

of actors and the relations between them. In Accominotti *et al*. (Chapter 5), the authors estimate the resilience of this financial market by using node removal simulations to assess the substitutability of actors. The results show less hierarchical and more resilient financial network than nowadays'. Applying a multi-layer approach would provide a distorted view: in fact, since the unity of chains would be lost, node removal simulations would under-estimate the impact of shocks, as some dependent actors would still remain connected to the network (as described before in Figures 1.4 and 1.5). Additionally, as we have argued previously, classical network measures tend to over or underestimate the relative importance of some actors (in the case study of Accominotti *et al*., (Chapter 5) those in acceptor role), thus providing scope for misinterpretations.

1.5. Summary and way forward

Properly understanding the micro-foundations of macro phenomena remains one of the biggest challenges in social sciences in general, and in economics in particular. Real-life economies feature a great number of hybrid organizations aimed at dealing with spillovers – i.e., "mesoscopic" entities situated half-way between the individual and aggregate level, whose boundaries are often loosely-defined and unstable. Over the last decades, network theory has provided social sciences with a number of useful tools for chasing these "strange animals". However, the tools that are commonly applied to the analysis of real-world networks are based on dyadic relationships, and present some limitations to the proper understanding of those higher-order (supra-dyadic) structures that play a crucial role in real life.

This paper has argued that simple network analysis tools allowing to go beyond these limitations exist and deserve to be applied more extensively in empirical research. We focus on two tools that appear to bear a particularly high potential for the understanding of economic phenomena. The first one is the "place-based methodology", allowing to assess actors' substitutability in affiliation networks: this technique substantially improves our ability to assess the resilience of horizontal hybrid organizations that are widespread in real economic life (like e.g. power elites, interlocking directorates, collaborative R&D project, etc.). The second tool is the "chain-based methodology", allowing to assess structural equivalence in interaction networks: this technique substantially improves our ability to assess actors' substitutability in sequential interaction networks: this technique substantially improves our ability to assess the resilience of vertical hybrid organizations that are widespread in real economic life (like e.g. shipping networks, supply chains, financial intermediation chains, etc.).

On the whole, our contribution points to the fact that much work still needs to be done in the social sciences in order to properly understand the overlooked coordination mechanisms that connect individual action to aggregate outcomes. Face to this enormous challenge, more refined (yet still basically simple and intuitive) analytical tools like the "place-based methodology" and the "chain-based methodology" can provide a great contribution to chasing those "strange animals" that lay at the core of complex systems.

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Chapter 2 – The visible hand of cluster policy makers: An analysis of *Aerospace Valley* (2006-2015) using a place-based network methodology

Abstract:

The paper focuses on cluster policies with particular attention to the role of R&D collaborative incentives in the structuring of knowledge networks in clusters. We disentangle the main network failures in regional innovation systems, and discuss the selection procedures designed by policy makers to foster knowledge collaborations. We draw evidence from the French Aerospace Valley cluster from 2006 to 2015. The case study is based on a dataset of 248 granted research consortia, from which we build 4-cohort knowledge networks that enable us evidencing the evolving structural properties of the cluster over time. We suggest avoiding the bias and limitations of 1 and 2-mode network analysis by developing an original place-based network methodology that emphasizes on structural equivalence and groups' behaviors. We discuss the results focusing on the convergence degree between the structural properties of the cluster selected by the Program and the policy makers' objectives. Finally, the methodology allows us to identify the agents of the structural and technological changes observed throughout the period.

Keywords: *Cluster policy; Networks; Collaborative incentives; Groups behaviors; Behavioral additionality; Aerospace Valley*

JEL codes: D85; O25; O30; R10

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2.1. Introduction

The development of cluster policies relies on the growing awareness from academics and policy makers that network failures have to be merged with traditional market ones in the design of public innovation incentives (Woolthuis *et al*., 2005; Vicente, 2017). That is why cluster policies have been implemented in many countries since the end of the 1990s (Uyarra and Ramlogan, 2012; Maffioli *et al*., 2016). They coexist nowadays with innovation policies based on individual incentives, such as research tax credit and innovation grants sponsored by public agencies (Nishimura and Okamuro, 2011). Cluster policies aim at designing R&D collaborative incentives to strengthen knowledge networks in order to stimulate the expected benefits of local knowledge spillovers (Broekel *et al.*, 2015). Cluster policies basics broadly rely on two related network failures. First, the potentialities of knowledge spillovers from science to industry can be inefficiently exploited due to the cultural divide and the weak absorptive capabilities between the two communities. Considering that positive impacts of knowledge spillovers are geographically bounded (Audretsch and Feldman, 1996), cluster policy guidelines will tend to favor local incentives towards networks mixing public research organizations and companies. Second, entrepreneurship matters in clusters (Rocha and Sternberg, 2005; Delgado *et al.*, 2010). Their effectiveness can be assessed by the rate of SMEs and spinoffs' birth and entry. The latter is the mark of the level of technological variety and renewal, and therefore represents a significant indicator of the cluster long-run dynamics. Here again, these births and entries are geographically bounded, and contained in the close perimeter of universities and big companies (Audretsch and Lehman, 2005). But the entry dynamics is not a significant condition of cluster success *per se*. New entrants sometimes need to benefit from collaborative opportunities, especially in industries in which modularity and interoperability matter (Suire and Vicente, 2014). Then, collaborative incentives between SMEs and big companies are also a regular means used in cluster policies to foster regional performance.

The aim of this research is to have a deeper insight of these policy guidelines, and to find and test adapted network methodologies to deal with (i) the links between the public micro-incentives for knowledge collaboration and the structural properties of the network that emerge from these incentives, and (ii) the identification of the agents at the origin of structural changes. In that respect, the place-based network methodology and the nested cohesive block analysis are developed and offer promising avenues. As a matter of fact, it is common in the literature to assess whether network position increases individual innovative performance (Zaheer and Bell, 2005; Cattani and

Ferriani, 2008). Nevertheless, very few contributions have studied the impact of cluster development programs not on the links between the actors' position and performance but on the links between the structural properties of networks these incentives produce and the patterns of knowledge dynamics at work within the cluster (Crespo *et al*., 2014; Giuliani and Pietrobelli, 2016). This question requires going beyond the different centrality degrees developed in the literature to measure individual position in networks. It requires investigating different concepts related to complex structural properties imported from network theories in order to better disentangle the consequences of different properties of network connectivity on the cluster development patterns. Moreover, it also requires overcoming methodological issues that arise when one deals with aggregate relational data at the regional scale. To improve our knowledge on that emerging research topic, we will focus on a single case study: the *Aerospace Valley* in Toulouse – France from 2006 to 2015, i.e. from the start of the policy to the year from which data are available. Aerospace Valley is one of the leading public-funded clusters granted by the French Cluster Program, and it is also the name of the association nurturing R&D collaborations and managing the international visibility of the cluster. As a consequence, Aerospace Valley can be considered as a particular cluster and knowledge network whose nodes are organizations involved in R&D projects selected by the association, and ties are collaborations having received public incentives. Our goal is not to find causality between the policy and the innovative performance of the organizations affiliated to the cluster program. To do so, systematic analysis on several places should be carried out, and counterfactual analysis required (Giuliani and Pietrobelli, 2016). Our goal is different and just as important for whoever wants to have a better understanding of how policy makers shape the organization of innovation processes in regions. Indeed, our basic starting assumption is related to the fact that, in spite of their control on the selection of R&D collaborations at the micro and dyadic levels, policy makers cannot have a perfect real-time knowledge and control of the structure as a whole. In network theories, this type of micro-macro scales problems is typical (Watts, 2004; Newman *et al.*, 2006): the "macro-behavior" of the network and its structural properties, both resulting from the aggregation of ties, can escape their own intention. Since clusters are foremost networks (Giuliani and Bell, 2005; Vicente *et al.*, 2011), dealing with the links between micro incentives and macro structures can be an alternate means to discuss how innovation policies can shape collaborative patterns and the structure of knowledge networks, as previously documented in the context of European Framework Programs assessment (Breschi and Cusmano, 2004; Vonortas, 2013).

The contribution is divided as follows: Section 2.2 goes back to the structuring of R&D networks in clusters and the design of public collaborative incentives aiming at repairing network failures. Section 2.3 aims at exemplifying these incentives and their consequences in the evolving structure of a particular cluster. We start by explaining the historical and technological context in which the Aerospace Valley cluster has been selected by national authorities to be eligible to public-funded incentives for R&D collaborations, before describing the cluster policy guideline developed in order to sustain its development. Section 2.4 presents the data collection procedure which enables us to build an original and complete dataset of public-funded collaborative R&D projects for this cluster. Then we discuss the methodological issues for building networks over the period. We disentangle the problems that generally arise for the study of networks resulting from the simple aggregation of collaborative and multilateral R&D consortia. To circumvent them, we suggest a place-based network methodology that focuses on structurally-equivalent relational behaviors. Section 2.5 shows how this methodology helps us identifying the evolving structural properties of knowledge networks in the cluster over time. Section 2.6 discusses the results under a particular focus related to the convergence degree between the network statistical findings and the objectives stated by the policy makers, with a particular focus on the agents of the structural and technological changes over the period.

2.2. Network failures, behavioral additionality, and the design of collaborative incentives in cluster policies

Cluster policies support the idea that an additional source of R&D productivity at the meso level remains hidden behind the simple aggregation of the innovative capabilities of each organization considered in isolation. Therefore, the expected economic return is directly related to the multiplier effect induced by network incentives and collaborative subsidies. This multiplier effect is directly associated to the particular type of additionality – named behavioral additionality – generally expected by governments when they implement collaborative incentives in R&D activities (Fier *et al.*, 2006; Clarysse et *al.*, 2009). While input and output additionalities are usually expected from individual incentives to innovate when market failures are considered, behavioral additionality is put forward as the main argument of policy implementation when systemic failures are observed in regional or larger innovation systems (Luukkonen, 2000; Breschi *et al*., 2009; Gök and Edler, 2012). Network failures constitute a large part of these systemic failures (Woolthuis *et al.*, 2005) and concern the structural organization of innovation process (Vicente, 2017). Taking them into account can explain why cluster policies based on collaborative R&D grants have gradually substituted individual grants, and why the need for network-oriented methodologies to evaluate collaborative programs is getting more and more challenging (Vonortas, 2013; Giuliani and Pietrobelli, 2016). Fixing network failures implies a large spectrum of policy interventions and raises the typical question of selection. Indeed, selection is the key principle as well as the key difficulty, due to the information asymmetries between collaborative grants providers and receivers. That is why cluster policy makers usually design filtering processes in order to reduce these asymmetries. Moreover, by influencing collaborative behaviors of local agents, policy makers also influence the collaborative structure as a whole. Each selected collaboration contributes to the network structuring and connectivity. Here again, a new asymmetry occurs, since policy makers can have difficulties to perceive the aggregate network structure that evolves over time as new agents and new collaborations enter the network. Subsidizing a set of "good collaborations" does not necessarily imply shaping "good networks". Therefore, understanding cluster policies as a means to boost innovative outputs through behavioral additionality requires working both on the selection process of knowledge collaborations at the micro level (2.1) and on the connectivity properties of the network as a whole (2.2).

2.2.1. Filtering and selecting knowledge collaborations in clusters

For cluster public fund raisers, repairing network failures first consists in identifying the nature of these failures, in order to develop an oriented selection mechanism for the provision of collaborative grants. Not all collaborations are equally relevant to sustain. Policy makers have to grant a minimum of collaborations for a maximal-expected economic return, by ranking strategic priorities for their collaborative incentive schemes.

2.2.1.1 Public knowledge dissemination and absorption

One of the typical network failures relies on an insufficient level of reciprocal absorptive capabilities of knowledge between public research organizations and firms. In spite of the "public good" property of knowledge outputs produced by universities, the regional benefit from local knowledge spillovers does not only result from geographical proximity, but from the intentional effort of agents to interact in multiple ways in order to improve their mutual understanding in problem solving (Breschi and Lissoni, 2001; Bishop *et al*., 2011). A cultural gap and a weak social mobility and proximity between the two communities are often mentioned as a source of inefficiency (Hemmert *et al*., 2014). Therefore, providing incentives for knowledge exchanges between academic and private R&D labs remains one of the main filtering mechanisms in cluster programs. Nevertheless, this type of support is not necessarily useful for clusters that have historically succeeded in overlapping academic and business networks. But because academic research plays a crucial role in network during the early stage of technological domains (Owen-Smith and Powell, 2004), this means to foster academic knowledge dissemination is more relevant for clusters for which technological renewal matters. The economic return of cluster policy as well as the behavioral additionality gained from collaborative incentives is expected to be higher in this type of context in which academic research and business communities remain poorly connected (Morrison and Rabellotti, 2007). At the reverse, for clusters involved in the upstream phases of market development, the need for this type of public-funded collaborations is less crucial, and can be a source of crowding-out when implemented in an excessive myopic way.

2.2.1.2 SMEs entry and connectivity

Like organic systems, cluster long-run performances depend on the renewing degree of firms' demography. While some clusters succeed in engendering spinoffs and start-ups, others fail and tend to concentrate knowledge relationships between big and long-established companies (Rocha and Sternberg, 2005). Beyond the question of new entries, the issue for cluster policy makers is also related to the growth and survival rates of nascent companies. Delgado *et al.* (2010) and Wennberg & Lindqvist (2010) show that clustering effects have a higher impact on new companies birth and survival than pure agglomeration externalities. In industrial domains in which systemic technologies require integration between separated pieces of knowledge disseminated between different companies, connections to the main companies holding the central part of the system are often for the new entrants the opportunity to cross the bridge between R&D and business prospects (Suire and Vicente, 2014). Therefore, repairing network failures in clusters consists in building selection mechanisms that are conditional to the attendance of young or nascent SMEs in consortia. Designing this type of incentives can decrease the homophilic relational behaviors between core-companies that relegate new entrants in the network periphery. In terms of expected economic returns, providing this type of collaborative incentives could be more effective than pure individual incentives that put SMEs in a situation of public fund dependence, without any sufficient guarantees that they alone might succeed in finding market opportunities. But at the reverse, this filtering mechanism can be a source of crowding-out for clusters in which social networks between new entrepreneurs and managers of long-established firms work well.

2.2.1.3 Local cohesiveness and global accessibility

Clusters are not closed systems. Their success depends both on their internal structuring and their degree of embeddedness in global networks. Since the large fieldwork analysis of Storper & Harrison (1991) and Markusen (1996), it is acknowledged that clusters strongly differ in their balance between inward and outward knowledge relationships. Each organization manages its relational portfolio according to its own perception of the benefits from voluntary knowledge exchanges and the risk of unintended knowledge spillovers. Geographical proximity increases these opportunities, but also increases these risks (Breschi and Lissoni, 2001; Boschma, 2005). When collaborations on knowledge open new opportunities but are likely to generate distrust and appropriation concerns (Gulati and Singh, 1998), building relationships with distant partners limits the risks of unintended spillovers. Moreover, global relationships enlarge the variety of external knowledge sources (Morrison *et al*., 2013), and are particularly strategic between distant competitors wishing to collaborate on how to turn separated and competing technologies into interoperable ones (Balland *et al*., 2013). Therefore, the balance between local and global collaborative incentives constitutes a challenging point for cluster policy makers.

2.2.1.4 Technological relatedness, diversification and new growth paths

Cluster dynamics are not never-ending stories of specialization, nor random processes of jumping from one industry to another. The technologies and markets on which clusters evolve over time move along a gradient of related and unrelated diversification. In the Silicon Valley, the photovoltaic industry in the 2000s has at first glance nothing to do with the computer industry in the 1980s. It is nevertheless noteworthy that they share knowledge on storage technologies for data and energy on one side, and nanostructures on the other side, coming both from the semiconductors industry which has continuously developed since the 1970s. Several factors explain these regional diversification processes (Boschma, 2017), from skills mobility (Neffke and Henning, 2013) to institutional agency (Borras and Edler, 2014). Among them, the dynamics of inter and intra-industry collaborations plays a critical role (Broekel and Brachert, 2015), and then appears as an additional source of network failures. In regions in which several clusters are identified as such by policy makers, the bridging between them constitutes a source of path creation potentialities. The debates on the superiority of related or unrelated diversification on cluster performances are far from being over and empirical evidences are too contextual to enable the design of standard policy lessons. However, diagnosis of the network structures of clusters can help policy makers better orientate their collaborative incentives on particular directions. As suggested by Suire and Vicente (2014), providing public incentives towards collaborations in closely-related industries should be more effective for clusters that failed to set up their technologies on mass markets, while collaborative incentives toward previously-unrelated industries and skills can favor path renewal for clusters entering a phase of transition.

These network failures, presented separately for convenience, are not necessarily independent of each other. For example, when there is a lack of diversification within a region, this may be the consequence of a lack of global connectivity of the cluster, since the diversification opportunities result from collaborations with partners outside the region (Fitjar and Rodríguez-Pose, 2011; Morrison *et al.*, 2013). Likewise, the connectivity of SMEs to networks is not independent from the overlapping of academic and business networks, in particular when this concerns university spinoffs and their need to connect the business community (Mustar, 1997; Sternberg, 2014). Relying on one of these network failures is not without consequences on the others, and these interdependencies must be taken into account by cluster policy makers.

2.2.2. Connectivity and the structural properties of networks in clusters

When cluster policy makers provide incentives for collaborations, they contribute to the circulation of knowledge like a *visible hand* trying to take the control of the expected positive effects of unintended knowledge spillovers. But having the perfect control of the evolving structural properties of networks is somewhat difficult, even impossible, since all the new supported collaborations but also the renewing and ending ones continuously modify the properties of the structure. If failures at the dyadic level can be easily fixed, repairing structural failures is not within policy maker's reach. They are difficult to fix, but some of them have been identified as key properties that matter for the long run performance of social networks (Watts, 2004; Rivera *et al*., 2010; Ahuja *et al*., 2012) but also clusters and regions (Crespo *et al*., 2014; Breschi and Lenzi, 2016).

2.2.2.1 Connectivity vs. density

The balance between network connectivity and density is an important feature of networks, and one of the critical parameter of their aggregate performance. Network connectivity has been considered as an important feature of knowledge network since it enhances information flows and knowledge spillovers (Fleming *et al.,* 2007). A high level of relational density does not necessarily imply a high level of connectivity. It depends on how collaborative incentives are distributed among the organizations in clusters (Crespo and Vicente, 2016). For a given amount of relationships, knowledge can always find a path to flow between any pairs of organizations, or, at the reverse, can meet several breaking points. In extreme cases, when incentives are oriented toward the reinforcement of closure into separated cliques of organizations, increasing density cannot increase connectivity. Closure and cohesiveness in networks are important for enhancing trust and coordination, in particular when systemic innovations require complex processes of knowledge integration. But cluster policy makers also need to pay attention to the overall connectivity in order to favor knowledge circulation and maintain new collaboration opportunities. Although cluster policy guidelines generally stress on the necessity to increase the overall density of networks in clusters (Vicente, 2017), cluster managers who are actually involved in cluster development also have to focus more surgically on particular bridging links between cohesive groups.

2.2.2.2 Hierarchy

Knowledge networks in clusters are neither pure centralized structures of interaction nor pure “flat” ones (Markusen, 1996). In between, clusters are typified by networks in which organizations differ in terms of degree centrality. The extent of the relational portfolio of each organization depends on their size and their willingness to collaborate. On the one side, monitoring large portfolio of collaborations is not within every firm’s reach, since time and human resources are required for that purpose. On the other side, whatever their size, the need for firms to access external knowledge is also a critical indicator of their willingness to collaborate. Consequently, the cluster will differ according to the level of hierarchy in the structure of knowledge interactions. A strong hierarchy, represented by a very sloping degree distribution, is generally the sign of mature clusters in which big and long-established organizations have developed a large portfolio of knowledge collaborations (Brenner and Schlump, 2011). On the other hand, a weak hierarchy, represented by a very flat degree distribution, is the sign of a burgeoning and nascent cluster which has not yet succeeded in reaching a high level of coordination in knowledge exchanges. For markets in which competition and industrial organization are based on systemic and modular products, the existence of core-organizations able to manage the convergence and interoperability between separated pieces of knowledge is one of the key conditions for clusters to reach a leading position on markets (Balland *et al*., 2013). When clusters display hierarchy, they often exhibit a core-periphery structure (Borgatti and Everett, 1999) in which highly-connected organizations designing technological standards co-exist with loosely-connected ones, generally new entrants such as spinoffs and SMEs. This topological form of networks conveys a structure in which the growing capabilities of central organizations to manage the systemic process of innovation do not play against but co-exist with new entries. This structure of knowledge interactions in clusters has been documented by Owen-Smith and Powell (2004) for the biotech industry in Boston, and by Cattani and Ferriani (2008) for the movie industry in Hollywood. Other network-based analysis of clusters document this type of structure in developing countries, whether in mature technology-intensive industries (Giuliani *et al.*, 2018), or in agro-industry like wine or cheese industry (Giuliani and Bell, 2005; Giuliani, 2013; Crespo *et al*., 2014). Therefore, cluster policy practitioners have to pay attention on the existing structure of knowledge interactions. They can help some of the burgeoning organizations become core-ones in nascent clusters or, at the reverse, provide incentives for entrepreneurship in mature clusters.

2.2.2.3 Assortativity

Beyond the shape of the degree distribution, the shape of the degree correlation also matters. Called assortativity in network theories (Rivera *et al*., 2010; Ahuja *et al*., 2012), the degree correlation offers a formal view on how highly and poorly-connected organizations interact together. A network is strongly assortative when highly-(poorly-) connected organizations tend to form relationships with other highly-(poorly-) connected organizations, and disassortative when core-organizations tend to interact more with peripheral ones. Therefore, assortativity is an indicator of the knowledge pathways between big organizations and less central ones, such as spinoffs and SMEs. As evidenced by Crespo *et al.* (2016), a too strong assortativity in mature clusters weakens their endogenous capabilities on renewing themselves over time. The main challenge for successful and mature clusters is to avoid entering into decline when the markets on which they are well-installed also decline. Network assortativity, after a while, becomes a source of conformism and negative lock-in (Watts, 2004), due to an excessive redundancy of knowledge flows within the core-component of the network (Vonortas, 2013). As a corollary, fresh and explorative knowledge produced by peripheral organizations has difficulties to reach and irrigate the core of the network (Fleming *et al*., 2007). Accordingly, disassortative structures of knowledge interactions enable clusters to have a higher propensity to continually overlap emergent and mature markets, by multiplying pathways between the burgeoning ideas developed by new entrants and the market experience acquired by core-organizations. Therefore, policy makers have to consider this network property carefully. For that purpose, they need to pay attention to the phase of the business cycle on which clusters are situated.

The concept of network failures is not only a pure and uncontextualized theoretical argument to justify public incentives for knowledge collaborations in clusters. It also requires an approach taking into account the territorial context and the historical contingencies on which these incentives are implemented. The actual network failures can be weak or strong, and depend on a wide range of critical parameters policy makers have to capture in order to better contextualize their intervention. In particular, as intriguingly shown by Fleming *et al.* (2007), salient structural properties developed in the literature, like small-world properties, can win and lose in significance according to the territorial and technological contexts in which these properties are studied. In the same vein, Crespo *et al.* (2016) showed that hierarchy and assortativity play differently in the performance of clusters when the maturity and renewal stages are introduced as key controls in the search from the significant properties of cluster performance.

2.3. The context of *Aerospace Valley* in Toulouse

2.3.1. Cluster context: mature markets and the need for regional diversification and relatedness

Greater Toulouse (France) is a leading and historical place for aeronautics and space industries in Europe (Niosi and Zeghu, 2005; Zuliani, 2008; Gilly *et al.*, 2011). The main oligopolistic companies of these two related industries and some of their plants are located in Toulouse (Airbus, Airbus Defense and Space, ATR, Thales Alenia Space, Safran, among others), and the city hosts the main French high schools of engineering and research in this technological domain (Sup'Aero, ONERA, Federal University of Toulouse, among others) as well as the headquarter of the National Center for Spatial Studies (CNES). This cluster displays three main characteristics: (i) its maturity, since it leads the European aeronautics and space industries, (ii), its centrality, since it is at the center of the whole of European industrial and innovation networks in the technological field; (iii) its developing diversification, since it faces challenges related to environmental constraints and new balances between military and civilian market opportunities. The aerospace industry displays specific properties in terms of industrial organization. It traditionally combines a strong hierarchy between the different firms involved in the supply chain with a systemic production process organized around a hub and spoke network architecture. As pointed by Wink (2010), the industry was until the end of 1980s typified by close links with the military industry implying strong confidentiality requirements and a high share of internal R&D. Diversification was low and the high capital intensity was at the origin of strong entry barriers, together with the government regulation. After this period, the industry met new challenges leading to salient structural changes. On the one side, the aircraft industry started to blur its own sectoral frontiers by looking for partners outside its engineering-based value chain. The main incumbents built relationships with nature, informatics and material sciences in order to find solutions for the weight reduction of airplanes and to improve their eco-efficiency. On the other side, the space industry started to develop civilian applications and strongly diversify its partners' portfolio for that purpose, in particular in the transversal domain of embedded systems. These structural changes have given birth to new industries, such as GNSS (Global Navigation Satellite Systems), drones, and other related industries.

2. 3.2. Cluster policy guideline: a two-stage selection process

Aerospace Valley is a cluster-governance structure born in 2005, as the result of the implementation of the still ongoing French Cluster Policy. The cluster has been selected by the French government as one of the seven "world-wide clusters" in the French cluster classification (beside eleven "globally-oriented clusters", and fifty three "national clusters"). The aim of the national policy consists in fostering innovation by selecting a set of 2-dimension vectors of regions and technological domains that are eligible for receiving grants for R&D collaborative projects. *Aerospace Valley* is one of these leading selected vectors, with "*greater Toulouse and its administrative NUTS2 region*" and "*aeronautic, space, and embedded systems*" as vector coordinates. The governance structure of the cluster is appointed to provide networking activities and facilitate the emergence of R&D collaborative projects between the industry and the academia. In particular the structure is responsible for organizing the first stage of the selection process for the national calls for proposal launched by the FUI (Single Inter-Ministry Fund) and the ANR (French Research Agency). This first stage consists in a certification process of the most promising R&D

research consortia that meet the strategic objectives of the cluster. Once this certification dealt with, the second stage of the selection process is organized at the national level. The FUI and ANR regularly launch calls for proposal for R&D collaborative projects for which only consortia certified at the cluster level can apply. Collaborative incentives for cluster development are thus organized at two levels. First, the local certification process is an incentive for firms and public research organizations to work together in order to acquire public funds for their research activities. Second, the national selection is a strong incentive for cluster managers to nurture synergies and collaborations in order to get an increasing number of grants and maintain their position in the French cluster classification.

The guideline has not been set in stone since 2005. First, it has changed at the national level over the period. Second, cluster managers, in the limits of the French guideline constraints, have a degree of latitude to adapt their incentives for R&D collaborations. The main persisting constraint is the necessity for R&D collaborative projects to gather private companies and public research organizations. At the reverse, other constraints and incentives have evolved over the period. First, the constraint of being located in the geographical perimeter of the cluster to attend a project has been relaxed in an early stage. Too closely-related to Porter' ideas of cluster organization, this constraint reduced collaborative opportunities and the influence of clusters abroad. Once relaxed, it became possible to apply to the national grants with projects certified by more than one cluster governance structure. This change aimed at finding a better "cluster policy mix" between inward and outward collaborative incentives, as suggested by Morrison *et al*. (2013). Second, in order to deal with the Matthew effect according to which the selection process naturally allows the rich to get richer, strong incentives to include SMEs in R&D consortia have been designed at the national level and absorbed at the cluster level. Lately, strong incentives have been added in order to boost not only exploration, but also exploitation and markets, putting the concept of "factories of the products of the future" beside the "projects factories" at the heart of the new guideline. Finally, with the possibility given by the national constraints to grant inter-cluster collaborative projects, many clusters including *Aerospace Valley* have recently provided strong incentives toward industrial diversification, in order to better overlap mature and emerging markets.

2.4. Data collection and methodology

Characterizing networks in clusters using public-funded R&D collaborative projects requires particular caution in terms of data collection, time-window definition, and adapted methodologies of network analysis.

2.4.1. Data collection and disambiguation

Data collected on collaborative projects certified by *Aerospace Valley* and granted at the national level between 2006 and 2015 constitute the material used to analyze the evolving structural properties of the cluster. These data are extracted from *Aerospace Valley* website and the national list of selected projects. They concern the FUI and ANR programs, both being the main national programs aiming at restoring incentives to collaborate on knowledge. These data include project scientific abstracts, and information about the consortium members (location, institutional form, size). If the collection of projects does not suffer from limitations, that is not the case for the project members. Indeed, an extensive effort of disambiguation was required to work with fine-grained data. This effort focused on an appropriate targeting of departments and plants actually involved in projects, in order to avoid the over representation of multi-plant companies and large public research organizations. Project websites, companies activity reports and scholars affiliation have been consulted in order to refine the database. When contradictory information remained, e-mails to academics and engineers were sent and the answers enabled us to reach a sufficient fine-grained extraction.

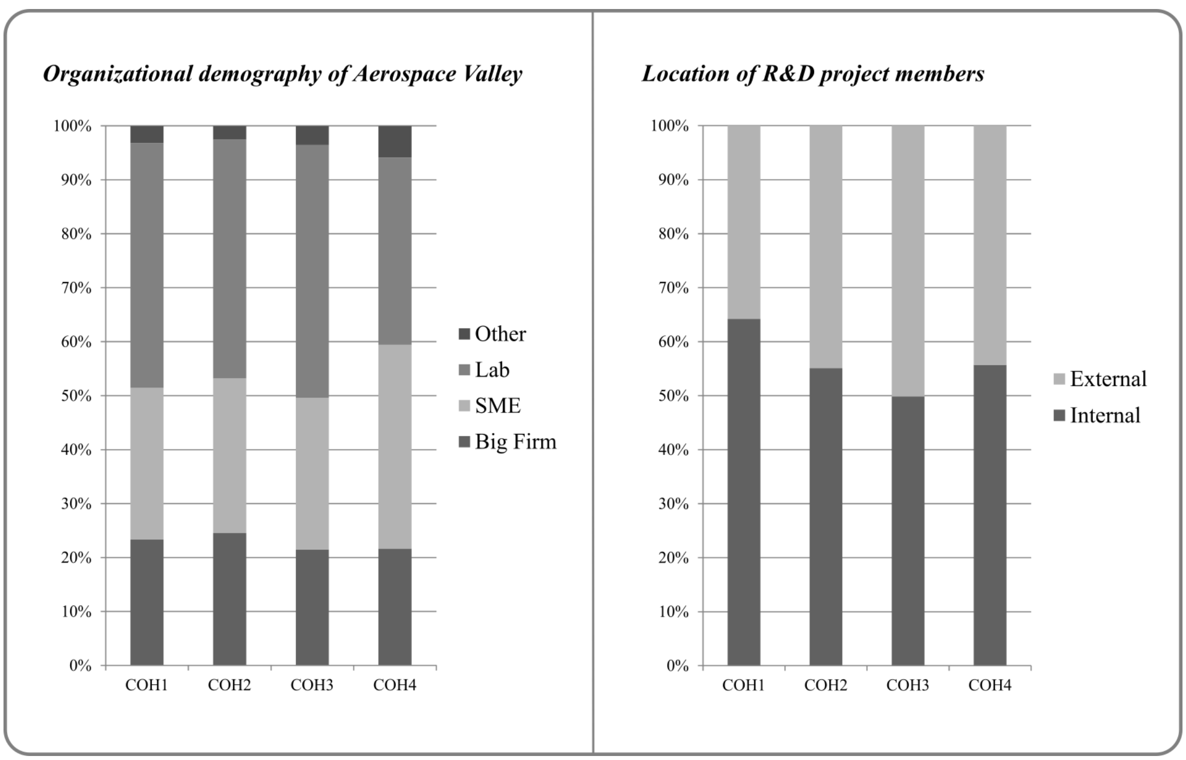
Over the period, 248 projects were granted. We split the period into four sub-periods using start date of projects in order to affiliate projects to cohorts with comparable time window and size. Table 2.1 presents basic statistics on collaborative projects over the period.

Table 2.1: Network descriptive statistics

	#nodes	#projects	Mean size projects	Min size projects	Max size projects
Cohort#1	313	56	7,84	2	32
Cohort#2	314	52	7,88	2	22
Cohort#3	395	78	6,79	2	25
Cohort#4	323	62	6,65	2	13

The nodes have been typified according to 4 categories: Big companies, SMEs (under 100 employees), PROs (Public Research Organizations), and others (including technological platforms and agencies, public institutions). Their location is also taken into account in a binary way by distinguishing nodes located into the administrative area of the cluster and the others. Figure 2.1 describes the evolving demography of nodes according to these specifications.

Figure 2.1: Evolving demography of Aerospace Valley network



2.4.2. Overpassing bias and capturing groups' behavior: the place-based network methodology

Analyzing how public collaborative incentives drive network structuring in clusters requires aggregating collaborative projects funded in a same time window (same cohort), and reproducing the process for all the other time windows. Several previous empirical studies applied this methodology in the context of regional cluster analysis (Owen-Smith and Powell, 2004; Giuliani and Bell, 2005; Vicente *et al.*, 2011; Levy and Talbot, 2015; Crespo *et al*., 2016), as well as in the context of larger networks at the European level (Breschi and Cusmano, 2004; Breschi *et al*., 2009; Balland *et al*. 2013; Kang and Hwang, 2016). When collaborative projects are considered, network analysis can start by the construction of a *2-mode* network, i.e. an affiliation network drawn from a rectangular matrix and composed of one type of node (the organizations) connected to another type of node (the projects). In this type of networks, there is no link connecting nodes of the same type. But at the reverse, two projects can be linked by one or several organizations, and two organizations can be tied by one or several projects. This type of network has been suggested by Breschi and Cusmano (2004) and Balland *et al.* (2013) since it allows having a first view of how projects in a same technological field can be linked together by multi-affiliated organizations. *2-mode* networks can be turned into *1-mode* networks, in order to capture the structure of innovative activity in clusters. *1-mode* networks are drawn from a square matrix and are composed of a set of nodes representing organizations and a set of ties representing knowledge flows between them. This methodology has proven its reliability to identify critical organizations in knowledge dissemination at the micro-level, and salient structural properties at the meso-level. Nevertheless, as pointed by Robins and Alexander (2004), this network-based analysis is not exempt of biases and limitations.

First, when networks are drawn from the aggregation of R&D consortia, i.e. from the aggregation of cliques of fully-interconnected organizations, different biases can occur (Uzzi and Spiro, 2005). Most of them are related to the risk of confusion in ego-network properties such as degree centrality and brokerage, due to the heterogeneity in the size of cliques (Breschi and Cusmano, 2004). They can give rise to misleading interpretation in the actual role of organizations in knowledge dissemination. To give an example, let us consider an organization that is affiliated to a 15-member consortium, and only to this one. It will have a high degree centrality, while, as shown by Bernela and Levy (2017), its influence and involvement in the innovation system can be very weak, in particular if this organization does not actually interact with all the other consortium members. Let us now consider another organization involved in 3 collaborative projects, each affiliating only 3 partners. Its degree centrality will be less significant due to a thinner relationships portfolio, while one can expect a higher involvement in projects and a more strategic position in the network. Dealing with this issue is a challenge for network-based cluster analysis, in particular when the size of consortia strongly differs, as it is typically the case in that analysis in which the consortia go from 2 to 32 organizations (see Table 2.1 above). Therefore, methodologies are required to correct this bias. The idea is to better apprehend the skeleton of the network by capturing the actual influence of nodes. For instance, Breschi and Cusmano (2004), in their network analysis built from European collaborative programs, suggest using 1-mode "star" networks instead of considering consortia as fully-connected cliques. They consider each consortium as a sub-network only connecting prime contractor to participants. Vicente *et al.* (2011) use an alternate method based on the diamond of Robins and Alexander (2004). A diamond appears when two organizations connected to a project are also connected to another project. Both allow limiting these biases and offering the means to study the backbone of networks, without the noise introduced by the heterogeneous size of R&D consortia.

Second, as early demonstrated by Pallotti and Lomi (2011), not only nodes position and direct ties explain knowledge dissemination in networks. Starting from the ideas on structural equivalence developed by Lorrain and White (1971) and Burt (1987), they show that groups' behaviors also matter. Structural equivalent organizations have similar patterns of relations to others, and thus share and face same resources and constraints (Stuart and Podolny, 1996; Gnyawali and Madhavan, 2001). They tend to contribute to innovation communities in a same way not only because they influence each other by direct ties, but because they face similar dependencies and relational contexts (Mizruchi and Galaskiewicz, 1993). Identifying groups' behaviors based on structural equivalence enables having a complementary way to deal with the influence organizations have in the aggregate structure of knowledge interactions. By giving the skeleton of the network, it also allows to better capture the changes on the structural and relational patterns (Breiger, 1976; Borgatti and Everett, 1992; Doreian, 2012).

Rather than limiting the study to a simple *1-mode* network analysis, we suggest developing an alternate methodology that would correct the bias as well as consider groups' behaviors, without compromising the possibility to analyze nodes' position in networks. To do so, we use the so-called "network of places" approach early developed in sociology by Pizarro (2007) and now operational for large dataset-based empirical analysis with the R-module *"Places: Structural Equivalence Analysis for Two-mode Networks"* (Lucena-Piquero, D., 2017). To define a place P_i of structural equivalent organizations, let us start by considering a finite set of organizations $I = \{i_1, i_2, i_3, \dots i_p\}$, each affiliated to one or more projects belonging to the set of projects, noted C (in order to consider each project as a fully-interconnected clique), with $C = \{c_1, c_2, c_3, \ldots c_n\}$. We can define a place P_i of an organization $i \epsilon I$ as a subset of C such as at least one of the organizations of I belongs to every one and only to the projects included in the subset P_i. Therefore, for $i \epsilon I$, $P_i = \{c_j \in C: i_i \in c_j\}$. If two organizations $i, j \in I$ have the same subsets of C, they belong to the same place. Then, they are structurally equivalent (Borgatti and Everett, 1992). Places become the new nodes of the network, that are connected by a relation R when $P_i \cap P_j \neq \emptyset$. Therefore, the set P of all the places defined in C and the set R of their relations constitute the network of places. This set P can also be defined as a set $P(k,l)$, where k represents the number of projects in which organizations are involved together, and l the number of organizations belonging to the place. This reduction process based on structural equivalence and groups' behavior gives the skeleton of the organizational *1-mode* network, without losing the organizations, which remain in the structure, but now as simple places' constituents. In addition, it provides a simple, accurate and fast algorithm for the study of structural equivalence (Doreian, 2012).

Figure 2.2: A stylized construction of a network of places

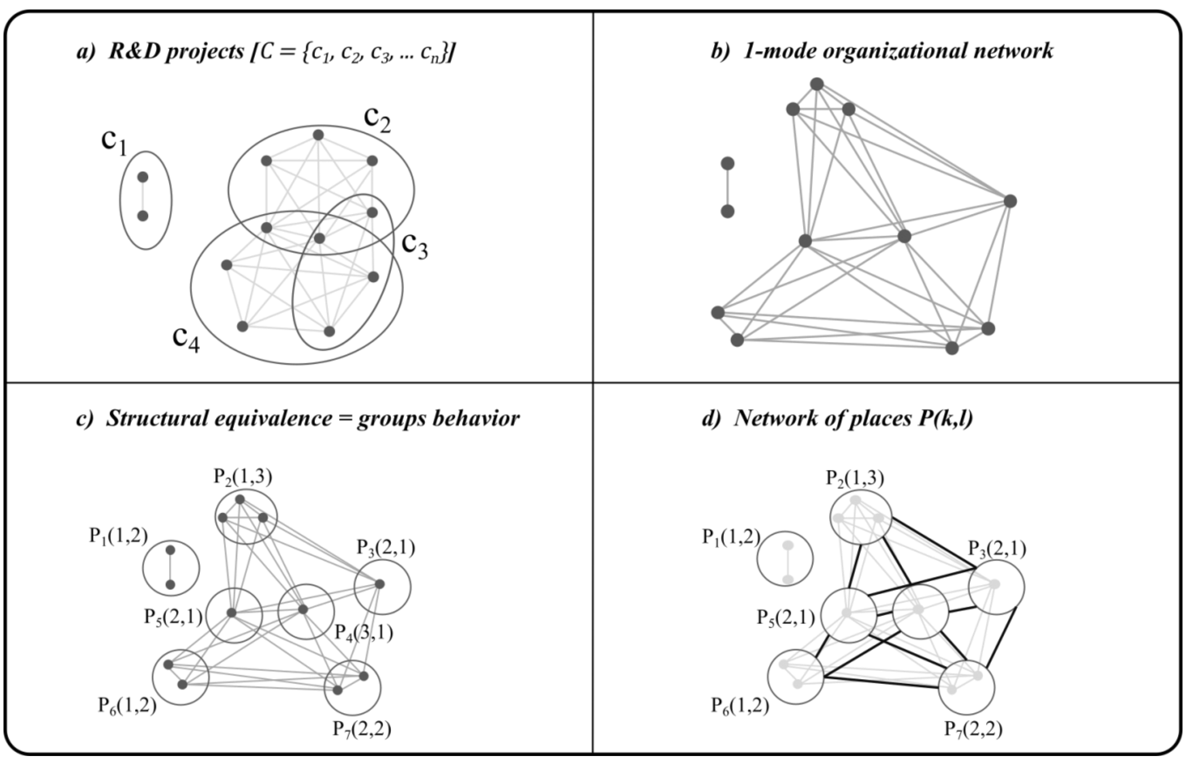


Figure 2.2 highlights in a stylized way the process that turns a network of projects (cliques of fully-connected nodes) into a network of places, where nodes are now places gathering structural equivalent organizations. Figure 2.2a presents a structure of knowledge interactions composed of 4 collaborative projects, each of them composed (in transparency) of fully-connected cliques of organizations. Figure 2.2b turns this structure into a simple *1-mode* network. Figure 2.2c sorts structural equivalent organizations into distinct groups, while Figure 2.2d preserves in transparency the previous *1-mode* network, and displays now the network of places.

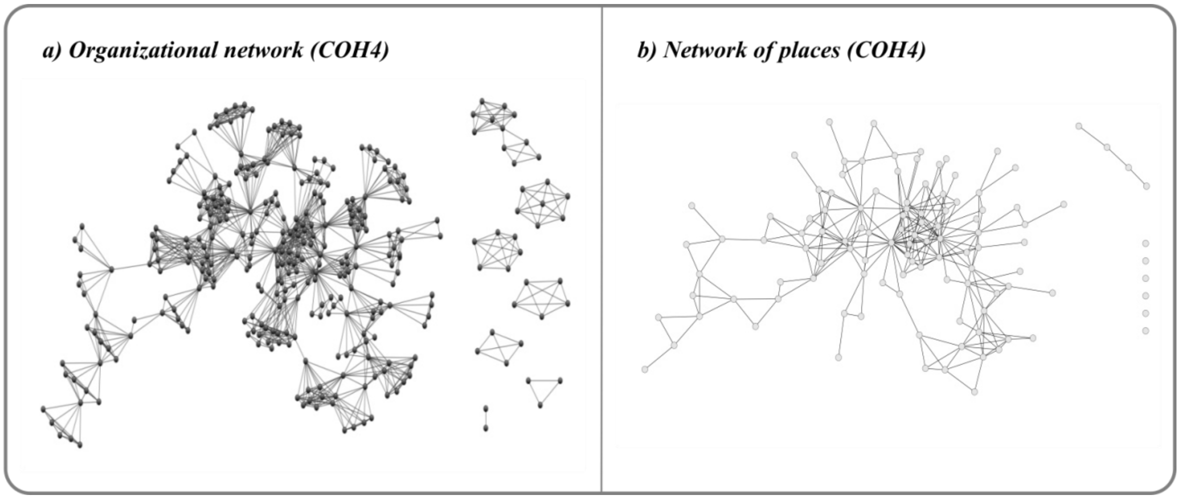
Table 2.2: Descriptive statistics (network of places)

	#places	**Mean *k* per place**	**Min *k* per place**	**Max *k* per place**	**Mean *l* per place**	**Min *l* per place**	**Max *l* per place**
Cohort#1	118	2	1	18	2,65	1	18
Cohort#2	104	1,88	1	14	3,02	1	12
Cohort#3	150	1,85	1	14	2,63	1	17
Cohort#4	112	1,71	1	7	2,88	1	10

We turn the *1-mode* network of organizations into a *1-mode* network of places in order to better focus on the groups' behaviors of the *Aerospace Valley* network skeleton. Table 2.2 presents basic statistics of this new network.

Figure 2.3 provides an actual illustration, limited here at the fourth cohort of the *Aerospace Valley* cluster, in order to have a better view of how this reduction process gives the skeleton of the network and neutralizes the bias related to the strong heterogeneity of R&D consortia size.

Figure 2.3: 1-mode network and network of places (Aerospace Valley cluster, cohort#4)

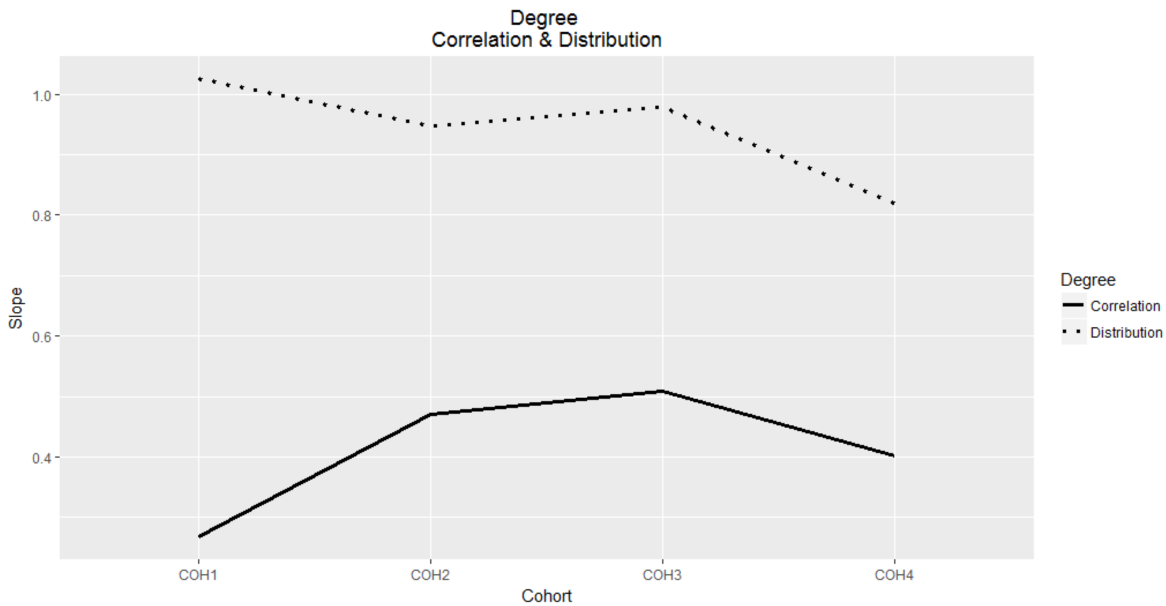


2.5. Identification of the evolving structural properties of *Aerospace Valley* Cluster

By designing collaborative incentives and selection routines of R&D consortia, cluster policy makers expect reaching their objectives related to better public knowledge dissemination, SMEs entries, global connectedness and technological diversification. But is the visible hand of the policy maker as dexterous as that of the juggler to repair network failures? A detailed analysis can help dealing with this question. It consists in discussing the degree-related structural properties of the network of places, in order to discuss whether or not the selection routines meet the policy makers' objectives.

5.1. Degree distribution (hierarchy), degree correlation (assortativity)

Figure 2.4: Degree distribution and correlation over time



If we stick to a pure structural level, the evolving properties of hierarchy and assortativity give a first overview of how the topological forms of the network of places have changed over the period. Figure 2.4 summarizes these evolutions. First, hierarchy, which is measured by the gradient of the degree distribution, remains high but has declined over the period with a slight increase from cohort 2 to 3. It means that the *Aerospace Valley* cluster is typified by a high but decreasing level of places centralization. Because places represent homogenous groups' relational behaviors, this high level of centralization indicates the coexistence between groups of organizations with different sizes of relational portfolio, from a couple a highly-connected organizations that collaborate with many others to poorly-connected organizations. But over the period, the influence and coordination capabilities of groups have been more distributed between a larger number of less central places. Second, the network of places is typified by a bell curve of degree correlation. It indicates a changing balance in the paths between highly and poorly-connected places and the organizations that belong to them. Indeed, highly-connected organizations in cohort 1 tend to collaborate more with poorly-connected organizations than in cohort 2 and cohort 3. This pattern shows that the network tends to be more and more assortative, with an increasing tendency of highly connected organizations to interact together. Nevertheless, the assortativity decreases in the last period, showing a reverse tendency. The most noteworthy is that hierarchy and assortativity play together in a different way from cohort 1 to cohort 2 and from cohort 3 to cohort 4. In the first period, the decreasing hierarchy goes with an increasing assortativity, signifying that a more distributed influence in the network has engendered more paths between places that have close degree. But this is not the case in the last period, in which the influence has been more and more distributed in the network, but this time with an increasing tendency of highly and poorly-connected places to interact together.

2.5.2. Connectedness and p-cohesive blocks modeling

This result invites to go more in depth into these structural properties in order to have a better understanding of the drivers of these changes. The idea is to highlight, in the line of Moody and White (2003) methodological proposal, how places connect together in a nested system of cohesive blocks and form a multiconnected network (Powell *et al.*, 2005). A close method relying on the *k-core* notion has also been implemented by Breschi and Cusmano (2004) to extract in the very large European network of public-funded R&D consortia the areas of the network where interaction among actors is particularly intense. In our case, for each cohort, we extract the number of *p*-cohesive blocks. A cohesive block is a component defined as a subset of the network where the associated value of connectivity *p* gives the strength of cohesion of the block. The value *p* is then the maximal number of places in the subset, above which the block cohesion disappears. Strongest cohesive blocks are cliques, i.e. those in which every place is directly connected to every other place. Therefore, we can characterize the network by a hierarchical nesting of cohesive blocks. The process consists in finding by iteration a maximal number *q* of *p*-cohesive blocks, with $q > p$. Once these blocks identified, their rank-size distribution offers a relevant means to assess the “multilevel embeddedness” (*nestedness* in the terminology of Moody and White) of places in the overall network. This rank-size distribution offers a relevant means to both identify cohesive blocks and order them according to both nested and fragmented groups. Indeed, cohesive blocks can overlap when places belong to multiple groups. The more cohesive blocks overlap, the more they bring closer in the distribution. Therefore, the shape of the distribution offers a relevant way to observe how high and low-value cohesive blocks connect together, and then how hierarchy and assortativity play together in the overall structure of knowledge flows.

Figure 2.5: The construction process of the p-cohesive blocks of the cohort 1

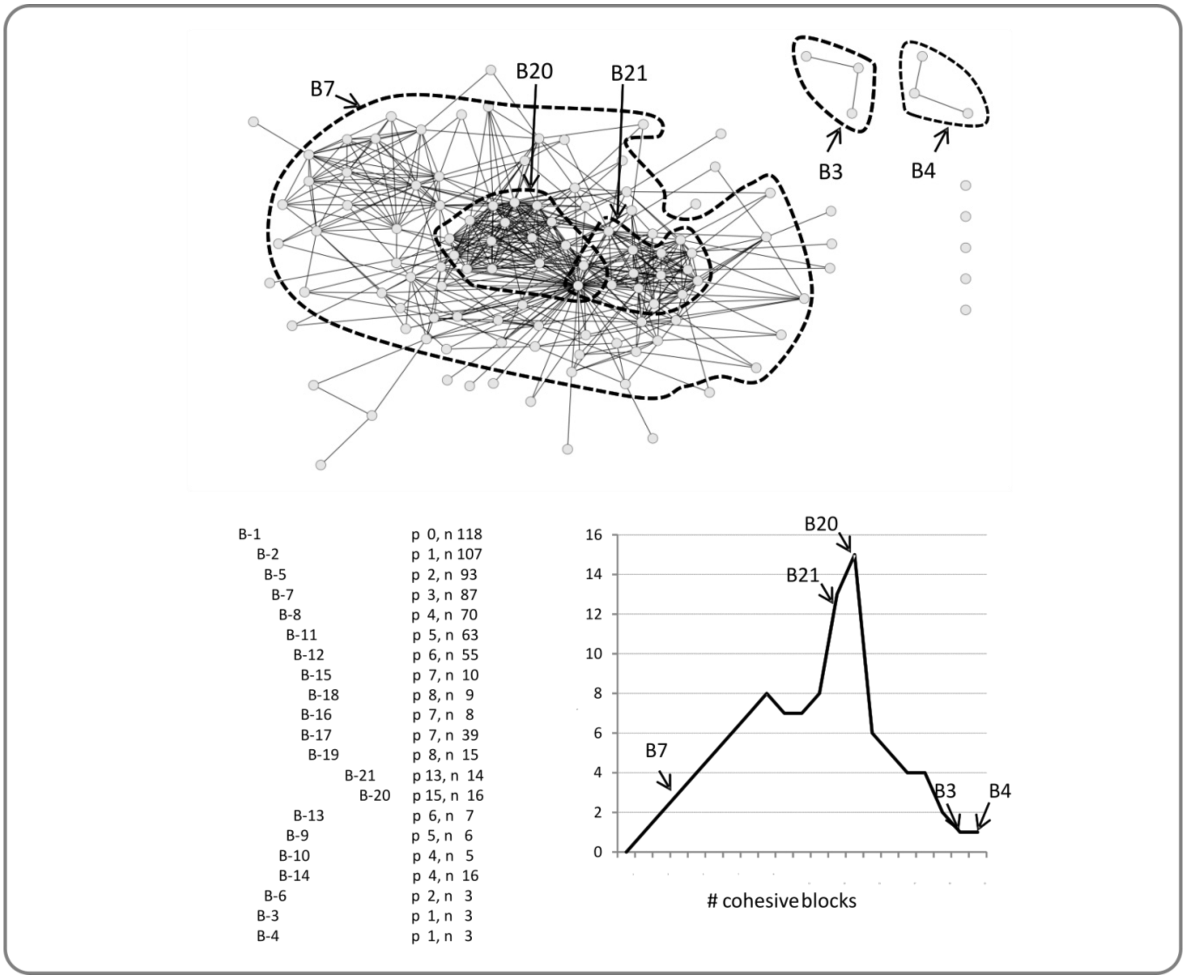
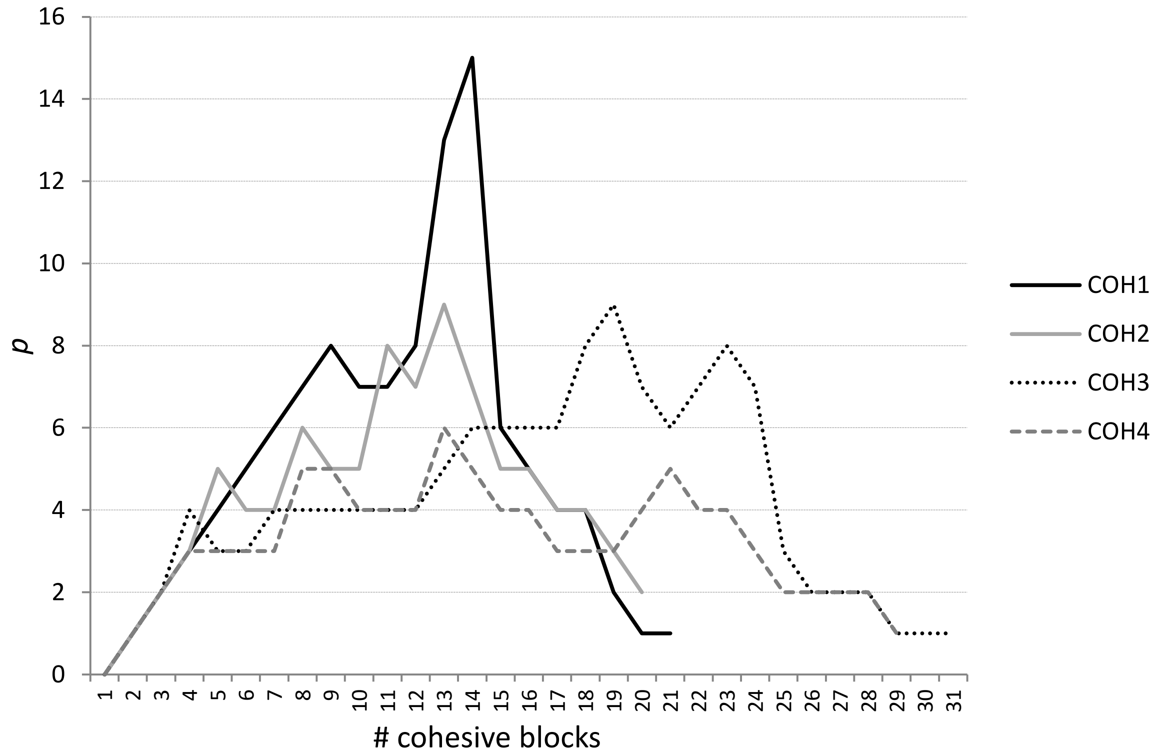


Figure 2.5 describes the construction of the *p*-cohesive blocks and the iteration process offering the nested and hierarchical system of *p*-cohesive blocks for the cohort 1. For instance, the block B-1 is a *0*-cohesive block representing the entire network. The value is *0* since no place is able to give a cohesive structure. The block B-7 is one of the subset of B-1 defined as a *3*-cohesive block in which at least 3 places offer cohesion in a subset of 87 places. The iteration process goes on until B-20, which is the cohesive block having the highest value of cohesion. And finally, other cohesive blocks with a decreasing *p*-value are extracted from the part of the network that does not include subsets of the previous ones. The shape of the distribution displays two close peaks, i.e. two highly-cohesive blocks (B-21 and B-20). In this cohort, these two strongest cohesive blocks overlap since two central places belong to both, explaining why they are ranked one after the other in the

distribution. Therefore, for cohort 1, the distribution shows the high level of centralization of the network and the weakly-distributed control of knowledge flows.

Figure 2.6: p-cohesive blocks (4 cohorts)



We repeat this process of nested construction of *p*-cohesive blocks for the four cohorts. Results are summarized by the four distributions in the Figure 2.6. From cohort 1 to cohort 4, the maximal *p*-value decreases while the number of blocks increases. This observation confirms the previously-observed decreasing hierarchy over the period, but also shows that the tendency of closure between leading places decreases as well, explaining why the number of "pockets" of influence increases in the overall network. This finding supports the idea of a more distributed influence in the coordination of R&D activities over the period and a gradual shift in the balance between closure and bridging that can better explain why in the last period hierarchy decreases at the same time than assortativity. Indeed, one can observe on Figure 2.6 that when the higher *p*-values decrease over the period, the "distance" between peaks in the distribution increases, which shows that the blocks with the highest cohesion are less and less closely interconnected by other highly-connected places. This finding shows that more poorly-connected places bridge highly-cohesive groups, explaining the decreasing level of assortativity and a better connection between highly and loosely-connected places.

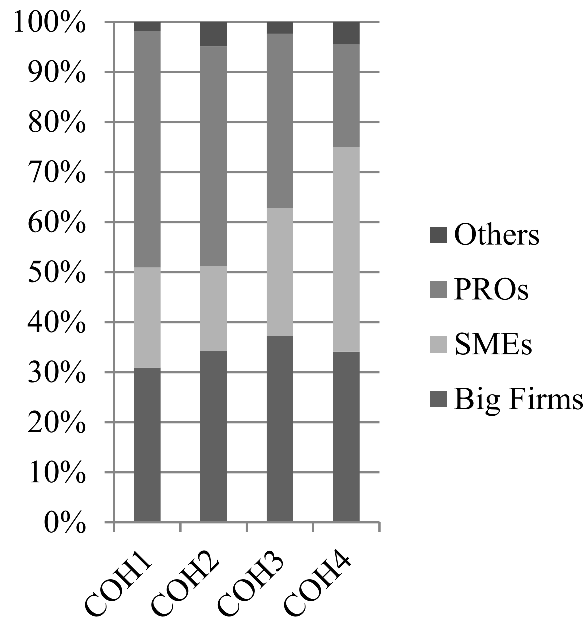
2.6. Discussion of the findings

Turning these findings into more qualitative readings related to the role of public collaborative incentives on the cluster structural change is a challenging question. As evidenced above, the network structure has changed over time, from a highly-concentrated to a more distributed structure of dominant cohesive blocks of places. The balance between closure and bridging has changed over the period, and organizations seem to have reoriented their collaboration pattern toward more path-breaking and less assortative relational behaviours. A suited solution consists in looking at the organizational demography of places. In doing that, the composition of places and how it evolves over time can allow identifying who the agents of structural change actually are.

2.6.1. The changing structural role of SMEs

A first way to assess the changing structural properties of *Aerospace Valley* is to focus on the so-called elite component (Powell *et al.*, 2005) of the 4-cohort networks. The elite component is composed by the places belonging to the two highest *p*-cohesive blocks. This elite component corresponds to the peaks of the multi-component distribution. Figure 2.7 provides simple statistics of this component and how its demography evolves over time.

Figure 2.7: The elite component of the Aerospace Valley network



The first observation, as regards the organizational demography of the whole network (see Figure 2.1), reveals that the compared shares of each organizational category in the whole network and in the elite one evolve according to a particular pattern. For big companies, as expected, due to their intrinsic high relational capabilities, their presence in the elite network is largely superior to their presence in the entire network, but slightly decreases in the fourth period. SMEs at the reverse are less proportionally present in the elite network than in the entire one in the first two periods, then they start to fill the gap during the third one, and finally succeed in reversing the pattern during the fourth one, with a presence in the elite network slightly superior as regards the entire network. Considering that the extent of relational portfolio is generally strongly correlated to the organization size, this pattern raises the question not only of the SMEs entries, but also the question of their evolving structural role in the cluster. Finally, becoming a victim of the fast growing entry of SMEs in the elite network, the share of public research organizations decreased over the two last periods.

How to explain such a structural pattern? A first trivial answer relies on the fact that policy makers have offered stronger incentives to involve SMEs in consortia. These incentives have produced visible and not surprising effects on the fourth period, with a jump in the number of SMEs involved in the entire network. But this answer does not suffice to explain why SMEs have succeeded in entering more than proportionally the higher *p*-cohesive blocks, which was a neither intentional nor possible objective from policy makers.

The decreasing values of *p* and the changing distribution of *p*-cohesive blocks over the period find explanations in the relational capabilities and behaviors of SMEs as regards big companies. By entering step by step the elite network, SMEs have changed the pattern of the more central cohesive groups. First, SMEs being more constrained in the extent of their relational portfolio than big companies (Street and Cameron, 2007), the network hierarchy has decreased, giving rise to a core of the network less and less focused on a couple of highly-connected monopolistic companies. From the start to the end of the period, SMEs have progressively reinforced their role in the connectedness and cohesiveness of the network, being less and less peripheral, and more involved in the overall coordination of technological dynamics. Their stronger presence in the highest cohesive groups, where triadic closure is higher than elsewhere in the network, shows that they are not only purveyors of fresh knowledge at the margin. At the reverse, they increasingly tend to attend the design of technological standards that drive the future market exploitation. Second, SMEs displays an alternate pattern of collaborations as regards big companies. Literature in Geography of Innovation has shown in an early stage that SMEs and big companies to some extent differ in terms of innovation strategies. Audretsch and Lehman (2005) have evidenced that nascent and big companies have different perceptions about the opportunities to turn knowledge exploration into markets. New entrepreneurs and R&D managers of long-established companies differ in their timorousness facing uncertainties and risks in market-oriented researches, the former being steadily less conformist than the latter. These consistent differences in innovation management also find their counterparts in the relational behaviors and strategies. Since they may be willing to absorb more risks than big companies managers, new entrepreneurs tend to favor weak ties over strong ones in order to explore new windows of opportunities. Considering the well-known inverted U-shaped relationship between tie strength and new knowledge creation (McFadyen and Cannella, 2004; Lowik *et al.*, 2012), these differences in relational behaviors might suggest that new firms are certainly more numerous on the left-hand side of the curve, while big companies monopolize a large part of its right-hand side. Therefore, between under and over-embeddedness, the evolving composition of elite places can explain why, as SMEs enter the elite part of the network, *p* decreases at the same time as the distance between the higher *p*-cohesive blocks increases. The tendency of SMEs to adopt bridging strategies over closure deconcentrates the nested systems of cohesive blocks observed when the elite groups were dominated by big companies, giving over time a more and more decentralized structure in the distribution of influential places.

To illustrate this dominant pattern of network evolution in Aerospace Valley, some examples can be provided. When we go in-depth in the database from cohort 1 to cohort 4, we observe the co-attendance of the main big incumbents of space and aircraft industry in several projects. For instance, over the cohort 1, Airbus and Thales are connected together in more than ten central projects focused on the traditional space and aircraft industry. If we add firms such as Snecma or Continental, we also find at least five projects in which the four companies are connected together. If we turn back to the network of places, the cohesive subgraphs identified as the "elite" (the pics) in the first cohort are mainly composed of these organizations. These projects affiliated to the "elite" can be considered as social and cognitive centers of the network, to the extent that they are in the confluence of the research activities, like unmissable "meeting points" in the cluster. If we invest the pics of the fourth cohort, several changes can be observed in the elite part of the network. As a matter of fact, the elite in the network of places consists of more subgraphs (the pics), which are more distant and involve more SMEs. These SMEs, partly marginally involved in the first cohorts and partly involved for the first time, are now connected in many projects but rarely together. At the reverse, they tend to connect unconnected parts of the network. For instance, Magellium and Airod Technologies are both prime contractors of at least three projects but only once together. In these projects different organizations are also involved and disseminated at different points of the network. These projects concern emerging markets such as drones for agriculture, observation devices and consoles for irrigation management and other transversal technologies using satellite positioning. This changing composition of the elite sheds light on how diversification and structural properties of knowledge networks work together, as it confirms the new organizational patterns observed by Wink (2010) in the aerospace industry. It also illustrates but not explains how spinoffs (Magellium, born in 2003, is a spinoff of Thales) matter for the endogenous development of clusters (Hervas-Oliver *et al.,* 2017).

2.6.2. Cluster/pipeline structure as a driver of diversification and less assortative knowledge networks

A second way to assess the changing structural properties of *Aerospace Valley* also consists in starting again by the demography of the network, but this time in relation with the inter-clustering dimension of selected R&D consortia. The public incentives to apply to multi-cluster projects, which have been implemented early after the initial policy guideline, have increased the extent of possible knowledge interactions for the organizations located in the *Aerospace Valley* area. The evolving structural properties of knowledge network probably find explanations in the way with which the different organizations of the cluster have benefited from these incentives.

Figure 2.8: Single & multi-granted projects and diversification

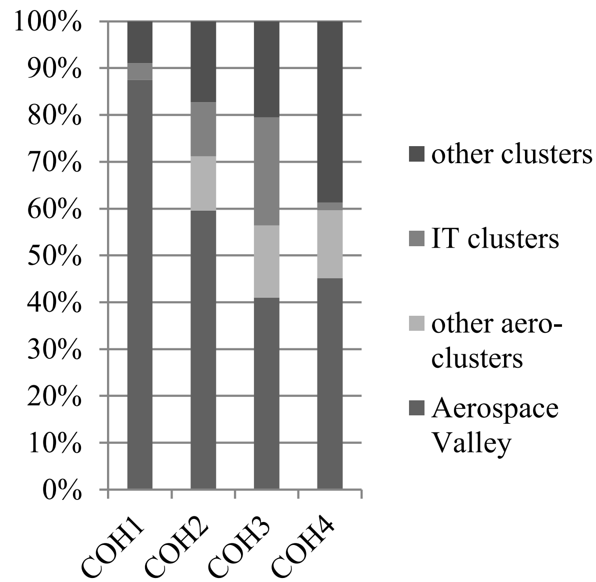
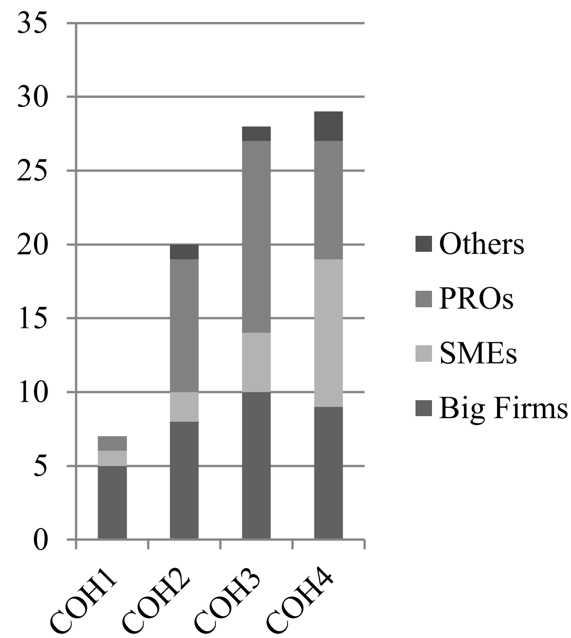


Figure 2.8 displays the shares between single and multi-granted collaborative projects over the period, taking into account that the shares between the organizations affiliated to the *Aerospace Valley* cluster and others affiliated in other clusters remain roughly stable over the period (see Figure 2.1 above). The more salient observation is related to the strongly-decreasing share of single-granted R&D consortia over time, with stabilization in the last period. Less than half of the projects are supported only by the cluster association, while the others are sustained by at least another French cluster. A small part concerns projects supported by other aerospace clusters, this part being stable over the three last cohorts. But the most noteworthy evolution is related to the growing technological diversification of the network. Firstly, we observe a growing share of collaborative projects conjointly supported by French IT clusters during the three first cohorts. These pipelines are typical of many clusters and industries that invest in digitalization. For *Aerospace Valley*, these pipelines mainly concern both embedded systems and space industries, around the development of GNSS (Global Navigation Satellite Systems), which require technological convergence between telecommunications and spatial data transmission (Vicente *et al.*, 2011). Secondly, the same occurs

for projects conjointly supported by other clusters specialized in many other industries, over time and with a particular growth during the last cohort. Therefore, knowledge pipelines also exist between different places and industries[7], and their recent development seems to be the sign of a structural change in the long-run technological dynamics of the cluster.

Figure 2.9: Organizations linking aerospace industry and other technological fields



How to explain the parallel between this growing technological diversification and the evolving structural properties of the network skeleton? Figure 2.9 allows understanding this changing pattern during the last period. Indeed, if we consider all the places of the 4-cohort network in which organizations connect at least two collaborative projects among which one of them is granted by a cluster out of the aeronautics and the IT industry, we observe that the share of SMEs has strongly increased from the three first periods to the last one. Here again, SMEs appear as the main agents of the cluster structural change, and not only at the topological level of the network, but also at the cognitive level. Their tendency to be less conformist than big companies in their search from partners is also reflected in their higher willingness to break the industrial frontiers. The decreasing assortativity of the network during the last period is then supported also by technological bridging and relatedness, increasing the potential of diversification over time. For instance, SMEs like M3

[7] 15 industrial sectors are listed by the French cluster policy, each cluster being affiliated to one of them.

Systems and Nexio, involved in R&D consortia since the start of the Aerospace Valley Program, have progressively changed their relational strategies. Mainly involved as simple participants in single-granted projects related to space industry from cohort 1 to cohort 3, these two small companies succeed in entering the core of the network as leading companies coordinating multi-granted projects on the emerging markets on navigation satellite systems. The project GEOTRANS-MD, in which M3 system is involved in cohort 4, has been certified by *Aerospace Valley* but also *Systematic*, the central cluster of Ile de France (Paris) specialized in automation and electronic systems. This project consisted in designing a standard applicable in the framework of the European legislation on the tracking of hazardous materials transport. The project LOCRAY, in which Nexio is involved in cohort 4 as prime contractor, has been certified by *Aerospace Valley* but also by *Systematic* and *Mov'eo*, the main French cluster specialized in new mobility and transport of the future. This project is dedicated to near-field measurements, electromagnetic compatibility and their compliance with EMC standards. Being still involved in local R&D consortia, these two small companies succeeded in acting as geographical gatekeepers (Morrison, 2008: Morrison *et al*., 2013), becoming central in the knowledge pipelines related to the emerging markets using satellite navigation or electronics as transversal technologies.

2.7. Conclusion

It is common in the literature to study the impact of cluster policies by capturing the output and input additionality effects. These effects generally require investigating the causality between the design of public incentives and the performance of treated organizations in terms of outputs (patents, exports ...) and inputs (R&D expenses, absorptive capabilities …), compared to non-treated organizations and after the treatment ends. The paper was aiming at dealing with another complementary but too weakly-explored challenge, related to the search for behavioral additionality effects in a particular public-supported cluster. We have investigated how the visible hand of cluster policy makers develops micro-incentives to shape knowledge networks, and linked the expected and unexpected changes in the macro-structure to the changing position and relational behavior of agents.

At the methodological level, searching from the structural properties of networks composed of R&D consortia has required avoiding the bias and overpassing the limitations of classical *1* and *2*-mode networks. The place-based network methodology has enabled us suggesting a new way to capture the evolving structure of the network skeleton, centered on a clear-cut identification of structurally-equivalent relational behaviors. This way to proceed has highlighted the evolving structural properties of the cluster over time. The evolving indexes of degree distribution and correlation show that the structure of knowledge interactions has changed over the period, from a highly-hierarchical structure, centralized around a couple of long-established oligopolistic companies, to a more democratic, less assortative, and multipolar structure of knowledge flows. The analysis of the evolving composition of places has allowed a better understanding of who the agents of the structural change actually are. Indeed, one of the salient findings relates to the continuing entries of SMEs in the elite part of the network, which has changed the relational behavior of the agents of the core-component of the network, with a stronger tendency to favor bridging strategies over closure, at the relational as well as the cognitive levels. If we follow previous theoretical (Rivera *et al*., 2010; Crespo *et al*., 2014) and empirical findings on the efficient properties of local knowledge networks (Uzzi and Spiro, 2005, Breschi and Lenzi, 2016; Crespo *et al*., 2016), this changing pattern in the *Aerospace Valley* network may involve the possibility of a more adaptive and innovative cluster. More unexpectedly, these findings do not converge with evidence found for geographically and institutionally larger networks. As a matter of fact, papers dealing with European collaborative programs (Framework Programs) tend to observe an ossification of networks and an increasing oligarchic structure of interaction (Breschi and Cusmano, 2004; Kang and Hwang, 2016). The hypothesis that can be made is then based on the nature of incentive schemes. As previously observed by Balland *et al.* (2013), the incentives underlying cluster policies at the regional level are based on exploration logic. The challenge at European level is quite different. Incentives are dominantly oriented towards technological exploitation, and rely on the need to better integrate knowledge to produce dominant design for competitive global markets. Ossification and cohesion within the networks are therefore a coherent objective, even if the risks of lock-ins must be taken into account by the European institutions (Breschi and Malerba, 2009).

At the policy level, even if the contribution is restricted to a single-case study among the whole of clusters supported by the French policy, some lessons about the effects of public incentives can be drawn. At first glance, the broad objective of helping clusters to turn mature industry into diversified markets seems to have been achieved. Under the growing constraint to apply to inter-cluster projects, *Aerospace Valley* has reached a threshold in technological relatedness and transversality during the last period of the study. The cluster association staff has succeeded in nurturing fewer and fewer conformist collaborative projects, which have then been selected and granted at the national level. But did the local staff as well as the national experts actually control this new pattern of knowledge interactions? It is not sure. Or at least a part of this pattern has probably escaped them. Indeed, the growing incentives oriented to SMEs were originally merely dedicated to repair a network failure related to their difficulty to connect knowledge networks. For policy makers, nothing could have predicted that SMEs would enter the elite network more than the network *per se*, nor than they would have a stronger tendency to have non-assortative behaviors and capabilities to blur technological frontiers. Therefore, the visible hand of cluster policy makers does not control all the process that shapes the structural properties of knowledge networks. The changing pattern of *Aerospace Valley* network took a long time. SMEs were first relegated at the network periphery, without any significant role on the network structuring. After a while, they succeeded in positioning themselves in the elite part of the network, without any more public incentives, but with their own growing experience in the attendance at collaborative projects. In terms of cluster policy economic return, this growing experience is the mark of a positive effect of behavioral additionality. We succeed in partially capturing this effect. Indeed, by pushing large firms into collaborating with SMEs, the latter have gained a great deal of experience enabling them to better integrate the ecosystem and in return to succeed in establishing themselves as central actors able to take the leadership of projects. Without this initial impetus from policy makers, these opportunities to reach the elite part of the cluster could not have run for them. This leadership was not the aim of public incentives, so that it clearly results in behavioral additionality effect. However, we only partially shed light on this effect, as it would also require measuring the maintenance of links when funding expires, which remains on the agenda for future research.

But is the growing role of SMEs in the elite network de facto a loss of control by large firms? It may be a misleading question. Given that part of the SMEs result of spinoff process and local labor mobility, social networks of the incumbents' executives are not necessarily as far away as one can imagine. It is difficult to observe such a pattern when using data composed of organizations and not individuals. But one of the perspectives for a near future would be to couple the organizational network to the network of individuals, to see in the line of Audretsch and Lehman (2005) or Hervas-Oliver *et al*. (2017) how these leaders themselves promote the creation of new companies in order to absorb with them the risks of market diversification. Finally, an open question still remains, which also probably escapes the intentions of cluster policy makers. The pressures to increase the attendance of SMEs at projects have strongly evinced public research organizations from the elite network. It could weaken the cluster in the near future, limiting the diffusion of fundamental and explorative knowledge through the entire network, and the long run dynamics of the cluster.

References of the Chapter 2

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Chapter 3 – Do R&D diversification policies change the cognitive structure of knowledge networks? Evidence from France using a meso-structural approach

Abstract:

National authorities have implemented R&D diversification policies in order to foster the emergence of new topics, thus developing new markets and increasing the competitiveness and resilience of R&D systems. This work explores the effects of diversification – i.e., the combination of knowledge from different sectors of activity – on knowledge networks. It proposes a new methodology for the identification of network meso structures, aimed at improving the detection of their structure and of their main research topics. Using data on collaborative research projects from funding program FUI, we analyse 31 research networks by activity sectors and cohorts. We find that diversification incentives are actually associated to the emergence of well-integrated diversified topics. However, there is no evidence of an effect of these policies on the enlargement of knowledge networks' portfolios of topics. Additionally, the effect of diversification policies on the emergence of diversified topics is unequal across sectors. This suggests that more "surgical" measures (best suited to the technological nature or cycles of clusters and productive sectors) might actually be needed.

Keywords: R&D diversification policies; cross-sectoral collaboration; meso-structural analysis; knowledge network and communities; place-based methodology

JEL codes: D85; O25; O30

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3.1. Introduction

In order to improve the competitiveness and resilience of local and national innovation systems, R&D policies have supported inter-cluster/inter-regional collaborations (Oxford Research As, 2008). Among these policies, cross-sectoral incentives for collaboration have become central, because the combination of unrelated knowledge and technologies is considered as a source of innovation, providing new products and solutions, and thus improving competitiveness (Porter, 1998; Boschma and Frenken, 2012; Lämmer-Gamp *et al*., 2014). Hence, both local and national authorities have increasingly tended to fund R&D programs for collaborative projects targeting cross-sectoral collaborations among clusters' participants, with the aim of fostering the emergence of diversified research topics (Uyarra and Ramlogan, 2012; Broekel, 2015).

This important policy turn gives rise to a number of questions. Do cross-sectoral collaborations really generate new research topics? If so, do these new research topics enlarge existing portfolios? And do diversification policies equally impact all technological and knowledge systems?

The rise of diversification policies echoes research on the critical role of *relatedness* (Frenken *et al*., 2007; Hidalgo *et al*., 2007; Hidalgo *et al*., 2018). The principle of relatedness states that the emergence of new products, technologies, industries, or research topics depends on the productive and/or innovation resources that are already present in that geographic area. For example, mapping the U.S. "technology/knowledge space" using patent data, Kogler *et al*. (2013) show that cities are more likely to develop a technology class when they already have expertise in related technologies.

However, some scholars have pointed out that the link between relatedness and the emergence of new technologies and knowledge is not homogeneous. Concretely, the probability of successful emergence is higher when they are related to core or more cohesive parts of the technology/knowledge space (Boschma *et al*., 2014; Essletzbichler, 2015). Moreover, the diffusion of new topics for market changes contributing to systems' lifecycles requires interactions and overlaps between emerging and matures mature topics (Crespo *et al*., 2014; Crespo *et al*., 2016). In addition, the types of proximity existing among innovative actors do play a major role in shaping collaboration (Boschma, 2005; Bouba-Olga and Grossetti, 2008; Ozman, 2009), and an especially relevant role is played by cognitive proximity (Nooteboom *et al*., 2007). This is a central issue for cross-sectoral collaborations, where some distance among actors is implicit. Thus, the challenge of diversification lies in the integration of the new topics into innovation systems, which requires some relatedness and proximity to existing systems' technological and knowledge portfolios. However, few studies address the impact of policies on diversification processes. As pointed out by Mewes and Broekel (2020), there is a gap in the literature for what concerns the effects of R&D policies on (related) diversification.

One of the limitations of the research that has been conducted on the emergence of new technologies and knowledge stems from its adoption of a *micro* structural approach (based on pairwise relations). Since collaboration involves mainly project consortia, adopting a *meso* structural perspective (based on communities) would however be more relevant, as it would allow drawing new insights about the integration of new, cross-sectoral research topics into innovative systems. This is what this work endeavors to do. Its first contribution is to develop and test a novel method of community analysis for bipartite networks (as organization-project networks), where we combine the concepts of *structural equivalence* and *cohesion*. We first mobilize the “place-based methodology” (Pizarro, 2007) as a suited tool to build networks of communities of actors having structural equivalent positions, and then we apply to the resulting places’ network a “cohesive block” analysis (Moody and White, 2003) to obtain the structure of these communities. This process allows us to identify highly cohesive and overlapped communities, which we call “*peaks*”. We show that when this methodology is applied to data on collaborative projects, “peaks” can be interpreted as networks’ main research topics: this means that their identification provides the research topic portfolio of the system. The second contribution of this work is to explore empirically the effect of innovation policies on diversification processes – i.e., the effect of cross-sectoral collaborations on sectoral research topic portfolios. To do so, we use data from collaborative projects funded France’s national FUI program across the period 2006-2015 (18 calls for tender). We apply our methodology on a selection of 31 networks from this database, and explore the structure of communities. Cross-checking our results with qualitative information, we show that the way communities are structured does provide relevant information about the *micro* and *macro* cognitive structure of the innovation systems. Finally, we quantitatively explore the effect of public incentives for diversification on sectors’ research topic portfolios, which allows us drawing implications for the design of R&D policies

The remainder of the paper is organized as follows. In Section 3.2, we discuss the literature on diversification in R&D policies and the associated concepts of relatedness and proximity. In Section 3.3 we define communities and present our methodology for identifying and analysing their structure, and discuss the *micro* and *macro* implications of this *meso* approach. Section 3.4 presents our data, and explains how we construct knowledge networks on their basis. The results of our qualitative and quantitative analyses are presented in Section 3.5. Finally, Section 3.6 discusses our results, and draws some conclusions.

3.2. Literature review: innovation, cluster policies, and diversification

Since clusters are key components of national innovation systems, governments have increasingly implemented *cluster policies* to strengthen knowledge flows and collaborations in productive and innovative agglomerations (Vicente, 2018). Cluster policies often consist of local incentives schemes aimed at repairing network failures – viz., facilitating collaboration among actors who are poorly integrated into local dynamics (Maffioli *et al*., 2016; Vicente, 2020). Such incentives may include the creation of dedicated agencies, the implementation of support programs for the development and integration of stakeholders, and the funding of R&D activities, esp. collaborative projects among different types of actors (Uyarra and Ramlogan, 2012; Broekel, 2015). Although local institutions can implement local and specific policies, national institutions generally keep for themselves the task of establishing major lines of action as well as controlling the resources mobilized to fund monetary incentives. Thus, cluster management combines interests and tools both at the national and at the local level (Porter, 1998; Cooke, 2002; Brenner and Schlump, 2011).

A general aim of cluster policies is to couple and balance local cohesion with global exchange. On the one hand, *local cohesion* refers to the capacity of interaction across cluster participants, and has to do with the exchange of knowledge and resources. Cohesion implies forms of proximity between actors, which facilitates exchange and collaboration at different levels (Boschma, 2005; Bouba-Olga and Grossetti, 2008; Ozman, 2009). The optimal level of cohesion varies across clusters (depending, among other things, on their technological base and life cycle stage, see: Ter Wal and Boschma, 2011; Abbasiharofteh, 2020), and the literature suggests that too much cohesion can be as damaging as too little (Boschma 2005; Nooteboom *et al*., 2007; Molina-Morales *et al*., 2011). On the other hand, *global exchange* refers to the possibility or capacity to integrate knowledge and resources from outside the cluster. The incorporation of new knowledge resources, including from the outside, is essential in the innovation process (Ozman, 2009). A cohesive system without outside interactions may not be able to develop new knowledge, falling into a technological lock-in (Boschma, 2005; Ter Wal and Boschma, 2011). Therefore, the innovative performance of a cluster depends on the balance between its capacity to exchange and collaborate internally and its capacity to absorb new knowledge resources from outside (Giuliani and Bell, 2005; Ter Wal and Boschma, 2011).

To deal with *global exchange*, national authorities have encouraged inter-cluster interactions under two main respects: research coordination and diversification (Lämmer-Gamp *et al*., 2014). (i) *Research coordination* policies aim to develop and guide interactions among clusters with the same technological base – i.e., in the same sector of activity. This means managing key economic sectors both at the local and national level (Houel and Daunis, 2009), to coordinate exchanges and avoid redundant efforts. The rationale is to combine a technological lock-in with a geographical lock-out, where local cohesion within clusters is combined with global exchange across clusters of the same sector (Crespo *et al*., 2014). (ii) *Diversification* policies are cross-sectoral incentives aimed at supporting and guiding interactions across clusters from diverse activity sectors or technological fields. Diversification consists of combining knowledge and technologies that are usually unrelated with the goal of creating new products and services, and thus developing new or underdeveloped market niches (Powell *et al*., 2005; Hidalgo *et al*., 2007; Boschma and Frenken, 2012). At the local level, diversification is a suitable strategy to overcome technological cycles, avoid lock-in, and improve the cluster resilience against exogenous changes (Crespo, *et al*., 2014; Boschma, 2015; Content and Frenken, 2016; Abbasiharofteh, 2020). Additionally, since mature topics display too much inertia, diversification is an opportunity for less central or new entrant actors – as SMEs and public research organizations – to scale up their participation into the research system, thus capturing new niches (Powell *et al*., 2005; Coenen *et al*., 2015; Lucena-Piquero and Vicente, Chapter 2). The limits to diversification reside in the difficulties associated with cognitive (and sometimes geographical) distance in collaboration, as well as in the risks inherent to the exploration of new paths of development. R&D subsidies (esp. directed towards collaborative projects) can compensate for the risks of diversification and induce actors to explore new activities, so they are frequently (and often, successfully) employed to establish or strengthen relations between dissimilar actors from different regions (Mewes and Boekel, 2020).

As said, the emergence of a new knowledge or technology is conditioned by its integration into the innovation system. Thus, successful diversification requires some relatedness or overlap between new research topics and central/mature existing ones.[8] This means that a significant number of actors should be able to join and participate into the development of new topics. Consequently,

[8] Certainly, some cross-sectoral collaborations may represent individual successes (such as the development of a new product or new uses), but we consider that the main objective of these policies is to diversify the portfolios of topics of knowledge systems.

integration requires forms of proximity between new diversified topics and the rest of the knowledge network.

In research collaborations, *cognitive* or *technological* proximity (Nooteboom *et al*., 2007) plays a major role, since some closeness between actors' cognitive bases is necessary in order to communicate, understand, coordinate, absorb, and process new knowledge. However, other forms of proximity can also be relevant, like geographical proximity (Boschma, 2005), organizational proximity, or social proximity. *Organizational proximity* does not refer to the existence of a formal organization, but of a common space of relations for the organization of human activities; according to some scholars, this includes cognitive proximity (Gilly and Torre, 2000; Torre, 2009). Organizational proximity has two dimensions: *affiliation* (or adherence), which means the existence of some relational closeness determining the actors' potential to interact or undertake joint actions,[9] and *similarity*, which means the existence of a common reference space and knowledge. Finally, *social proximity* (Alba and Kadushin, 1976) refers to overlapping membership to social circles, reducing distance between actors[10]. Thus, the level of proximity required for research collaboration is not necessarily reflected at the *micro* level (i.e., by dyadic proximity between all pairs of actors involved in a project), but can more significantly be captured at the *meso* level.

Given that diversification policies (esp. the funding of cross-sectoral R&D projects) have a relevant place on national and local policymakers' agendas, it seems legitimate to ask whether these efforts really generate integrated research topics. Since research is a collective activity and integration is defined in terms of overlapping communities and topics, we propose to answer this question through a *meso* structural approach capturing the identification of integrated topics in knowledge networks.

[9] Under this respect, Gilly and Torre (2000) refer to several forms of interactions, including agent-agent relations, but also agent-innovation relations (collective innovation activities) and innovation-innovation relations (technological complementarities).

[10] Alba and Kadushin (1976) define a "social circle" as one actor's relational environment (which is treated as a set), and calculate proximity considering both the intersection and the union of social circles. In our conceptualization, we consider sets (collaborative projects) as social circles, and we keep the idea of overlap between sets as a form of proximity, regardless of the number of actors included in the overlap or the total number of actors involved in all sets.

3.3. Methodology: a meso-structural approach to the study of communities

3.3.1. Communities: Structural equivalence and cohesion

According to the *structural perspective* (Nadel, 1957), the features and dynamics of actors are determined by the positions they occupy in a relational network. Communities are *meso* structures that act at an intermediate level between *micro* and *macro* phenomena, and properties and dynamics that go beyond individual interactions emerge from them. In this work, we opt for a conceptualization of communities based on both structural equivalence and cohesion.

The concept of *structural equivalence* early appeared in the Social Network Analysis (SNA) literature. In short, every two actors are structurally equivalent if they connect in the very same way to the network (Lorrain and White, 1971). A structurally equivalent position can be occupied by one node if it has an unequal adjacent neighbourhood, or by several nodes if they share the same adjacent neighbourhood. This implies that several actors occupying the same position have access to the same relational resources and are under the same relational constraints – i.e., they share the same relational environment. In view of that, scholars have generally assumed that actors sharing the same position have similar behaviours, performance, identity, etc. (e.g. Burt, 1987; Gnyawali and Madhavan, 2001; Pizarro, 2007; Phelps *et al*., 2012). As a result, structurally equivalent actors can be seen as bearing redundant structural information, and structurally equivalent positions can be summarized as single nodes or blocks. On that basis, it is possible to construct "meta" networks whose nodes represent structurally equivalent positions condensing all redundant information, which allows obtaining the "skeleton" of the original network. Structural position networks, referred by some scholars as *block-networks* or *image-networks* (e.g. Doreian, 2009), provide a summary of network structure, and can be studied with the usual SNA metrics. These methodologies have long been applied in economics and other social sciences (e.g. Aarstad, *et al*., 2009; Pallotti and Lomi, 2011), including in the study of innovative systems (e.g. Walker *et al*., 1997; Stuart, 1998; Lucena-Piquero and Vicente, Chapter 2; Yang *et al*., 2019).

The concept of *cohesion* refers to the interconnection among actors of a set and can be easily appreciated by the number of nodes having to be removed to observe network fragmentation (Moody and White, 2003). In terms of interpretation cohesion is often associated to phenomena like access to resources (social capital), rules and norms, trust, identity, or constrains (Burt, 1987; Aarstad, *et al*., 2009; Smith-Doerr and Powell, 2005). Several methods have been developed for the study of cohesion via the identification of communities or subgroups in a network (Wasserman and Faust, 1994; Moody and White, 2003). In innovation studies, cohesion is mainly interpreted in terms of knowledge spillovers (Ahuja, 2000; Reagans and McEvily, 2003; Uzzi and Spiro, 2005; Molina-Morales *et al*., 2011). A common finding of this literature is that cohesion favours innovation, and is conditioned to some forms of proximity (Boschma, 2005; Nooteboom *et al*., 2007; Powell *et al*., 2005). In the next sub-section, we explain how we combine structural equivalence and cohesion for the study of communities in bipartite networks.

3.3.2. Places, blocks, and peaks: Revealing the topography of networks

We propose a combination of methodologies for the study of communities in bipartite knowledge networks. First, we apply the "place-based methodology" to obtain the network of structurally equivalent positions – the "skeleton" of the network. Second, we apply to the network of places the "cohesive blocks" method (also known as "k-components" method), to obtain the communities' structure. One of the outputs of this method is a graph where the communities' structure looks like a topographic map, and highly cohesive communities like "peaks" of the "mountains". For illustrative purposes, explanations are followed by a toy example. Additionally, the role of proximity and structural features are discussed for *micro*, *meso,* and *macro* levels.

3.3.2.1- Places[11]

R&D activities in industries take the form of collaborative projects, where actors collaborate to reach specific goals. In SNA these situations are conceptualized as bipartite networks (also known as affiliation networks or two-mode networks), where individuals are linked to sets by an affiliation relationship (see Figures 3.1a and 3.1b). Formally, elements of one population (individuals or sets) are linked to elements of the other population, but no link exists between elements of the same population (Wasserman and Faust, 1994). An example of bipartite network is an organization-project situation, where organizations are involved in one or several research projects.

[11] For expositional convenience, this section replicates the explanations of Sections 1.3.2 to 1.3.4 in Chapter 1.

Figure 3.1: Affiliation, bipartite network and one-mode projection

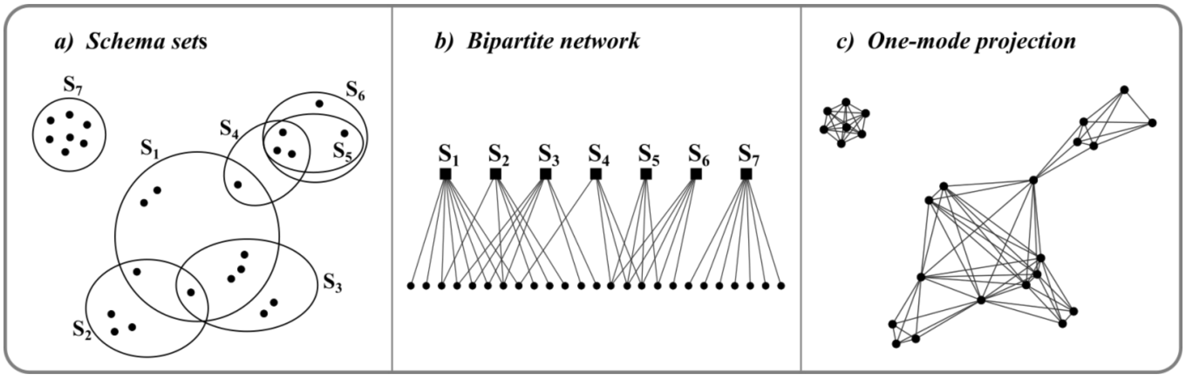


Figure 3.1a represents a situation of 25 actors/organizations (points or nodes) involved in 7 research projects (sets). Some actors are involved in just one project (as S7's actors), but other are involved in several projects - those at the projects' intersection. Figure 3.1b is a *bipartite network* depicting this situation. Each actor (points) is linked to the set(s) (squares) in which it is involved. Observe that no link exists between actors or between sets. Figure 3.1c is the *actor's network projection* of the bipartite network. Nodes represent actors, and two actors are linked by a tie if they belong to the same set. The clustering phenomenon is clearly observable in the case of the subgraph on the left, which correspond to the set S7. Here all actors involved on the project are linked together, forming a clique. In these projections, the degree of a node (the number of ties reaching the node) is the number of all other actors involved in the same projects.

Scholars do not usually analyse bipartite networks, but rather their projected networks. Breiger (1974) proposed to project bipartite networks into two one-mode networks (where all nodes are of the same type, or "mode"): 1) one network of individuals that are linked if they belong to the same sets, and 2) one network of sets that are linked if they share the same individuals (see Figure 3.1c). Projected networks are usually analysed using common SNA metrics.

One major problem associated to this methodology is the artificial clustering it generates (Newman *et al*., 2001; Uzzi and Spiro, 2005). In the projected network of individuals, all the individuals affiliated to a set are directly linked with one another, generating an artificial clustering effect that can disturb classical network metrics – mainly those based on degree and community detection – and can thus lead to misinterpretations. This problem increases as the range of sets' sizes (i.e., the number of individuals) widens.

To overcome this problem, we apply the “place-based methodology” (Pizarro, 2007) to obtain a network of structurally equivalent positions[12]. In bipartite networks, every two actors are structurally equivalent if they belong to the very same sets (Borgatti and Everett, 1992; Pizarro, 2007). Consequently, a bipartite network can be summarized by grouping structurally equivalent actors into single nodes (called “places”), thereby creating a bipartite network of places and sets. More formally, a bipartite network of places and sets is a network of structurally equivalent positions, where each node represents a unique combination of affiliations to the set mode. Figure 3.2a represents the bipartite network of places and sets from our example. All organizations participating into the same combination of projects are grouped into a place, because they occupy a structurally equivalent position.

Figure 3.2: Places’ network

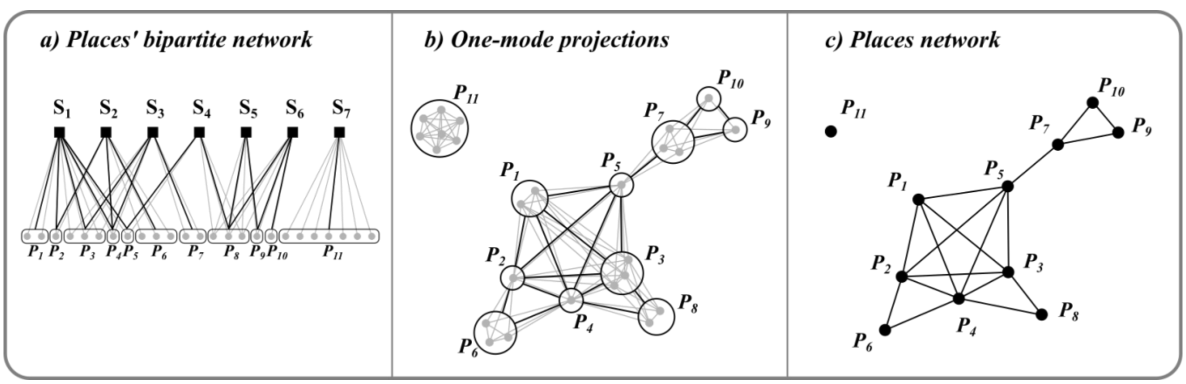


Figure 3.2a represents the *places’ bipartite network*. For illustrative purposes, this network is superposed on the original bipartite network (greyed out). Each place P_i corresponds to a unique combination of affiliations to sets (there is not two places linked to exactly to the same set(s)), and all the nodes in a place P_i are linked to the very same set(s). In Figure 3.2b the places’ network is superposed on the one-mode projection (greyed out) presented in Figure 3.1c. As we can see, structural equivalent actors occupy a place (circles in this graph), and they are linked in exactly the same way to the rest of the network. Likewise, links between places (circles) follows the links between structural equivalent positions. Thus, nodes and links of the one-mode network are summarized in the places’ network. Figure 3.2c represents the *places’ network* obtained from the bipartite network, where all the redundant or repetitive information of the one-mode network of Figure 3.1c is summarized. Here the degree is related to the number of unique combinations of affiliation to set(s), so the degree is a measure of the relational diversity.

[12] We computed places and places’ network with the R-package "Places: Structural Equivalence Analysis for Two-mode Networks" (Lucena-Piquero, D., 2017).

Since a network of places and sets is a bipartite network, we can project it and obtain a network of places linked by sets' memberships and a network of sets linked by common places. The first one corresponds to a network image of structurally equivalent positions. The network of places is a summary of the projection network of individuals, where all redundant information (individuals who are members of the same sets) is removed (see Figures 3.2b and 3.2c). Consequently, the artificial clustering problem is now solved. Indeed, in networks of places, the projections of sets do not form cliques (i.e., groups of nodes that are all linked to one another), because all structurally equivalent individuals are grouped in the same places. Affiliation to a set does not necessarily mean that the individuals within the set do actually interact with one another: for instance, in a paper co-authored by one hundred researchers, it is evident that no author will have exchanged or worked directly with all the others. The properties of this relation are the properties of the set: common knowledge or cognitive proximity, a similar behaviour (they worked on the subject of the paper), a common identity (they are the paper's authors), or even the same reputation effect (they are authors of this widely cited paper).

Similarly, in a network of organizations affiliated to research projects, organizations having contributed to the very same projects will be grouped into the same place: this does not mean that they have the same knowledge or skills, but rather that they have research capabilities or innovation resources that can lead to the same objectives, and that are necessary for the achievement of all the projects in which they are involved. In this sense, the organizations included in the same place contribute equally to the innovation system, and benefit from similar outputs (e.g. access to technologies, or reputation associated to projects' results). Thus, structurally equivalent actors combine the two dimensions of organizational proximity (that includes cognitive proximity), i.e. affiliation and similarity (Gilly and Torre, 2000). Consequently, in the network of places extracted from a knowledge network, nodes can be interpreted as unique combinations of innovation resources involved in common projects, which evidences their proximity.

3.3.2.2- Cohesive blocks

The second step of our analysis consists of the application of the "cohesive blocks" methodology to networks of places. Proposed by Moody and White (2003), this methodology reveals the nested hierarchical structure of the subsets (communities) of a network on the basis of the nodes' connectivity.[13] As in a topographic profile, the network is represented as nested slices of *k*-cohesive blocks, where *k* refers to the number of vertices that need to be removed in order for the subgraph to be disconnected. The highest value of *k* for a network corresponds to the most cohesive subgraph. Because it is a nested system, a *k*-block is integrated into a *bottom* (the parent block), where the members of the *k*-block are connected with a lower degree of connectivity to the members of its parent block. As we have argued before, in bipartite networks the use of cohesive blocks (like other cohesive measures based on connectivity or density) is not exempt from difficulties. The clustering associated to one-mode projections can lead to misinterpretations. However, the application of cohesive blocks to networks of places avoids this problem.

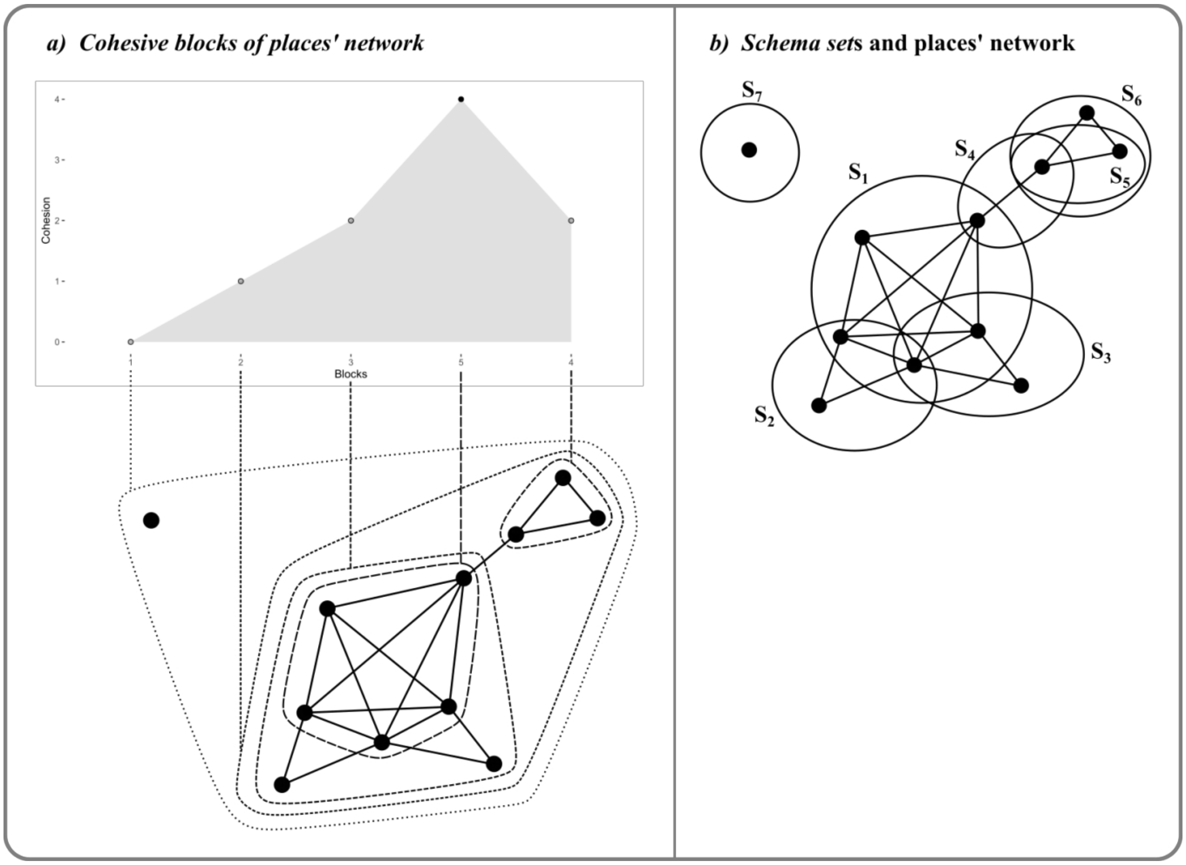
Previous works using the "cohesive blocks" method have focused on the most cohesive blocks of the net, called the "elites" (Powell *et al*., 2005; Lucena-Piquero and Vicente, Chapter 2). These blocks contain the most "influential" actors of the network, because they have a great coordination capacity: since this methodology provides a nested structure, the members of the most cohesive blocks are close to all the other actors of the network, thus forming its cores. While the study of "elites" provides important information about the *macro* structure of the network and its key actors, other communities with lower cohesion levels are not taken into consideration, although they can be relevant at the "local" structural level. In our study, we include both the blocks with the highest level of cohesion in the network and the blocks that show a higher level of cohesion within the sub-graphs in which they are hosted. We call these blocks the "peaks" of the network.

3.3.2.3- Peaks

We define "*peaks*" as blocks that are cliques and that have a higher cohesion than the other possible blocks hosted in the same bottom. More formally, a peak is an *l-block* hosted in a *k-block*, where (a) the peak is a complete subgraph (a clique), (b) there are no blocks hosted in the peak, and (c) and $l > j > k$, being *j* the minimum cohesion level possible for blocks hosted in the *k-block*. We also identify as peaks all the blocks with the maximal cohesion level of the network. In short, a peak is a community that shows a higher level of cohesion than its immediate environment. Additionally, we consider that a peak must have a cohesion level equal or higher than 3, which implies that the peak must have more than four nodes.

[13] For the cohesive blocks analysis we use the R-module Igraph, "The Igraph software package for complex network research" (Csardi and Nepusz, 2006).

Figure 3.3: Cohesive blocks of places' network



The result of the cohesive block analysis of the places' network is represented in Figure 3.3a. The graph on the top is the output of the analysis, where blocks are represented by dots on the x axis and the y value is the cohesion level of the block. On the bottom, we have drawn the blocks from the places' network. *Block 5* is the most cohesive block of the net, and it is a peak (dot in black). Its cohesion level is 4, and it has 5 nodes which form a clique. *Block 4* also forms a clique, but its cohesion level is 2, so it is not considered as a peak. *Block 5* is hosted in *block 3*, which has a cohesion level of 2 and 7 nodes. In turn *blocks 5*, *4*, and *3* are hosted in block *2*, which has a cohesion level of 1 and 11 nodes. *Block 1* contains the entire network, and its cohesion level is 0 because the graph is not fully connected. In Figure 3.3b, we have overlapped the sets' diagram with the places' network. Note that each set(s) combination is occupied by one node, a place. The comparison between the cohesive block structure of Figure 3.3a and Figure 3.3b reveals that set *S1* is responsible for the cohesion of *block 5*, which is a peak. Additionally, the peak is at the intersection between *S1* and sets *S2*, *S3*, and *S4*.

The combination of the two methodologies (places and cohesive blocks) allows capturing some interesting structural phenomena associated to the overlap of sets and the connectivity among actors. We shall argue that these have relevant implications if interpreted in terms of proximity and relatedness. But before doing so, we need to introduce another concept, the "peak's main project(s)", which connects the *micro* and *macro* levels.

3.3.3. Micro and macro properties of the network

At the *micro* level, since a peak is a clique, there is at least one set responsible for the connectivity of the peak (it connects every actor of the peak). This the "peak's main set", or (in our application to collaborative projects) the "*peak's main project(s)*".[14] Other projects can contribute to the connectivity of the peak, but a peak's main project(s) is common to all the actors of the peak. Besides, there are projects that overlap with the peak's main project(s), thus being responsible for the connectivity between the peak and other nodes in bottom blocks. A node at the intersection between the peak's main project(s) and other project(s) is a place occupied by at least one actor involved in all these projects. In terms of interpretation, a peak's main project can therefore be seen as the combination of the innovation resources also required in other projects (those that connect the nodes in the peak to other nodes in bottom blocks) – meaning that there is some degree of *relatedness* between the peak's main project(s) and the other projects. As for *proximity*, all actors of a peak are close to one another, since they share the research subject and goals of the peak's main project(s); projects overlapping with the peak's main project(s) are close to this one since they share innovation resources; and since a peak is at the top of a nested system, its nodes are close to many other nodes from bottom blocks – meaning that the peak's main project(s) share(s) innovation resources that are also close to these involved in many other projects at bottom blocks. From this it follows that peaks' main projects are projects that are well-integrated into the knowledge network projects, as they are related and (cognitively) close to most other projects. This is well visible in Figures 3.3a and 3.3b: *block 5* is the only peak of the network, and *S1* can be identified as its main project because it is responsible for the connectivity inside the peak, and all actors in the peak are involved into it. Project *S1* overlaps with projects *S2*, *S3*, and *S4*, which connect the nodes in the peak' main project directly to nodes in *blocks 3* and *4*, and indirectly to the rest of the nodes in *block 2*. Furthermore, a "diversified peak" is a peak whose main project(s) is cross-sectorial.

All this allows us to infer that the subjects present in the peaks' main projects must be representative of the subjects present on bottom blocks. Consequently, we consider the subjects of the peaks' main projects as main research *topics* of the knowledge network. However, two caveats are of order. The first one is that other forms of proximity than cognitive proximity can play a major role in determining the main research topics of a system. For example, in a sectoral knowledge network with several peaks (so, several main topics), two structurally distant peaks can be very cognitively close, as other forms of proximity (esp. geographic proximity) can strongly impact the

[14] Usually in our dataset there is only one peak's main project, but for generalization purposes we do not exclude the possibility that several peak's main projects may exist.

configuration of communities, thus generating some research redundancy in the system. The second caveat is that not all peaks have the same importance for the network in terms of closeness, influence, or coordination capacity. The importance of a peak depends on (a) its relative cohesion level (with regard to bottom blocks which also host other communities), and (b) the number of peaks hosted in a common parent block. Thus, a unique highly cohesive peak will be more relevant for the network than a relatively lowly cohesive peak which is hosted in a bottom block with many other peaks.

At the *macro* level, the communities' structure provides relevant information about some properties such as the hierarchy, the disassortativity.[15] These properties reveal whether one or several small subsets of actors which are better connected to the rest of the network than the other nodes. For some networks, as in production and innovation clusters, a significant level of hierarchy can be associated to the level of maturity of the system (Crespo *et al*., 2014; Suire and Vicente, 2014; Crespo *et al*., 2016; Abbasiharofteh, 2020). Actors in the well-connected subset and those that are close to them (usually local big firms) can adsorb knowledge from the periphery or poorly connected parts of the network, and also have the capacity to influence and coordinate production in the system (Verspagen and Duysters, 2004; Crespo *et al*., 2016;). However, hierarchical systems are at risk of lock-in (Ter Wal and Boschma, 2011; Crespo *et al*., 2014; Boschma, 2015). The study of communities' nested structure provides information about the level of hierarchy and the presence of relevant well-connected subsets of actor (cores) that influence, coordinate, and guide the network's activities. Thus, the number of peaks of a network as well as their cohesive level reveals information about the hierarchy, the assortativity, and the core(s)-periphery structure. For example, a large network with only one high cohesive peak can be considered as hierarchical and disassortative, thus with a core-periphery structure. On the contrary, a network with several low-cohesive peaks can be considered as low-hierarchical, assortative, and multi-cored.

In sum, applied to bipartite knowledge networks, our methodology can provide relevant information about the *micro* relational dynamics among organizations and the *macro* structural properties of the network. In the next section, we move on to apply this methodology to our dataset.

[15] *Hierarchy* refers to the distribution of the nodes' degree in a network: a network is hierarchical if a small number of actors have a significantly higher degree than most actors in the network. *Disssortativity* is a measure of similarity usually based on node degree correlation: a network is disassortative if nodes tend to be connected to actors with a very different degree.

3.4. Data: France's FUI program for the funding of cluster activities

As many countries around the World, France has developed specific policies in order to foster the development of local productive and innovative clusters. In 2005, the French government launched the "Pôles de competitivité" policy (Fontagné et al. 2013). The *pôles* are local associations aimed at guiding industrial clusters, improving their competitiveness, and managing spillovers across local actors. The *pôles* can develop their own actions and provide support to local development through various tools, including direct funding or access to national funding programs (Brossard and Moussa, 2014). The main national funding program for clusters is the FUI[16] program, which supports collaborative R&D projects. To access funding, consortia must be certified by at least one *pôle de competitivité*. Through the project selection process, national authorities can thus implement major policy lines impacting both the local (*pôle*) level and the national one (Uyarra and Ramlogan, 2012; Lucena-Piquero and Vicente, Chapter 2).

Since 2005, national cluster policy has been shaped around four major guidelines: two of these are aimed at including actors (like public research organizations and SMEs into the R&D activity of the *pôles*, while the other two are aimed at fostering collaborations across clusters. The first of these last two guidelines aims to foster collaboration across clusters in the same sector of activity, in order to coordinate and give coherence to research at the national level, while the second one to foster collaborations across clusters in different sectors of activity, in order to diversify research and stimulate technical change within clusters.

Here, we focus on the last two policies and we use the sectors as aggregated units of reference. For the period 2006-2015, the official classification used by French government includes 14 sectors of activity, and each *pôle* is associated with at least one of these sectors. Our data gather all the projects funded by the FUI program during 2006-2015 (18 calls for tender). This dataset include 1,408 funded projects and 6,826 actors (identified by the SIRET code in the French industry classification). For each project, we have the name and the sectors of activity of the *pôles* that certified it.

In order to reconstruct French knowledge networks from this dataset, we class data by cohorts and sectors. Concerning cohorts, we split the ten-year period into 4 subperiods that are broadly similar in terms of time and number of projects. Concerning sectors of activity, the French government associated sectors to poles, but not to projects. Therefore, we develop a procedure to classify each

[16] *Fonds Unique Interministériel.*

project by sector(s). For this, we use the government's sectoral classification of the pôle(s) certifying the project and the NAF codes[17] of the actors involved in the project. We double-check this with information on the subjects of projects whenever available from the Internet. Using this classification, we end up with 1,002 mono-sectoral projects and 406 cross-sectoral projects. Table 3.1 provides information on each of the sectors by cohort.[18]

Table 3.1: Distribution of projects by sector-cohort networks

Sectors	# Projects Cohort 1	# Projects Cohort 2	# Projects Cohort 3	# Projects Cohort 4
Aerospace	32	44	41	45
Agriculture/Agri-food	26	33	31	40
Consumer Goods	6	6	12	11
Bioresources	4	6	11	15
Biotechnology / Health	33	37	46	37
Chemistry	2	6	9	15
Ecotechnologies / Environment	8	13	26	31
Energy	13	25	33	47
Engineering / Services	10	22	39	45
Materials	19	44	51	71
Microtechnology / Mechanics	13	33	45	69
Optics / Photonics	6	13	11	16
ICT	101	115	131	151
Transports	41	58	43	40

Crossing our 4 cohorts with our 14 sectors, we construct 56 networks. In order to avoid inaccuracies, however, we remove all small networks – i.e., all networks (25) including less than 25 projects and less than 40 places (nodes). We therefore end up with a selection of 31 networks, which we use for the empirical analysis.

[17] The *Nomenclature d'Activité Française* or NAF code is a French codification system for economic and social actors. The code has a tree system, and we have used the digit-3 level for this process, which contains 272 classes. Our database contains actors in 225 of these classes.

[18] Note that each cross-sectorial project is counted in each of its sectors.

3.5. Analysis and results

3.5.1. Qualitative analysis of the sectors

In this section, we present a small selection of the cases (networks) that we have submitted to a mixed quantitative/qualitative analysis,[19] in order to show the *micro* and *macro* properties unveiled by our *meso* structural methodology. First, we describe one selected network – "Transports sector" for cohort 1 – and provide some details about its *micro* and *macro* relational and cognitive structure. Second, we describe the evolution of this sector across the 4 cohorts. Third, we briefly present three other relevant cases in order to highlight the diversity of structures of our sample. Finally, we discuss some observed phenomena regarding the identification of research topics.

The network "Transports for cohort 1" is constituted by 242 organizations involved in 41 projects. Applying the methodology described in Section 3.3, we obtain a network of 90 places structured in 18 cohesive blocks, where the highest cohesion level is 10. In this case, 3 peaks have been identified, and an interesting feature is that the two most cohesive peaks are close to each other, sharing the same parent block.

Figure 3.4: Transports – Cohort 1: Cohesive block structure

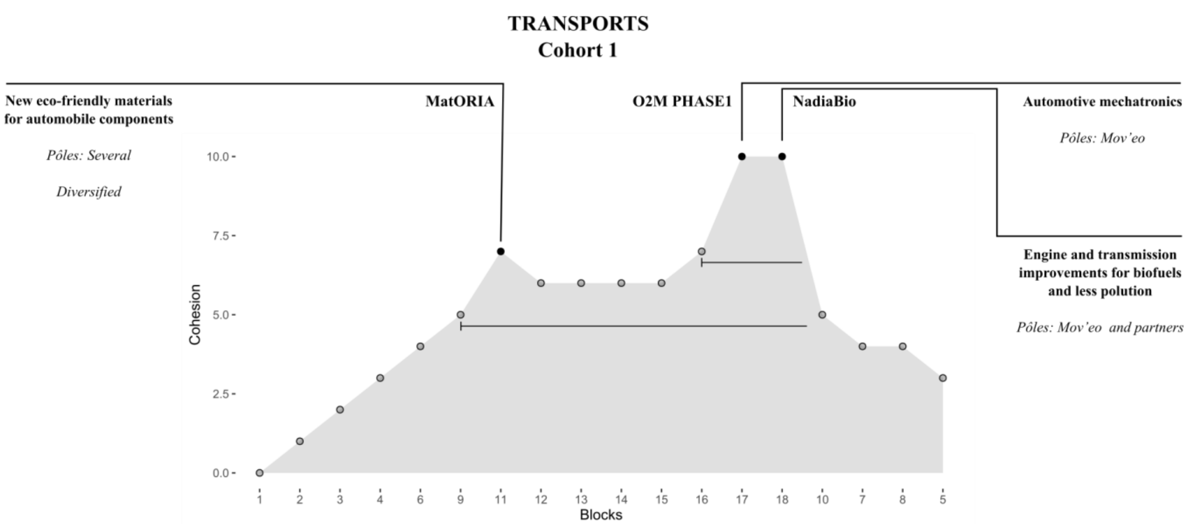


Figure 3.4 shows the cohesive block structure. Blocks are identified on the x axis, and the y gives their cohesion level. Peaks are identified by black dots. For each peak, the peak's main project(s) is noted. A short

[19] In order to verify and validate the proposed methodology, we have actually analyzed a large number of networks. The analysis of other networks is available under request.

description of the main topic and the poles involved is available on the side of the chart. In order to highlight the parent blocks we have drawn lines inside the chart, such that all blocks above a line are hosted in the concerned block.

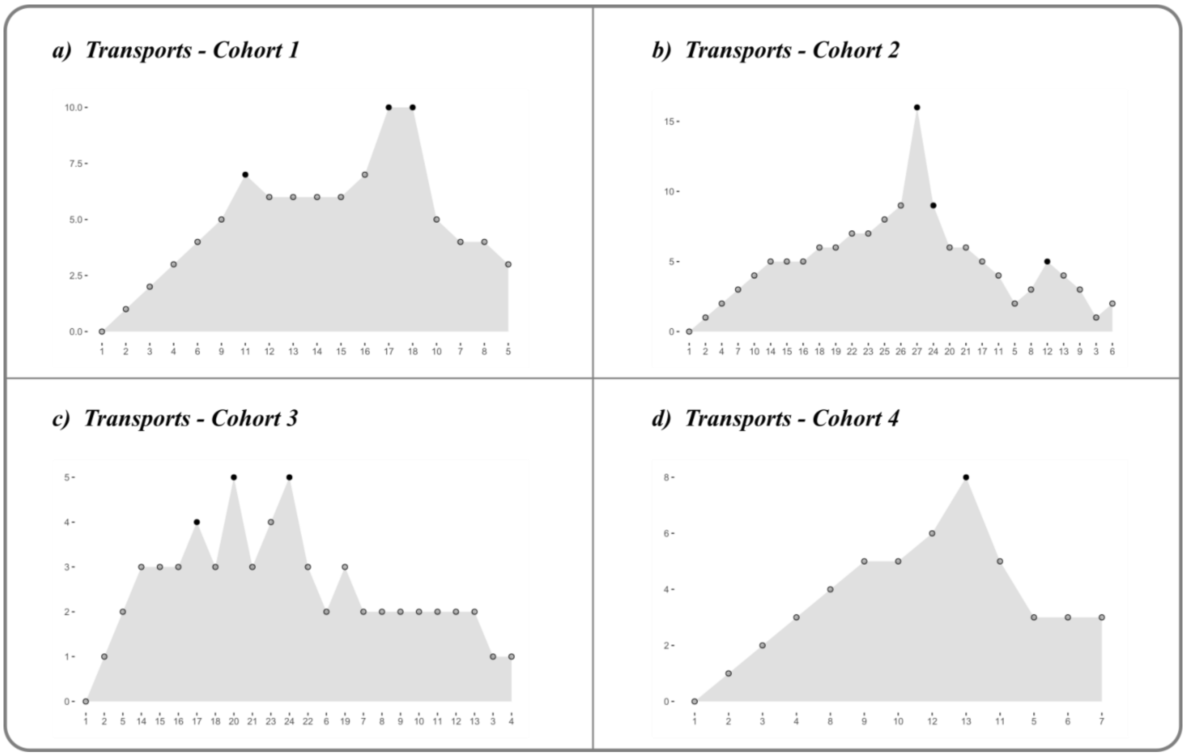
To describe some *micro* structural and cognitive properties of the network, it is convenient to focus on peak 18. This peak has a cohesion level of 10 and is composed by 11 places. The peak's main project is *NadiaBio*, which is focused on the development of engines for biofuels. This project is responsible for the internal connectivity of the peak since all the 11 places are involved in it. Among the 15 organizations involved in *NadiaBio*, 5 participate only into this project, so they are grouped into one single place. The 10 other places are composed by single organizations involved into the peak's main project as well as other ones. For example, one of these places is a public research lab (IFP in Rueil-Malmaison) which is involved in the projects *NadiaBio*, *BioCarbMat*, *Flex Fuel 3G*, *HYHIL* and *SIMBA*. In terms of proximity, these 5 projects are close since they all need the innovation resources provided by this lab.

The places in a peak are connected to those in the bottom block by projects that overlap with the peak's main project, and in some cases these projects contribute to the connectivity of the peak (see Figure 3.3a). The project *NadiaBio* overlaps with other 15 projects. Most of them have subjects that are clearly cognitively close to *NadiaBio*,[20] and are also certified by the pôle *Mov'eo* (located in the Normandy and Île-de-France regions), which suggests the existence of other forms of proximities (esp. geographic). Therefore, a detailed analysis of the projects and their overlaps on the nested systems shows that peaks' main projects' subjects are representative of their relational environment and can be considered as main topics of the network. Similarly, peaks' main projects are usually certified by the same pôle(s). The analysis also confirms that the differences in the structural properties of peaks correspond to the ones in cognitive and/or pole(s)'s affiliation. The three peaks in Figure 3.4 correspond to well-differentiated main topics: "mechatronics",i.e. engineering for both electrical and mechanical systems (peak 17); improvements in engine and transmission to reduce pollution (peak 18); and eco-friendly materials for automobile components (peak 11). As it can be seen, the topics of peaks 17 and 18 are cognitively similar since these peaks are structurally close, while the topic of peak 11 is more different since it is structurally more distant. We must add that

[20] As *EGRBoost* (improvement of EGR valve for less pollution), *REDNOX* (pollution reduction catalyst), *BioCarbMat* (materials for biofuel engines), *HYHIL* (Engine bench software for hybrid vehicles), *Flex Fuel 3G* (Engines for biofuels) or *SIMBA* (Simulation of airflow in engines). All data concerning places, peaks, and blocks composition is available under request.

the peak 11 is a diversified peak, and consequently a diversified topic – its main project (*MatORIA*) is also certified by a Materials' pôle (*Plastipolis*, located in Rhône-Alpes region).

Figure 3.5: Evolution of the sector Transports



The evolution of the sector "Transports" over the cohorts (Figure 3.5) offer some interesting information about the changes and the coherence in this sector's R&D.[21] The number of projects over the 4 cohorts is similar, but diversification (i.e. the proportion of cross-sectoral projects) is increasing over time. Concerning the evolution of the main research topics, in cohort 2 the mechatronics topic remains central (and the main certificating pôle is still *Mov'eo*), but now the topic is diversified. This is because the main project is focused on the development of a software platform (so a strong inclusion of ICT technologies). A second main topic concerns the visibility for vehicles and roads, with a strong role of embedded systems. Once again, the topic is diversified since projects involve actors and pôles from ICT sector. Finally, the third main topic, also diversified but located in a less cohesive peak, is about ship energy efficiency. Here, cross-sectoral

[21] However, the changes or continuities in R&D should not be confused with the productive evolution of the sector.

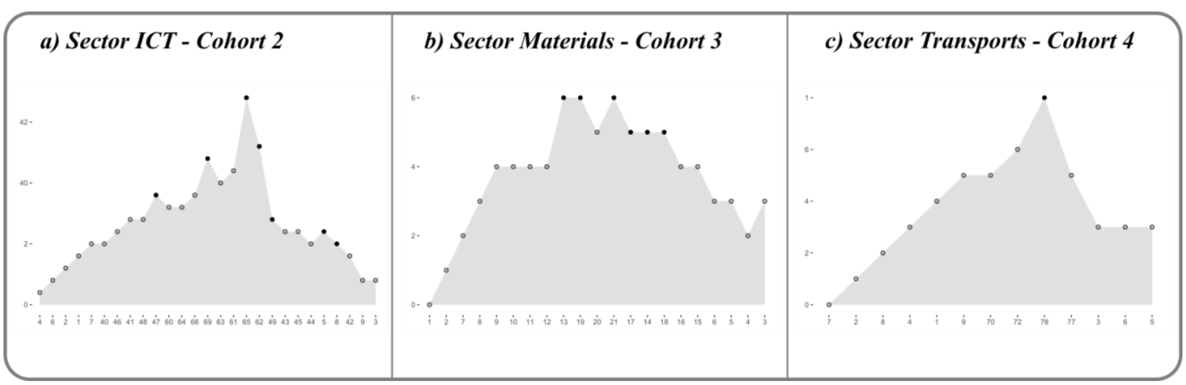
projects are between Transport and Energy sectors, and the main certifying pôles of this topic are *Mer Bretagne* (Bretagne and Pays-de-la-Loire regions) and *EMC2* (Pays-de-la-Loire region).

Also, three main topics are identified in cohort 3, where two are diversified. One of the main topics is about the improvement of engines (light and heavy vehicles) to reduce pollution, and the pôles involved are mainly *Mov'eo* and *ID4CAR* (Bretagne, Poitou-Charentes and Pays-de-la-Loire regions). The second main topic concerns embedded systems, and it involves actors and pôles from ICT sector. The third main topic is also diversified, and focuses on new materials – composites – for truck cabs in order to reduce weight and vibrations.

Finally, cohort 4 network is quite atypical. While diversification is high, only one peak is identified and it is not diversified. This main research topic focuses on mechanical performance (friction and vibration) of the engine and transmission – mainly for heavy vehicles. The main pôles are *LUTB* (Auvergne-Rhône-Alpes region) and *Mov'eo*.

Although the description of peaks' subjects as main topics is interesting, here we use it only to show that there is a correspondence between the relational and cognitive structure, thus validating the proposed method. In relation to our research questions, what is of interest is the structure of the networks. Figures 3.6a-c represent the structure of 3 networks.

Figure 3.6: Illustrative cases of cohesive block structures



The comparison of these three structures highlights some significant differences. The Transports' network for cohort 4 is a single-core network, while the other two are multi-core. In the Materials' network for cohort 3 the peaks – cores – have similar cohesive levels, and their closeness evidence some overlap, while the ICT's network for cohort 2 exhibits more differences regarding the structural importance of the peaks. This last structure shows some complexity since it combines close and distant peaks. In terms of proximity, in the ICT's network the relation between the structural position of peaks and their cognitive distance – the similarity of topics – is clear. Peaks that are close (e.g. the two peaks on the right or the two peaks on the top) have close topics, and are more distinct from the more distant peaks. On the Materials' network this relation is less evident. Because the topics are quite different, for any pair of nearby peaks we do not easily identify what the similarities of the topics are. The transversality of the sector may explain this apparent dissimilarity since some knowledge and technologies can have a wide range of applications.

In sum, the qualitative analysis shows the suitability of the proposed *meso* methodology for community analysis to identify the well-integrated topics of the sectors, featuring relatedness and proximity among knowledge and technologies.

3.5.2. Diversification policies and research topics emergence

In this section we suggest a quantitative approach to the effects of diversification policies, where diversification is defined as the proportion of cross-sectoral projects in a network. We test if diversification policies (a) generate diversified topics in sector's topics portfolio – measured by the number of diversified peaks; (b) enlarge sector's topics portfolio – measured by the number of peaks; (c) impact equally all sectoral knowledge networks.

For the two first questions we perform two very simple linear regression models. We check if the diversification part is related to the number of diversified peaks (Model 1) and to the overall number of peaks (Model 2) by sector. In both models we include the size of the network – measured by the number of nodes – as control variable, and we scale all variables. In order to avoid biases, we remove from our sample the ICT's networks because they are significantly bigger than the other networks. We thus end up with 27 observations.

Table 3.2: Regression models results of diversification impact

	Model 1 **# Diversified Peaks**	Model 2 **# Peaks**
Constant	1.255e-16 (0.1396)	6.964e-17 (0.1867)
Diversification Part	0.6692 *** (0.1479)	0.3153 (0.1978)
# Places	0.1335 (0.1479)	0.1113 (0.1978)
Multiple R-squared	0.5146	0.131
Adjusted R-squared	0.4742	0.05855
Model p-value	0.000171	0.1855
Observations	27	27

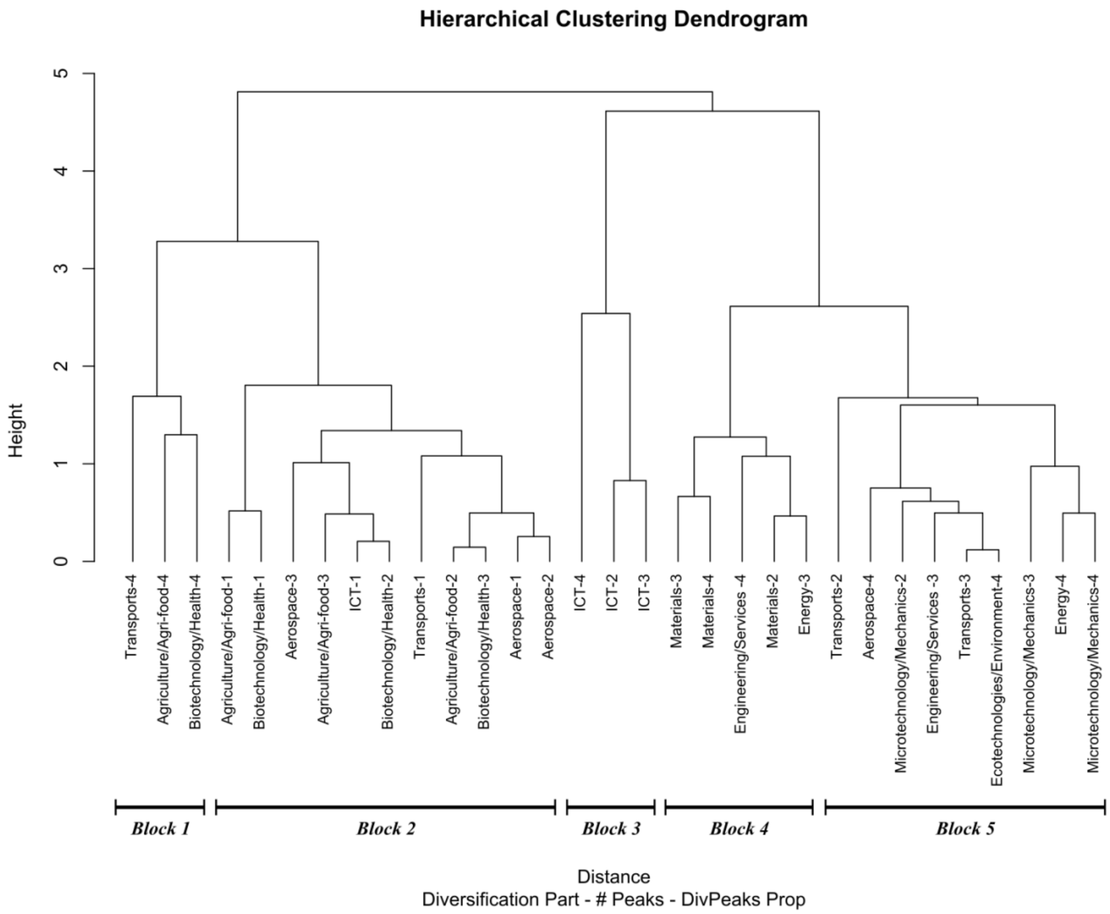
*Note: Standard errors are reported in parentheses. *** indicates significance <0.001*

The results show that there exists a significant statistical relation in Model 1 but not in Model 2.[22] Thus, the more cross-sectoral projects in a network, the greater the number of diversified topics, but the total number of topics in the portfolio does not increase. So, when policy makers foster cross-sectoral projects, some of these projects will usually be well-integrated, thus becoming diversified topics. However, diversified topics are not added to the sector's own topics, enlarging sector's topic portfolios, but rather seem to take the place of them.

To further investigate the link between the support to cross-sectorial projects and the presence of both sectoral and diversified main topics, we perform a Hierarchical Cluster Analysis (HCA) across the 31 networks in order to group cases according to the diversification part, the number of peaks, and the proportion of diversified peaks – number of diversified peaks regarding the overall number of peaks. The values of these measures for each network are available in the Appendix A.3. In HCA, the observations are grouped according to their level of similarity, measured by the Euclidean distance. Figure 3.7 represents the dendrogram of the HCA.

[22] We also performed several Count Regression Models in order to confirm these results. The lack of statistical relation of Model 1 has been confirmed by a Poisson regression model. A Zero-inflated Poisson regression confirmed Model 2 results.

Figure 3.7: Hierarchical Clustering Dendrogram



From top to bottom, the first level (height level 5) divides the sample in two groups. On the left, there are the networks without diversified peaks, and on the right, the networks with at least one diversified peak. The group on the left is further divided into two groups, where the variable that makes the difference is the diversification part. Of these two groups, the one of the right (*Block 2)* contains the networks without diversified peaks and low diversification part. As expected, all the networks of the first cohort are included here, and some networks of the second and third cohort (sectors Aerospace, Agriculture/Agri-food and Biotechnology/Health). All these networks have a significantly lower diversification part than all the other networks of the analysis. *Block 1* contains networks without diversified peaks and with a high diversification part, the three from cohort 4, so these cases can be classified as atypical since the diversification part does not lead to diversified main topics. Here, the network of Transports' sector is an exceptional case since it has diversified main topics in all the cohorts except in this one, which has a high diversification part (0,800). Note that for the sectors Agriculture/Agri-food and Biotechnology/Health the diversification part does not lead to diversified topics. Similarly, the three first cohorts of Aerospace sector have no diversified topics and have a low diversification part.

The big group on the right is also divided in two other groups, where the group of the left – (*Block 3*) contains the last three cohort of the ICT sector. Here, both the diversification part and the proportion of diversified peaks seem to play a role in the differentiation, since ICTs' networks are characterized by a low diversification part and a low proportion of diversified peaks. The group on the right is further divided into two groups according to the number of peaks, where *Block 4* is characterized by a high number of them. Note that all Materials' networks of the selection are in this group. On the contrary, *Block 5* is characterized by networks with less number of peaks. From this group, we highlight the networks of Transports for cohort 2 and Microtechnology/Mechanics for cohort 3 because all their peaks are diversified ones.

This Hierarchical Cluster Analysis highlights some interesting features. Even if there is statistical evidence of the link between the diversification part and the number of diversified topics, this link is not always expressed. Agriculture/Agri-food and Biotechnology/Health sectors have not cross-sectoral main topics, independently of the diversification part. Certainly, cross-sectoral projects can overcome some problems and/or rise on some products or services that contribute to the development of the sectors, but there is no evidence that they lead to deep structural and cognitive/technological changes. Similarly, these cross-sectoral projects may be key to the other sectors involved, leading to diversified topics, but not for these two sectors. Thus, to support cross-sectoral projects involving Agriculture/Agri-food and Biotechnology/Health sectors makes sense, however it cannot be expected that these projects contribute to the emergence of new research topics.

Materials sector is also an interesting case since its networks show a relatively high diversification part, high number of peaks, and high diversified peaks proportion. The high number of peaks shows that the research is not focused on few and central topics guided by a reduced number of actors, but on several ones. Both the diversification part (between 0,569 and 0,732) and the proportion of diversified peaks (between 0,571 and 0,667) suggest that the sector has the ability to collaborate with other sectors while integrating the emergent topics. So, the sector seems to have a "natural" capacity (or necessity) to collaborate with other sectors, and to easily integrate some cross-sectoral topics, all while keeping sectoral ones.

In sum, the HCA shows that sectors have an unequal reactivity to cross-sectoral projects. Thus, the support to cross-sectoral projects can lead to well-integrated cross-sectoral topics, but the differences suggest the need of more "surgical" measures to drive the evolution of research in sectors.

3.6. Discussion and conclusion

National and regional R&D policies have evolved into diversification policies with the aim of generating new products and improving the resilience of innovation systems. Amid these policies, cross-sectoral collaboration incentives across clusters have become central to foster the diversification of topic's portfolios and technologies. The aim of this paper was to test the effectiveness of such diversification policies in the mid-term on the basis of a database on publicly-funded collaborative R&D projects in France.

In order to deal with this issue, we have proposed a novel meso-structural methodology of communities' analysis for bipartite knowledge networks – as project-based networks – based on structural equivalence and cohesion. The "place-based" methodology merge actors with equivalent contributions to knowledge networks, thus overcoming the artificial clustering problem and providing the "skeleton" of the network. The "cohesive blocks" methodology unveils the nested communities' structure, allowing the identification of local highly cohesive and overlapping communities – the peaks. The combination of both methodologies reveals both micro dynamics – how actors and their innovation resources are related – and macro properties – the structure of the whole network.

A relevant feature of this meso-structural methodology is that it allows studying socio-cognitive knowledge structures without systematic qualitative data on actors (e.g. innovation resources or activity domain) and projects (e.g. main objectives or outputs). In other words, since some proximity – mainly cognitive – is required to collaborate, the methodology provides the topics' portfolios of knowledge networks (among other results) using only actor-project affiliation data. This is because the methodology conceptualizes the proximity in terms of position and contribution to collective action – rather than in individual attributes – thus linking relational to cognitive structure.

An analysis of France's FUI French funding program (from 2006 to 2015) through this meso-structural methodology suggests that diversification policies – through cross-sectoral project funding – successfully generate diversified topics. However, these new topics do not enlarge sectors' topic portfolios, and the effect of diversification policies is unequal across sectors. These results raise a number of issues. First, diversification policies appears to use a "blind force" strategy, funding a high number of cross-sectoral projects (for 15 of the 31 networks more than half of the projects are cross-sectoral, reaching a maximum of 84%). Certainly, some cross-sectoral projects can be ill-integrated in some of the sectors but well-integrated in others. Similarly, not all cross-sectoral projects are intended to be developed as topics, but rather to provide solutions to specific problems. However, more "surgical measures" may be considered to select projects according to the objectives of diversification policies. Second, the FUI program appears to apply a "one-size-fits-all" strategy, with two main implications. The first concerns the "nature" or technological base of the sector, since not all sectors react equally to the presence of cross-sectoral projects in order to develop well-integrated diversified topics. It may be appropriate to go deeper into the characteristics of each sector, in order to better understand this phenomenon and thus to be able to better target policies. The second point concerns the sectors' lifecycles and the role of diversification for each phase. Here, doubts arise about the advisability of fostering diversification in all sectors, without awareness of the possible undesirable effects that may be generated. In the end, acquiring greater knowledge of the situation in each sector may be useful in designing more appropriate actions.

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A.3. Appendix

This appendix reports descriptive statistics for the 31 selected networks.

Table 3.3: Network descriptive statistics

Network	Nodes	Project Diversification Part	# Peaks	Maximum Cohesion Level	# Diversified Peaks	Diversified Peaks Proportion
Aerospace-1	74	0,1875	3	10	0	0
Agriculture/Agri-food-1	45	0,076923	1	5	0	0
Biotechnology/Health-1	57	0	2	5	0	0
ICT-1	252	0,138614	5	19	0	0
Transports-1	90	0,243902	3	10	1	0,333333
Aerospace-2	116	0,25	3	14	0	0
Agriculture/Agri-food-2	54	0,181818	2	7	0	0
Biotechnology/Health-2	62	0,189189	5	4	0	0
Materials-2	92	0,590909	7	7	4	0,571429
Microtechnology/Mechanics-2	54	0,545455	3	5	2	0,666667
ICT-2	261	0,26087	7	17	1	0,142857
Transports-2	139	0,482759	3	16	3	1
Aerospace-3	97	0,365854	4	10	0	0
Agriculture/Agri-food-3	54	0,258065	5	4	0	0
Biotechnology/Health-3	66	0,217391	2	3	0	0
Energy-3	51	0,606061	8	3	4	0,5
Engineering/Services -3	57	0,641026	4	4	3	0,75
Materials-3	104	0,568627	6	6	4	0,666667
Microtechnology/Mechanics-3	80	0,777778	3	5	3	1
ICT-3	266	0,374046	6	9	2	0,333333
Transports-3	77	0,674419	3	5	2	0,666667
Aerospace-4	79	0,644444	4	6	2	0,5
Agriculture/Agri-food-4	71	0,525	3	6	1	0,333333
Biotechnology/Health-4	48	0,459459	1	4	0	0
Ecotechnologies/Environment-4	51	0,645161	3	4	2	0,666667
Energy-4	72	0,808511	3	4	2	0,666667
Engineering/Services -4	68	0,8	8	4	6	0,75
Materials-4	128	0,732394	6	6	4	0,666667
Microtechnology/Mechanics-4	122	0,84058	4	6	3	0,75
ICT-4	272	0,456954	12	10	2	0,166667
Transports-4	78	0,8	1	8	0	0

Chapter 4 – The Origination and Distribution of Money Market Instruments: Sterling Bills of Exchange during the First Globalisation

Abstract:

This paper presents a detailed analysis of how liquid money market instruments – sterling bills of exchange – were produced during the first globalisation. We rely on a unique data set that reports systematic information on all 23,493 bills re-discounted by the Bank of England in the year 1906. Using descriptive statistics and network analysis, we reconstruct the complete network of linkages between agents involved in the origination and distribution of these bills. Our analysis reveals the truly global dimension of the London bill market before the First World War and underscores the crucial role played by London intermediaries (acceptors and discounters) in overcoming information asymmetries between borrowers and lenders on this market. The complex industrial organisation of the London money market ensured that risky private debts could be transformed into extremely liquid and safe monetary instruments traded throughout the global financial system.

Keywords: money market, industrial organization, information asymmetry, bill of exchange

JEL codes: E42, G23, L14, N20

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4.1. Introduction

At the beginning of the twentieth century, the pound sterling's dominance over the global financial system was at its height. The City of London hosted the world's most important centre for international short-term lending and borrowing[24] and the main instrument for these money market transactions was the *sterling bill of exchange* (or bill on London). The sterling bill of exchange was a tradable asset originated by private agents located anywhere in the world to obtain short-term credit from London. It was one of the most liquid financial assets of the time and was traded in all significant financial centres.[25] Just before the First World War, about half of world trade was financed through this instrument.[26] Contemporaries generally considered that the sterling bill was 'a kind of world currency', 'the same as gold', or 'the equivalent of a bullion certificate'.[27] Many UK and foreign financial institutions were interconnected through the London bill market, whose importance for the international banking system was systemic.[28] The sterling bill was the cornerstone of the global financial system and its undisputed liquidity was key to the UK's financial dominance during the first age of globalisation.[29]

Why was the sterling bill of exchange considered such a liquid and safe credit instrument? And why did the London money market prove so robust in the decades prior to the First World War? While these questions have been asked before, any attempt to answer them has been confronted with a lack of systematic data on bill trading. Since the bill market was of the over-the-counter type, there was no central authority that recorded information on all London-originated bills. In this paper, we overcome this difficulty by relying on a detailed data set constructed from a unique archival source: the Bank of England's *Discount Ledgers*. These ledgers report systematic micro-level information on a profusion of bills circulating on the London money market and on all agents involved in their origination and distribution. Our data set contains information on all individual bills re-discounted by the Bank of England during the year 1906 (23,493 bills). Bills re-discounted by the Bank of England only represented a small share of all bills issued on the London market and did not constitute a fully representative sample. Nevertheless, the information they contain provides invaluable insights into the microstructure of the money market. We use descriptive statistics and

[24] Keynes, *Treatise on Money,* p. 282.
[25] Jacobs, *Bank Acceptances*; Warburg, *Discount System*; Withers, *Meaning of money*; Flandreau and Jobst, 'Network Analysis.'
[26] Kynaston, *City of London*, p. 8; Atkin, *Foreign Exchange Market*, p. 5.
[27] Baster, *International Banks*, p. 13; Gillett Brothers, *Bill on London*, p. 16; Greengrass, *Discount Market*, p. 37.
[28] Bills on London formed part of the liquid reserves of UK commercial banks and of the foreign currency reserves of commercial and central banks abroad (Eichengreen and Flandreau, 'Central Banks').
[29] King, *Discount Market*, p. xi; Atkin, *Foreign Exchange Market*, p. 5.

network analysis to reconstruct the complete network of linkages between agents involved in the design of these bills. Doing so allows us to describe the industrial organisation behind the production of sterling bills in the early twentieth century.

Bills of exchange always involved a *drawer* (a borrower located either in the UK or abroad), an *acceptor* (a London-based actor which guaranteed the bill's payment in pounds sterling at maturity), and a *discounter* (the buyer of the bill). The data that we have assembled enable identification of how these various agents interacted on the money market.

Figure 4.1: Geographical location of borrowers (drawers) on the London bill market

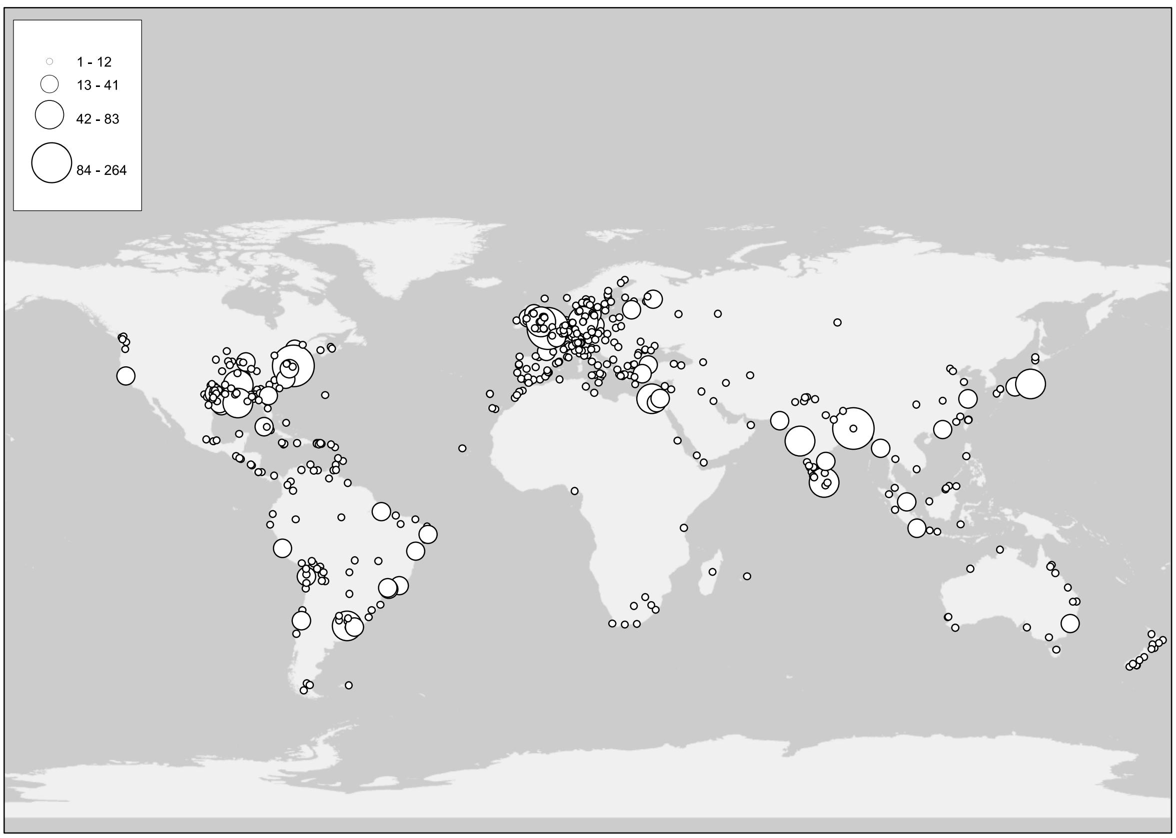


Figure 4.1 shows the geographical location (at the city level) of all drawers of sterling bills in our data set.

Our analysis based on a new dataset confirms the true global dimension of the London bill market at the start of the twentieth century. We show that drawers were numerous and scattered across the world (Figure 4.1). Our data set records 3,554 different drawers, most of which were small private firms or merchants. Since the average investor could not hold detailed information about all these debtors, large information asymmetries must have existed between borrowers and lenders on the money market. Such information asymmetries constitute market frictions, which typically result in adverse selection and a total absence of lending.[30] Data on the intermediaries involved in the origination and distribution of bills allow us to demonstrate how these market frictions were overcome.

We argue that the information problem inherent to the production of sterling bills was solved by a cumulative process in which London intermediaries successively added their guarantees to the instrument. Acceptors played the key role in producing information on borrowers and in reducing credit risk. However, their signature was also supported by that of the discounters who purchased the bills before distributing them to other investors. When they resold (endorsed) a bill of exchange, discounters added their personal, secondary guarantee to it and thus enhanced its credit – a circumstance known as the *joint liability rule*.

Our results therefore shed light on the complex structure of the London money market at the start of the twentieth century and on the various mechanisms through which the information problem inherent to the production of bills was solved. These mechanisms allowed borrowers from around the world to access London credit facilities and ensured that risky, private debts could be transformed into the highly liquid and safe monetary instruments that were traded throughout the global financial system.

Our paper contributes to the historiography on the use of bills of exchange as instruments of international credit and payment and on the evolution of the London money market.[31] We integrate perspectives from the literatures on the organisation of the London discount market,[32] the business and operations of merchant banks,[33] and the role of joint liability in lending.[34] We show how these various factors jointly contributed to the high liquidity of the London money market.

The rest of our paper proceeds as follows. Section 4.2 explains how the bill of exchange functioned. In Section 4.3 we discuss our primary source and data. Section 4.4 details the structure of the accepting and discounting industries in London at the beginning of the twentieth century and

[30] Stiglitz and Weiss, 'Credit rationing'.
[31] De Roover, *Lettre de change*; Scammell, *London Discount Market*; Nishimura, *Inland Bills*, Michie, *British Banking*; Cassis, *Capitals of Capital*; Mollan and Michie, 'City of London'.
[32] King, *Discount Market*; Scammell, *London Discount Market.*
[33] Chapman, *Merchant Banking*; Roberts, *Schröders*; Wake, *Kleinwort*.
[34] Ghatak and Guinanne, 'Joint Liability'; Santarosa, 'Long-Distance Trade'.

underscores the role of acceptors in reducing information asymmetries on the bill market, while Section 4.5 focuses on the role of discounters. Section 4.6 concludes.

4.2. The sterling bill of exchange

4.2.1. The bill of exchange: Definition and functioning

From the late sixteenth until the early twentieth century, a negotiable bill of exchange was the standard financial instrument for obtaining short-term credit and exchanging currencies.[35] The bill of exchange was defined legally in the UK as *'an unconditional order in writing, addressed by one person to another, signed by the person giving it, requiring the person to whom it is addressed to pay on demand or at a fixed or determinable future time a sum certain in money to or to the order of a specified person, or to bearer.'*[36] Whereas 'sight bills' were payable after a few days, 'long bills' had a longer maturity (typically three or six months) and therefore served as short-term credit instruments.

A bill always involved at least three agents: a 'drawer', an 'acceptor', and a 'discounter'. The drawer was the person who addressed the bill; the acceptor, the individual or institution to whom the bill was addressed; and the discounter, the bill's beneficiary. By *accepting* the bill, the acceptor committed to pay the specified sum to the discounter at the specified date. Because the bill of exchange was a negotiable instrument, a discounter's claim on the acceptor could always be transferred to another investor (or *re-discounter*) at any time before maturity.

Although its legal form remained practically unchanged for centuries, the bill of exchange proved to be a flexible instrument that could be employed to finance diverse types of operations. Bills could be drawn to finance domestic and international trade transactions, to raise short-term money or to engage in purely financial operations such as security investment, currency speculation, or interest arbitrage.[37] Bills of exchange were traded in all principal cities in the world. However, bills accepted in London largely outnumbered those drawn from London on other foreign centres.[38] This reflected the importance of the sterling bill in the global financial system; it not only served to

[35] De Roover, *Lettre de change*; Accominotti and Ugolini, 'International Trade Finance'.
[36] Article 3 of the 1882 Bill of Exchange Act.
[37] Goschen, *Theory of the foreign exchange*, pp. 23-42; Clare, *A B C of foreign exchanges*, pp. 80-87; Herger, 'Interest parity-conditions'.
[38] Clare, *A B C of foreign exchanges*, p. 11.

finance most of the UK's trade with foreign countries, but was also used to fund various commercial and non-commercial transactions taking place anywhere in the world.[39]

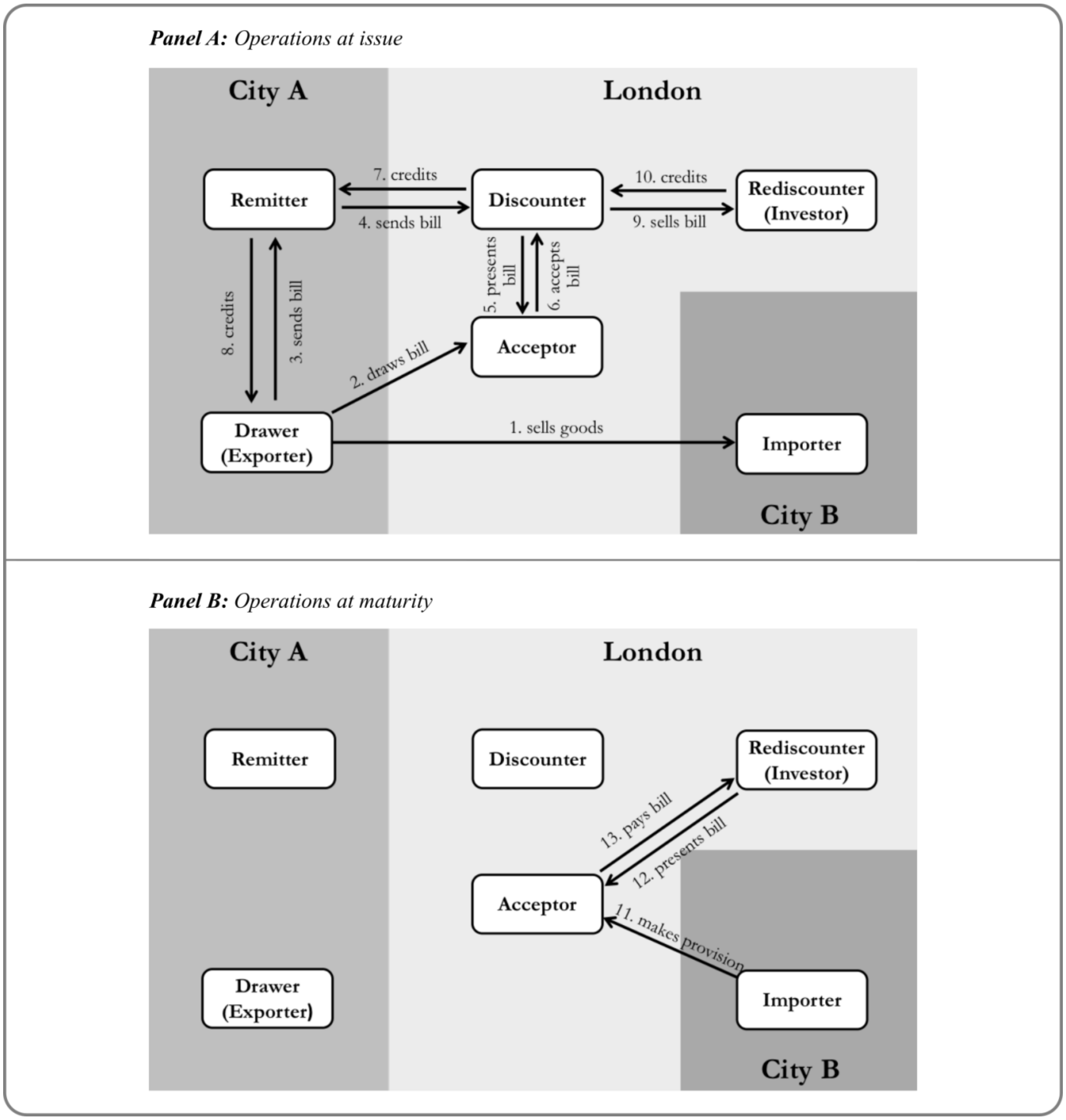
4.2.2. The bill of exchange: Examples

Figure 4.2 presents an illustrative example of a transaction commonly financed through sterling bills in the early twentieth century: an export of goods from 'city A' to 'city B'. The figure's panel A shows the operations involved when the bill is issued. An exporter in city A has agreed to sell goods to an importer in city B (path 1 in the figure) but needs credit in order to finance production and shipment before receiving payment. The exporter (here, the *drawer*) draws a bill on a London agent (the *acceptor*) and asks for an engagement to pay to the bearer of the bill, at a specified date in the future, a sum in pounds sterling corresponding to the proceeds of the sale (path 2).[40] The drawer then transfers the bill (3) to her local bank (the *remitter*), which arranges to send it to a *discounter* in London (4). The discounter might have been pre-selected – either directly by the drawer (if she has London correspondents other than the acceptor) or by the acceptor herself (if she is the drawer's only correspondent in London).

[39] Ibid., pp. 11-15; Goschen, *Theory of foreign exchanges*, pp. 32-33.

[40] In this example, the bill is 'placed to the importer's account', which means that the importer authorises her exporter to draw on the acceptor with whom she is in a business relationship. However, if the drawer were in a direct business relationship with the acceptor then it would be said that the bill was 'placed to the drawer's account'.

Figure 4.2: Example of a commercial transaction financed by a sterling bill of exchange



Source: Authors' schematic representation of transactions described by contemporaries (e.g., Gillett Brothers, *Finance of Trade by Bills of Exchange*)

Upon arrival of the bill in London, the discounter presents it to the acceptor (5); she 'accepts' the bill by countersigning it, thereby confirming her commitment to pay the bearer at maturity (6). Once the bill is accepted, the discounter credits the remitter's account (7). The remitter, in turn, credits the drawer's account (8) and so provides the financial means for producing and shipping the goods. The discounter can then either keep the bill until its maturity or resell ('endorse') it to a final investor (the endorsee, or *re-discounter*) willing to lend capital until the pre-specified date (9 and 10). The bill can be re-discounted an unlimited number of times before its maturity.

Panel B of Figure 4.2 summarises the operations taking place when the bill expires. Just before maturity, the importer – who has, by then, received delivery of the shipped goods – remits funds directly to the acceptor (11); those funds enable the acceptor to meet the bill's payment. On the bill's actual maturity date, the bearer presents it to the acceptor for payment (12 and 13). Thus the instrument disappears at maturity, or 'self-liquidates' in the wording used by contemporaries.[41]

It should be clear from this example that a bill's acceptor did not advance her own capital; rather, she committed only to repaying the bearer in the expectation of receiving a monetary flow from the importer before maturity.[42] In other words, the acceptor was just a *guarantor* of the bill who added her signature to it – usually in exchange for a fee.[43] In contrast, the discounter and re-discounter immobilised their own funds in order to purchase the bill. These actors were (respectively) the first and ultimate lender. The usual procedure was for investors (re-discounters) in sterling bills to purchase them from a limited set of London institutions (discounters), who in turn had obtained those bills either from their correspondents abroad (remitters) or from acceptors. These first discounters constituted the 'wholesale' segment of the London discount market.[44]

Recall that every seller of a bill of exchange also had to 'endorse' it, thereby adding a secondary guarantee to the bill. In case the acceptor failed to pay the bill at maturity, the last endorser was liable for repaying the sum due to the bearer. By originating a bill, the drawer was thus able to borrow from an unknown lender (the re-discounter) thanks to the guarantee provided by an acceptor and to the intermediation – and secondary guarantee – of a wholesale discounter. The bill of exchange was not collateralised by any financial asset or 'physical' goods; it was secured instead via the guarantees provided by the successive intermediaries involved in its origination and

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[41] Jobst and Ugolini, 'Coevolution', pp. 162-3.

[42] Nevertheless, acceptance houses reportedly followed certain rules in order to manage the risks of guaranteeing bills. One often cited rule was that they should not accept bills for more than three or four times the value of their paid-up capital and reserves (See Committee on Finance and Industry, *Minutes of Evidence*, vol.1, p. 73, par. 1204).

[43] Hawtrey, *Currency and Credit*, p. 129.

[44] Specialised wholesale *discount brokers* (connecting first discounters to re-discounters) had already emerged in London by the end of the nineteenth century. For instance, Sayers, *Gilletts*, pp. 51–52 writes that the discount house Gillett Brothers & Co. (a leading London re-discounter) used to purchase, in the 1890s, its entire portfolio of Indian-drawn bills through the intermediation of discount brokers Page & Gwyther.

distribution.[45] These intermediaries certified the quality of the bill's underlying debt and its repayment upon its maturity.

The specific type of transaction described in Figure 4.2 was common in the early twentieth century; yet bills of exchange could be mobilised in many other ways, and all these roads led to the London money market. A detailed exposition of the manifold uses of bills can be found in a handbook published by one of London's foremost discount houses.[46] Bills were first used to finance trade. Especially in early times, the drawer was often the seller of some goods and the acceptor their buyer. By signing the bill, the acceptor promised to pay the value of the sold goods after their delivery – thus allowing the seller to raise capital and finance shipment. In that case, the bill's acceptor was a UK importer.[47] Bills drawn directly on importers were called *trade bills* on the London discount market.

From the mid-nineteenth century onward, several trading and financial houses in the City began offering their respective signatures and allowed exporters to draw bills upon them rather than on their importers.[48] Bills accepted by reputable financial institutions were known as *bank bills* and were usually considered superior to trade bills because of the acceptor's higher standing. Hence, contemporaries referred to such bills as 'first class paper' as opposed to the 'lower class paper' drawn on less reputable, non-financial firms. In these cases, the acceptor was not engaged in the commercial transaction; instead it was a third party that agreed to accept bills in the importer's name – on the condition that the latter (privately) agree to provide the funds needed to meet the bills' payment at maturity.[49] Bills could also be drawn directly by the importer (rather than the exporter) on the financial house with whom she had the arrangement. In this case, the importer raised capital herself to finance the goods' shipment.[50] Sometimes, the acceptor did not have a direct relationship with the drawer but only with her bank, which took care of selling the bill to a discounter and of providing the funds to the acceptor before maturity. In such cases, often the drawer's bank also endorsed the bill before it was accepted.[51]

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[45] Flandreau and Ugolini, 'Lending of Last Resort'. The holder of an unpaid bill could not seize the commodities that it financed; the only recourse was to seize the acceptor's or previous endorser's assets.
[46] Gillett Brothers, *Bill on London.*
[47] Ibid., pp. 47-48
[48] Greengrass, *Discount Market*, p.46.
[49] Hawtrey, *Currency and Credit*, pp. 123-24; Gillett Brothers, *Bill on London*, pp. 27-29, 37-39, 41-43. In contemporary parlance, the importer engaged to 'make provision' and to 'cover' the acceptor before maturity. This particular case corresponds to the example described in Figure 4.2.
[50] Gillett Brothers, *Bill on London*, pp. 29-31, 39-40.
[51] Ibid., pp. 53-55.

As stated above, bills could also be used to finance activities other than trade. For instance, the drawer might be an industrial firm that needed a short-term, blanked credit to finance production and sought to raise capital on the London discount market with the guarantee of an acceptor.[52] Should the firm's production remain unachieved at the bill's maturity, then the acceptor could authorise the drawer to draw another bill so that the debt could be rolled over.[53] Finally, in many cases the drawer was a financial firm just willing to fund its own stock or bond investments or to refinance its banking operations. By originating a bill, a financial firm could replenish its liquidity while using the acceptor's guarantee as collateral.[54] Bills originated for purposes other than trade were referred to as *accommodation* or *finance bills*. Although the practice of drawing bills that were not based on 'genuine' commercial transactions was often decried, the distinction between 'finance' and 'real' bills was not clearly defined. For example, contemporaries debated whether bills drawn to finance a future, expected commercial transaction should be classified as accommodation paper.[55] Although certain bills provided details about the nature of the commercial transaction they financed (e.g, details on the sold goods and their shipment), doing so was optional (and irrelevant from the judicial standpoint) and in most cases investors could not directly recognise a 'finance' bill from a 'real' one. Hence, the standing of bills on the London discount market did not mostly depend on their intrinsic nature but on the reputation of the intermediaries which had guaranteed them.[56]

4.2.3. Bills as carriers of information

The information recorded on a bill of exchange allowed bearers to reconstruct many, but not all, of the underlying interlinkages that supported its origination and distribution. Simply looking at a bill was not enough to reliably determine the exact nature of the transaction that stood behind it. That said, each bill did record the name of its drawer as well as the names of all intermediaries who had guaranteed and/or purchased it.

[52] Goschen, *Theory of the foreign exchanges*, pp. 38-41.
[53] Gillett Brothers, *Bill on London*, pp. 45-47.
[54] Also in this case, the acceptor was not necessarily in a direct customer relationship with the drawer; thus, for example, the former might only have had an arrangement with the drawer's correspondent.
[55] Goschen, *Theory of the foreign exchanges*, pp. 38-41.
[56] Gillett Brothers, *Bill on London*, p. 22.

Figure 4.3: Bill of exchange, 1910

ACCEPTED 15 AUGUST 1910
Payable at the
London County & Westminster_Bank
Kleinwort Sons & Co.

Moscow, 10 August 1910
For £3,000

Three months after date pay against this Bill of Exchange to our order the Sum of Three Thousand Pounds Sterling Value in account and place it to account and charge it to account as advised by

Messrs Kleinwort Sons & Co.
London E.C.
ac Fenchurch Street

Société L. Bauer & Co.
Le Directeur-Gérant: C. Bauer

Pay to the order of:
Banque de Commerce de l'Azow-Don
10 August 1910
Société L. Bauer & Co.

For us at the order of:
The Union Discount Company of London Ltd., London
10 August 1910
Azow-Don Commerzbank

The figure's upper (resp. lower) portion transcribes the bill's front (resp. back) side. Text in italics corresponds to signatures. *Source:* London Metropolitan Archives, CLC/B/140/KS04/13/02/006.

Figure 4.3 transcribes a typical bill of exchange found in the archives of the leading acceptance house Kleinworts & Co. This £3,000 bill was drawn on 10 August 1910 by the Moscow-based Société L. Bauer & Co. (the drawer) and was made payable after three months by Kleinworts & Co. (the acceptor). After drawing the bill, the drawer immediately sold it to the Banque de Commerce de l'Azow-Don/Azow-Don Commerzbank (the remitter), probably the drawer's bank in Moscow. The very same day (10 August), the remitter sold/endorsed the bill to the Union Discount Company of London (the discounter), which thus became entitled to cash it in at maturity. Azow-Don Commerzbank shipped the bill to London, where Kleinworts accepted it (by affixing its signature) on 15 August before transmitting it to the Union Discount Company. The discounter kept the bill until maturity and did not resell it to another investor. Three months later, Kleinworts therefore repaid the Union Discount Company £3,000 through a London clearing bank (the London County & Westminster Bank), which was responsible for pure payment services. The discounter then returned the self-liquidated instrument to the acceptor, in whose archives it remains preserved.

The information recorded on that bill does not indicate the exact nature of the transaction it financed. The drawer (Bauer & Cie) might have been an exporter of Russian goods. Yet because the bill makes no mention of any shipment of goods, we cannot be sure that it was used to finance trade. Inspecting the bill itself leaves us in the dark also with regard to the exact nature of the relationships between the various parties involved. For example, the remitter (Azow-Don Commerzbank) might have selected the discounter (the Union Discount Company) directly; alternatively, the acceptor (Kleinworts) might have arranged for the bill to be discounted. In that event, Kleinworts would have instructed the Moscow bank to endorse the bill to the Union Discount Company (the discounter) before shipping it to London.[57]

One must bear in mind that, even if all details of the transaction were not known, a bill's purchaser could always identify the most important actors involved in its production. In particular, a bill recorded the names of all intermediaries whose signatures amounted to collateral for it. Those agents included the drawer (or borrower; here, Bauer & Cie); the acceptor (or guarantor; here, Kleinworts & Co.), and the discounter (or lender; here, the Union Discount Company).

The largest acceptors of bills in London were the merchant banks or acceptance houses that specialised in offering acceptance services for their customers at home and abroad.[58] Acceptors also included UK deposit banks, branches of foreign banks, and 'Anglo-foreign banks' – multinational banks based in London but whose business was concentrated in certain foreign geographical areas, where these banks specialised and maintained a large network of correspondents.[59] In addition, a large number of UK trading or manufacturing firms also accepted bills drawn on them by their trading partners.[60]

Among the largest discounters were the so-called discount houses of the City. These highly specialised institutions purchased large amounts of bills, which they then kept in their own portfolios or re-discounted to other investors.[61] Discount houses usually funded their investments with short-term deposits or 'call money' from other financial institutions (especially the large UK deposit banks).[62] However, discount houses were not the sole distributors of bills on the money market. Foreign and Anglo-foreign banks also played that role, while trading and manufacturing

[57] The Union Discount Company was a 'discount house' that was not actually involved in the business of correspondent banking. Thus, it is unlikely that this company was the London correspondent of Azow-Don Commerzbank. Hence we suspect that Kleinworts both accepted the bill and found a discounter (the Union Discount Company) willing to purchase it in London.

[58] Greengrass, *Discount Market*; Chapman, *Merchant Banking*.

[59] Jones, *British Multinational Banking*. Anglo-foreign banks are also often referred to as British overseas banks or British multinational banks.

[60] Sayers, *Gilletts*.

[61] Vigreux, *Crédit par Acceptation*, pp. 169-70; Sayers, *Gilletts*, pp. 37-38.

[62] For a detailed description of the business of discount houses, see King, *Discount Market*, Scammell, *London Discount Market*, Fletcher, *Discount Houses*, and Cleaver, *Union Discount*.

firms discounted bills as well. In contrast, UK deposit banks invested in (i.e., re-discounted) bills but seldom served as wholesale sellers on the discount market.[63]

4.3. Data

4.3.1. Data Source

Through its monetary operations, the Bank of England was an influential player in the London discount market. Large holders of bills approached the Bank – in times of monetary tension and before publication of their balance sheets – for re-discounting and thus obtaining cash.[64] The Bank of England gathered systematic information on all the bills it re-discounted, thereby monitoring its exposure to acceptors and discounters.[65] In its *Discount Ledgers,* it recorded complete information on the identity of the intermediaries (drawer, acceptor, discounter) involved in the origination and distribution of re-discounted bills.[66]

We collect information on all bills re-discounted by the Bank of England during one year.

We select a period equal to exactly one year in order to circumvent any seasonality concerns. Because the Bank only acquired bills through standing facility lending and never through open market operations, its bill portfolio only became sizeable in times of monetary tension.[67] To ensure our dataset captures a significant portion of the sterling bill market, it is important to select a year in which the Bank's discount window was rather active. The year 1906 is a good candidate here as the UK's external position varied throughout the year leading the Bank of England to alter its discount rate on six different occasions even though there was no full-blown financial crisis as in 1890 or

[63] Spalding, *Foreign exchange*, p. 200; Hawtrey, *Currency and Credit*, pp. 130.
[64] Tensions on the money market could occur when the demand for cash was unusually high, thus putting upward pressure on market interest rates. Such circumstances could arise from concerns about the UK's external balance or about the position of certain financial institutions, as well as from seasonal liquidity demands. UK financial institutions also re-discounted a large portion of their bills to the Bank of England just before publication of their balance sheet in order to increase the published amount of their cash reserves. This practice was known as *window-dressing*.
[65] Flandreau and Ugolini, 'Lending of Last Resort'
[66] Bank of England Archives, *Discounters' Ledgers* (C22/46-50), *Drawing Office Discounters' Ledgers* (C23/7), *Bankers' Ledgers* (C24/6), *Upon Ledgers* (C26/72-74).
[67] Ugolini, 'Liquidity Management'.

1907. [68] Figure 4.4 shows the evolution in the number of bills re-discounted by the Bank of England from 1889 to 1910, as well as the share of these re-discounted bills in the total amount of sterling bills issued on the market as estimated by Nishimura.[69] The figure shows that in 1906, the Bank re-discounted a higher share of sterling bills issued than in any other year, although that proportion remained limited overall (2.47 per cent). Bills re-discounted by the Bank in 1906 had an average value of £1,346 (compared to £1,556 on average in 1900-1910), an average maturity of 44 days (compared to 46 days), and were purchased at the average interest rate of 4.17 per cent (3.45 per cent).

[68] Flandreau and Ugolini, 'Lending of Last Resort' show that the quality of bills re-discounted by the Bank of England was not altered in crisis times. Nevertheless, bills rediscounted by the Bank during a full-blown financial crisis might not have been representative of the money market.
[69] Nishimura, *Inland Bills*.

Figure 4.4: The Bank of England's re-discount policy, 1889-1910

This figure displays the total number of bills re-discounted by the Bank of England annually from 1889 to 1910 (left axis), as well as the share of total sterling bills issued on the market (according to Nishimura's estimate) which were re-discounted by the Bank (right axis). *Source:* Authors' computations on Bank of England Archives, *Comparative Statement of Discount Operations* (C30/3). Estimates of total sterling bills issued are from Nishimura, *Inland Bills*, p. 93.

The *Discount Ledgers* contain the accounts of the Bank's clients. During any re-discounting operation, the Bank registered the bill's information in the discounter's account (in a column labelled 'with') and also in the acceptor's account (in a column labelled 'upon').[70] Thus each bill re-discounted by the Bank was recorded twice in the *Ledgers*. To avoid recording the bills twice in our database, we collect only the 'upon' entries of the Bank's *Ledgers*.[71] For each bill, we record the

[70] See Flandreau and Ugolini, 'Lending of Last Resort' for a description of the Bank's accountability in the re-discounting of bills.

[71] We prefer to collect the 'upon' entries because the 'with' entries are sometimes less detailed. Bills were usually re-discounted not individually but rather in packs known as 'parcels'. A specific category of the Bank of England's *Discount Ledgers* includes the accounts of discount houses (*Brokers' Ledgers*, C25/5). In these ledgers, the parcels of bills discounted were not always 'unpacked' in the 'with' entries. Yet in the 'upon' entries the parcels *were* unpacked – that is, under the headings of the acceptors of each bill contained in the parcel.

name and location of the three parties involved in its origination and distribution: the drawer, the acceptor, and the discounter.

We use these data to describe relations between agents on the London money market. From our data set for 1906, which contains 23,493 bills, we reconstruct the complete network of agents whose names appear on the bills. In this way we obtain a static network of 4,970 agents, or 'nodes'. Among these we find that the drawer role is played by 3,554 nodes, the acceptor role by 1,439, and the discounter by 145 nodes (note that some nodes played more than one role).

We record all relationships, or *links*, between triplets of agents in the network. We define two direct relationships between pairs of actors: between drawers and acceptors, and between acceptors and discounters. Thus a link exists between a given drawer and a given acceptor when the latter has accepted at least one bill drawn by the former, and there is a link between an acceptor and a discounter when the latter has discounted at least one bill accepted by the former. As a result, there also exists an indirect relationship between a drawer and a discounter (through an acceptor) when the latter has discounted at least one bill drawn by the former.

4.3.2. Representativeness

There are, of course, some limitations to our source and resulting data set. As far as we know, the Bank of England's *Ledgers* constitute the most comprehensive and detailed source on the sterling bill market. Nevertheless, bills re-discounted by the Bank only represented a small portion of all sterling bills issued, and this sample might not have been representative of the entire market.

For one thing, the Bank of England only re-discounted bills from a limited set of discounters that it declared 'eligible'. Eligible discounters were not representative of the final investor in sterling bills (the re-discounter in Figure 4.2). Our archival source does not allow identifying whether the agents who sold bills to the Bank of England were those bills' first discounters or if they had themselves bought the bills from other investors. However, eligible discounters made up the wholesale segment of the London discount market (the discounter in Figure 4.2), and therefore included all institutions that purchased bills through acceptors or foreign correspondents and then resold them to final investors (or to the Bank of England). This group of institutions included discount houses, Anglo-foreign and foreign banks, and merchant banks as well as non-financial, trading firms.

Biases might also have existed in the nature and quality of bills re-discounted by the Bank as compared with bills sold on the open market. Since there was no formal rule regarding the eligibility of drawers or acceptors, the Bank of England could in theory re-discount bills drawn or accepted by all sorts of agents.[72] However, it is possible that the Bank was a particularly cautious re-discounter, in which case one would expect the bills it purchased to be, on average, of higher quality than those circulating on the market. Alternatively, it is also possible that eligible discounters exploited the Bank's discount window strategically and re-discounted their lowest-quality bills in order to keep the best ones on their own balance sheet. If that was the case, one would expect the Bank's bill portfolio to disproportionately consist of bills accepted by weaker institutions. [73] Although a vast literature has discussed the Bank of England's rediscount policy, no attempt has been made so far to empirically assess the extent and direction of biases in its bill portfolio.

We perform three series of cross-checks on our data. First, Jansson reports the aggregate amounts of bills accepted by nine top acceptance houses. [74] We can rank these nine houses according to their total amount of outstanding accepted bills at the end of 1906, and compare the ranking of the same institutions in the Bank of England's portfolio of re-discounted bills that same year (Table 4.1).[75] The result is reassuring, as the two rankings almost perfectly match. The ranking of acceptors also exhibited little year-on-year variation.[76]

[72] There was no constraint on drawers, while the only constraint on acceptors was that they had to be based in London in order to allow for the collection of bills' repayment at maturity. The bills accepted by intermediaries who were not among the Bank's agreed customers were those recorded in the so-called *Upon Ledgers*: In 1906, they made for 23.39 per cent of all bills re-discounted.

[73] Here, we use the term 'portfolio' to denominate the entire set of bills acquired by the Bank of England throughout the year 1906 (rather than the Bank's bill holdings at one point in time).

[74] Jansson, *Finance-Growth Nexus*.

[75] The ranking of the selected houses in the Bank of England's portfolio is based on the number of discounters that purchased bills accepted by them.

[76] Jansson, *Finance-Growth Nexus*, p. 209

Table 4.1: Ranking of London acceptance houses in 1906

	Our database		Janson (2018, p 269)	
	Rank	Number of discounters	Rank	Amount accepted (million pounds)
Kleinworts	1	50	1	11.9
Schöders	2	45	2	10.3
Barings	3	43	4	6.7
Brandts	4	42	3	6.9
Brown Shipley	5	39	5	4.5
Rothschilds	6	33	6	3.1
Hambros	7	32	8	2.1
Morgan Grenfell	8	26	7	2.2
Gibbs	9	19	9	0.9

This table compares the ranking – in terms of their number of discounters in 1906 – of nine of our data set's acceptance houses with the ranking of the same houses established by Jansson, *Finance-Growth Nexus in Britain*, p. 269, based on their amount of outstanding accepted bills at the end of 1906, retrieved from the respective houses' archival records.

Second, we were able to retrieve from the archives of two major acceptance houses (Kleinworts and Barings) the list of their top 10 clients in 1906.[77] We check whether these clients' names also appear as drawers of bills accepted by Kleinworts and Barings and re-discounted by the Bank of England. Six (respectively, five) out of Kleinworts' (respectively, Barings') top 10 drawers also appear on bills in our dataset. This suggests that at least the largest drawers of sterling bills were well represented in the Bank's portfolio.

[77] The list of Kleinworts' top-10 clients was constructed from London Metropolitan Archives, CLC/B/140/KS04/12. The list of Barings' top-10 clients was constructed from the Baring Archive, 202368-202376, *Credit Department Annual Report 1906-1914* (file communicated by the archivists).

Table 4.2: Comparison of acceptors in Gilletts' total discounts and re-discounts to the Bank of England, 1906

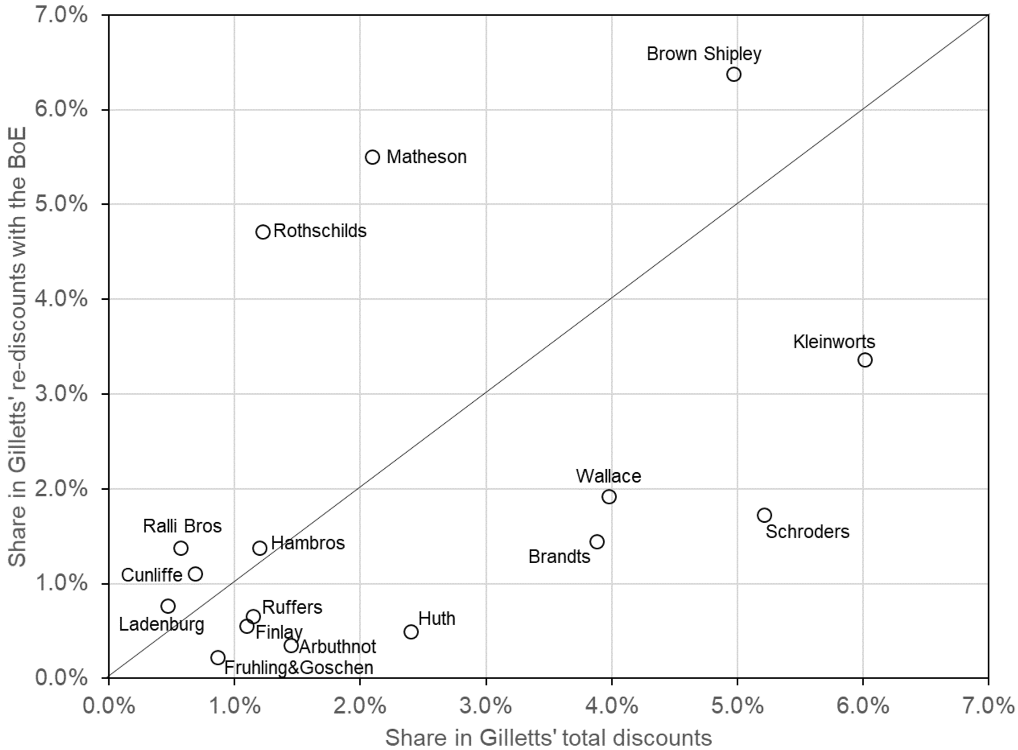
Type of acceptor	Share in Gilletts' total discounts	Share in Gilletts' re-discounts to BoE
Merchant banks	49.5%	32.0%
British clearing banks	9.8%	16.4%
Anglo-foreign banks	11.9%	30.9%
Foreign banks	13.1%	0.0%
Other (non-financial firms)	15.7%	20.7%
All	100.0%	100.0%

This table compares the share of various types of acceptors in Gilletts' 1906 total portfolio of discounted bills and in the portion of that portfolio which the firm re-discounted to the Bank of England.

Finally, the archives of one major discount house (Gillett Bros. & Co.) contain a detailed breakdown of the bills it purchased in 1906 by each principal acceptor.[78] We can thus compare the entire portfolio of bills which Gilletts discounted on the market with the small portion of that portfolio (0.85 per cent) which the firm re-discounted to the Bank of England. Table 4.2 shows how different categories of acceptors feature in each sample. The two samples are broadly consistent, even though we do notice discrepancies. In particular, bills accepted by Anglo-foreign banks are clearly over-represented in the sample of bills re-discounted to the Bank. Gilletts also discounted a significant amount of bills accepted by foreign banks' London branches (13.1 per cent of its total discounts) but did not re-discount any of those bills to the Bank of England. At the same time, there is no evidence of a quality bias in Gilletts' re-discounts to the Bank of England. Bills accepted by non-financial firms (trade bills) figure in similar proportions in both samples. While merchant banks are slightly under-represented in Gilletts' rediscounts to the Bank, we do not find any systematic bias in favour of the most reputable ones. Several first class signatures such as Rothschilds and Brown Shipley are slightly over-represented at the Bank, but other equally reputable institutions such as Kleinworts and Schroders are slightly under-represented (Figure 4.5).

[78] London Metropolitan Archives, CLC/B/100/MS24688/002. Note that this ledger only covers the 135 top acceptors that Gilletts held in their portfolio. Sayers, *Gilletts*, p. 46 writes that in 1905, these top acceptors accounted for 73 per cent of the house's total discounts. Jansson, *Finance-Growth Nexus*, pp. 252-5, relies on the same archival source to describe the evolution in Gilletts' bill portfolio over 1892-1913, and shows there was little volatility in the acceptor composition of the portfolio.

Figure 4.5: Share of individual merchant banks in Gilletts' 1906 discounts and re-discounts to the Bank of England



The values on the horizontal axis show the share of various acceptors in Gilletts' total amount of bill discounts in the year 1906. The values on the vertical axis show the share of the same acceptors in the total amount of bills which Gilletts re-discounted to the Bank of England. Only merchant banks that are present in both samples are included in the figure.

In addition, we also compare acceptors in Gilletts' bill portfolio and in the Bank's entire bill portfolio (across all discounters). Out of the 127 acceptors appearing on bills discounted by Gilletts in 1906, only 11 are absent from our dataset. These include 6 foreign banks, 1 Anglo-foreign bank and 4 non-financial firms. Table 4.3 displays the correlation between the importance of the various acceptors in Gilletts' bill portfolio and in our dataset. The coefficient of correlation is 0.52 and goes as high as 0.62 when we exclude foreign banks, which are under-represented at the Bank. The correlation is also strongly positive and statistically significant across all categories of acceptors.

Table 4.3: Correlation between the size of acceptors in Gilletts' and Bank of England's bill portfolios, 1906

Type of acceptor	**Coefficient of correlation**
All	0.52***
All (excluding foreign banks)	0.62***
Merchant banks	0.71***
British clearing banks	0.62***
Anglo-foreign banks	0.55***
Foreign banks	0.75***
Other	0.64***

This table shows the coefficient of correlation between the size of acceptors in Gilletts' 1906 bill portfolio and their size in the Bank of England's aggregate portfolio of re-discounted bills. The size of a given acceptor in Gilletts' bill portfolio is measured through the total amount of bills carrying this acceptor's signature. The size of a given acceptor in the Bank of England's portfolio is measured through its total number of discounters. The correlation is shown for all acceptors in the sample as well as for different categories of acceptors. ***: significant at the 1 per cent level.

Existing sources do not allow systematically comparing bills re-discounted by the Bank of England with the whole population of sterling bills circulating on the London market. It is evident that bills re-discounted by the Bank only represented a small share of the bill market and were not randomly selected. However, our comparison of the Bank of England's bill portfolio with that of one significant private actor on the money market does not reveal manifest quality differences between the two institutions. [79] We do however identify an interesting pattern. Compared to the rest of the discount market, the Bank re-discounted more bills accepted by Anglo-foreign banks and fewer bills accepted by foreign banks. Contemporaries were aware of the Bank's reluctance to re-discount bills drawn on foreign banks. One source for example described how bills accepted by certain foreign banks were considered 'first class' in the market but were 'tabooed' by the Bank of England.[80] This policy may have aimed at supporting British financial institutions in their competition with foreign banks in the acceptance business.

[79] We cannot conclude through a simple cross-check of our data with external sources whether biases in the Bank of England's portfolio of re-discounted bills were due to active discrimination on the Bank's side or to the discounters' own choice to disproportionately re-discount certain types of bills.
[80] Kynaston, *City of London*, p. 282.

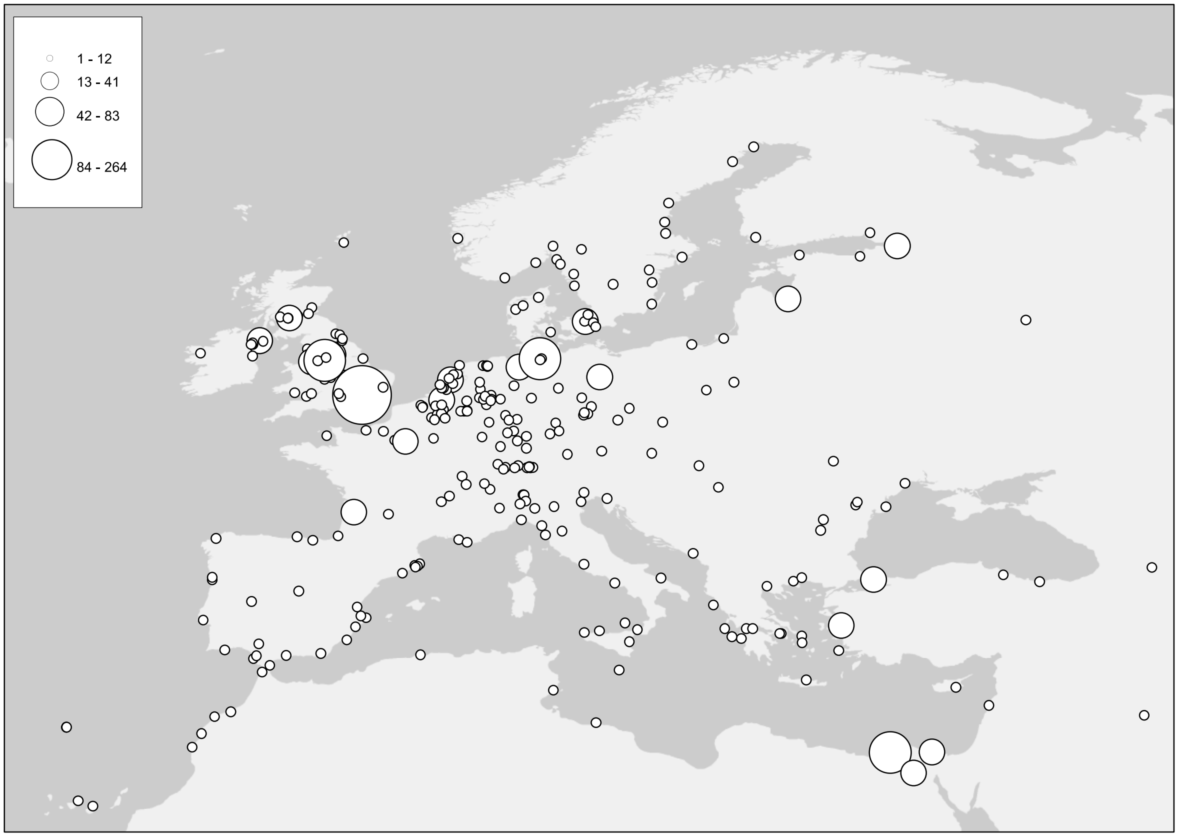
4.4. Anatomy of the London money market

4.4.1. Information asymmetries and the money market

We first use our data set to document where the debts underlying sterling bills re-discounted by the Bank of England were originated. Figure 4.1 showed how the drawers of bills were dispersed geographically. Among all the drawers of bills re-discounted in 1906, UK drawers represented only 13.56 per cent; 17.50 per cent of drawers were located in continental Europe, 20.40 and 15.14 per cent were in (respectively) USA/Canada and Latin America, 19.78 per cent in India and the Far East, 5.46 per cent in Africa, 2.11 per cent in Oceania, and 6.05 per cent in the rest of the world.

Not all the drawers of sterling bills were located in the world's largest metropolises or trading centres; many originated from cities with much smaller populations. This phenomenon is evident from the geographical location of European drawers, which Figure 4.6 shows were scattered across the continent. Many drawers of bills were located in smaller localities – especially in Central Europe, Scandinavia, Spain, and Italy – from which we conclude that many foreign local firms had access to London credit facilities. Thus it appears that, at the beginning of the twentieth century, firms from all around the world could borrow on the London bill market.

Figure 4.6: Geographical location of European borrowers (drawers) on the London bill market



This map shows the geographical location (at the city level) of all European drawers of sterling bills in our data set.

How could such diverse and geographically widespread borrowers gain access to the London money market and borrow through sterling bills? The investor in bills of exchange could barely rely on hard indicators to assess the borrowing firms' solvency (let alone their honesty), and their geographical dispersion made it difficult for a distant investor to assess conditions in the various markets where they operated. It follows that there must have been severe information asymmetries between borrowing firms and final investors on the London money market. Such market frictions could well have resulted in credit rationing for borrowers and an absence of lending.[81]

In order to understand how these frictions were overcome, it is essential to look at the role of intermediaries in the production of sterling bills. Before it reached the final investor, each bill was first accepted/guaranteed by an acceptor and subsequently distributed by a discounter.

[81] Stiglitz and Weiss, 'Credit rationing'.

4.4.2. The business of accepting

As we have explained, London acceptors were the guarantors of sterling bills. In case the drawer (or her trading partner) failed to reimburse her debt, the bill remained the acceptor's liability: she was still obliged to repay its bearer at maturity. An acceptor was the first exposed when borrowers defaulted, so she was strongly incentivised to gather detailed information about them.

Among the largest acceptors in the City were the specialised acceptance houses, which accepted bills drawn by their numerous domestic and foreign clients. Archival records of the merchant bank Kleinwort & Co. illustrate the role of these houses in producing private information about borrowers seeking to access the London money market. Founded in 1855, Kleinwort & Co. gradually established itself as a major acceptance house over the second half of the nineteenth century; by 1906, it was the leading acceptor of sterling bills (see Table 4.1). The firm typically offered credit lines under specific conditions to its customers around the globe. Under these arrangements, Kleinwort & Co. committed to accept bills (up to a certain amount) on account of its customers. The conditions of the credit lines – in particular, their total amount and the commission charged for accepting bills – varied as a function of the borrowing firm's credit standing.[82] In order to obtain information on its clients abroad, the house relied on its large network of foreign correspondents to produce detailed reports on clients' positions that described these firms' origins and commercial activities while assessing their financial situation (especially their capital) and the owners' personal qualities. These reports, which were often written in a foreign language, were gathered into 'client information books' and updated frequently.

The type of information gathered about borrowers could be acquired only through frequent contacts with those clients and was rarely quantifiable; thus it was 'soft' information.[83] For example, the information book on German customers described Heine & Fleich – a family business, located in Altona (Hamburg), that specialised in the trade of leather, skins, and furs – as a 'reputable firm' whose 'financial situation is favourable' and is 'considered solvent for its orders'. This report added that, 'on a personal note, the owners are described to us as competent and respectable merchants'. The case of Kleinworts therefore suggests that acceptance houses acted as relationship bankers toward their clients who wanted to borrow on the London money market. Through repeated

[82] See, for example, the *Client Account Ledgers* at London Metropolitan Archives, CLC/B/140/KS04/12/22.

[83] Stein, 'Information Production', p. 1892 defines *soft information* as 'information that cannot be directly verified by anyone other than the agent who produces it'. In contrast, *hard information* is 'verifiable information, such as the income shown on the borrower's last several tax returns'.

interactions with these clients, acceptance houses gathered private information about bill market borrowers.[84]

4.4.3. The special relationship between drawers and acceptors

We hypothesise that, through their information acquisition activities, acceptors made an indispensable contribution to resolving information asymmetries between borrowers and lenders on the money market. To provide quantitative evidence for this proposed mechanism, we rely on the theory of relationship banking. According to this literature, firms on which little public information is available usually borrow from only one or a small number of creditors.[85] Private information about borrowers can be acquired only through repeated transactions, and there are fixed costs involved. Therefore, lending to such borrowers is more efficiently handled by one single intermediary (or a small number of them). In contrast, firms whose standing and creditworthiness are publicly known will more efficiently borrow from a large set of creditors or directly from the capital market.[86] If the activity of accepting (guaranteeing) bills required private information about drawers (borrowers), then we should similarly expect the latter's bills to have been guaranteed by a small number of acceptors. Yet if the acceptor's guarantee had solved the information problem on the bill market, then drawers should have been able to sell their accepted bills to a larger number of discounters. Hence we check for whether the drawers of sterling bills were, on average, connected to more discounters than acceptors.

Our empirical strategy consists of comparing how acceptors and discounters (two different categories of *principals*) established relationships (or *links*) with drawers (or *agents*) on the bill market. We first focus on the 1,381 drawers whose names appear on at least two non-identical bills in our data set.[87] In Table 4.4, panel A reports the average number of acceptors and discounters per drawer. Although there are 1,439 different acceptors appearing in our data set and only 145

[84] See Boot, 'Relationship Banking', p. 10 for a definition of *relationship banking*. The fee charged by acceptance houses compensated them for these information acquisition activities. On the information role of acceptance houses, see Accominotti, 'London Merchant Banks' and ' 'International banking and transmission of the 1931 financial crisis' and Flandreau and Mesevage, 'The separation of information and lending'.

[85] Diamond, 'Financial intermediation'; Sharpe, 'Asymmetric Information'; Diamond 'Monitoring and reputation'; Rajan, 'Insiders and Outsiders'; Peterson and Rajan, 'Benefits of lending relationships'; Berger and Udell, 'Relationship banking and lines of credit'; Boot, 'Relationship banking'; Boot and Thakor, 'Can relationship banking survive competition ?'

[86] Boot and Thakor, 'Can relationship banking survive competition ?'

[87] Drawers for which only one transaction is recorded were, by construction, linked to just one acceptor and one discounter – which prevents us from drawing any conclusions about the structure of their personal linkages. Among the total of 3,554 drawers, 1,381 appear more than once in our data set.

discounters, drawers of bills were on average connected to a smaller number of acceptors (2.83) than discounters (3.33). Whereas the ratio of the acceptor population to the discounter population is 9.92, the median acceptor-to-discounter ratio of drawers is only 1.16. As shown in panel B of the table (row ‘All>1/Observed’), about half of the 1,381 drawers whose names appear on more than one bill had a strictly higher number of discounters than acceptors. In contrast, only 28.67 per cent of the drawers had more discounters than acceptors. This result holds irrespective of the number of transactions in which drawers were involved. Both small drawers (whose names appear on a limited number of bills) and large ones (that were involved in a much higher number of transactions) had, on average, fewer acceptors than discounters (see panel B, rows ‘Observed’).

Table 4.4: Acceptors and discounters per drawer

Panel A: Number of Acceptors/Discounters per Drawer

	Mean	SE	Max	Min
Acceptors				
No. of acceptors per drawer	2.83	(0.08)	38	1
% of all acceptors	0.20	(0.01)	2.64	0.07
Discounters				
No. of discounters per drawer	3.33	(0.08)	36	1
% of all discounters	2.29	(0.05)	24.83	0.69

Panel B: Repartition of Drawers

No. of transactions involved	Total drawers	Discounters > Acceptors	Discounters = Acceptors	Discounters < Acceptors
All > 1				
Observed	1,381	50.25%	21.07%	28.67%
Simulation 1	1,381	0.79%	89.28%	9.93%
Simulation 2	1,381	4.26%	72.21%	23.53%
2				
Observed	558	47.67%	26.70%	25.62%
Simulation 1	558	0.10%	99.06%	0.85%
Simulation 2	558	1.16%	94.65%	4.18%
3				
Observed	239	44.35%	30.54%	25.10%
Simulation 1	239	0.34%	97.20%	2.46%
Simulation 2	239	3.42%	85.26%	11.32%
4				
Observed	158	58.86%	13.92%	27.21%
Simulation 1	158	0.55%	94.44%	5.01%
Simulation 2	158	5.70%	73.00%	21.30%
5–9				
Observed	286	55.59%	12.23%	32.16%
Simulation 1	286	1.47%	84.39%	14.14%
Simulation 2	286	9.50%	46.71%	43.79%
10+				
Observed	140	50.00%	8.57%	41.42%
Simulation 1	140	3.24%	40.91%	55.85%
Simulation 2	140	5.71%	11.67%	82.62%

This table focuses on multi-transaction drawers, or those whose names appear on at least two non-identical bills in our data set. Panel A reports the mean, the standard error, and the maximum and minimum number of multi-transaction drawers per acceptor and discounter. Panel B (Observed) displays the share of multi-transaction drawers with more discounters than acceptors, with as many discounters as acceptors, and with fewer discounters than acceptors. The repartition is shown for all drawers in our data set who have more than one different bill (All > 1) as well as for drawers with different numbers of bills. Panel B (Simulation 1 and Simulation 2) also reports the same repartition in two simulated networks generated on the assumption that links between drawers and acceptors/discounters were formed randomly (for details, see text and the Appendix A.4.A).

Does this pattern reflect a true privileged relationship between drawers and acceptors, or does it arise from pure chance? In other words, given the demography of our network (the relative number of drawers, acceptors, and discounters), would we obtain the same result if links between agents had been formed purely randomly? In order to check this, we follow a standard methodology in social and banking network analysis which consists in comparing observed, 'real world' networks to random ones.[88] More precisely, we compare the distribution of drawers' acceptor-to-discounter ratio with that of a benchmark network (or 'null model') when link formation between drawers and acceptors/discounters is randomised. To that end, we perform two simulation exercises in which we generate 100 random networks (based on the Bernoulli graph model) with the same demography as the observed one but with simulated links (see Appendix A.4.A for details). In Simulation 1, random networks have the same number of nodes and the same number of links as the actual network, but we assume that links between nodes were formed in a purely random way – so that every acceptor/discounter had the same probability of forming a link with a given drawer. In Simulation 2, we again randomly recombine links between drawers and acceptors/discounters, but assume that each acceptor/discounter also maintained the same total number of links (with drawers) in the simulated network as in the actual one. Simulation 2 therefore allows assessing whether the pattern observed in the data does not arise from the individual characteristics of the nodes and, especially, the fact that there existed certain influential acceptors/discounters with a greater likelihood of establishing relationships with drawers. Panel B (rows 'Simulation 1' and 'Simulation 2') in Table 4.4 classifies drawers in the simulated networks according to whether they had more acceptors or discounters; Appendix A.4.A provides full details on simulated and observed distributions of the drawers' acceptor-to-discounter ratio. Appendix A.4.B provides summary statistics for various indicators describing the structural properties of the actual and simulated networks.

If links between nodes had been formed in a random manner, then only a small minority of drawers would have had more discounters than acceptors (0.79 or 4.26 per cent, versus 50.25 per cent in the observed network). Some 40 per cent of the drawers in Table 4.4 appear on only two different bills. If these small, two-transaction drawers had chosen their acceptors/discounters randomly, then an overwhelming majority of them would have had a different acceptor and a different discounter for each bill – and therefore as many acceptors as discounters overall. In the actual network, however, only 26.70 per cent of the two-transaction drawers had as many acceptors as discounters whereas

[88] See Wasserman and Faust, *Social network analysis Methods and Applications*; Nier *et al*., 'Network models'; Iori *et al*., 'Italian overnight money market'; Chinazzi *et al*., 'International financial network'; Craig and von Peter, 'Interbank tiering'; Martinez-Jaramillo *et al*., 'Mexican banking system's network'.

47.67 per cent of them had two discounters but only one acceptor. When instead focusing on the largest drawers (those that had more than 10 transactions), we see that, in the observed network, 50.00 per cent of them had more discounters than acceptors. By contrast, if these big drawers had formed their relationships with acceptors and discounters randomly, only a small minority of them (3.24 or 5.71 per cent) would have had more discounters than acceptors whereas a majority (55.85 or 82.62 per cent) would have established links with a strictly higher number of acceptors than discounters. Thus the evidence indicates that drawers tended to maintain a few relationships with acceptors but had access to a larger pool of discounters. Most drawers of bills could deal only with the limited number of acceptors that held information on them.

Finally, we assess the extent to which acceptors had drawers in common – that is, to what extent they 'shared' drawers. Had acceptors held proprietary information about their drawers, it seems unlikely that drawers would be shared among acceptors. Our findings support this hypothesis. Acceptors tended to share very few drawers (and often, none) with other acceptors. In fact, 40 per cent of the acceptors in our data set did not share any of their drawers, and no acceptor shared drawers with more than 13 per cent of the other acceptors. Yet if the links between drawers and acceptors had formed randomly, then acceptors would be much more likely to share drawers (see Appendix A.4.A).

The acceptors' tendency not to share their drawers is characteristic of markets in which intermediaries hold proprietary information about their customers. Acceptors specialised in guaranteeing the debts of a few borrowers, on which they had acquired information and with whom they had special relationships. The evidence therefore suggests that acceptors played an important role in producing information about borrowers on the London money market and in overcoming market frictions.

4.5. Market structure of the accepting and discounting industries

We next explore how information problems shaped the market structure of the accepting and discounting industries in London. As we have described, the acceptor's guarantee was crucial in the investors' willingness to purchase bills on the money market. Of course, the value of this guarantee depended heavily on the acceptor's reputation. Reputational effects could have resulted in a high concentration of the accepting industry, since a few large acceptors might have been able to capture the reputational rents associated with guaranteeing commercial debts. Indeed, Chapman argues that, during the second half of the nineteenth century, the accepting business became increasingly concentrated around a few specialised merchant banks and acceptance houses.[89] At the same time, the acceptors' information acquisition activities might have suffered from diseconomies of scale. Small, decentralised institutions are widely considered to be more efficient (than are large, hierarchical ones) at acquiring and processing soft information about borrowers.[90] The reason is that the information derived by a bank officer is often difficult for upper management to verify. For example, the qualitative information that Kleinworts obtained about the owners of Heine & Fleich could hardly be verified by anyone other than the agent who had produced it. These diseconomies of scale in the acquisition of soft information could have constrained acceptors' capacity to grow.

Table 4.5: Market concentration in accepting and discounting

	Acceptors	**Discounters**
HHI	116.05	422.53
Highest market penetration	9.14%	19.84%
Market share of top actors		
Top 3	11.21%	23.07%
Top 5	16.63%	33.72%
Top 10	28.10%	55.87%
Top 15	35.95%	71.69%

This table presents several indicators of market concentration for acceptors and discounters of bills re-discounted by the Bank of England: the HH index, the highest market penetration, and the market share of the top 3, top 5, top 10, and top 15 acceptors and discounters. See text for details on these indicators.

Table 4.5 presents indicators of market concentration in the accepting and discounting industries, constructed from the sample of bills re-discounted by the Bank of England.[91] The table provides common measures of concentration: the *Herfindahl–Hirschman index* (HHI),[92] *highest market penetration,*[93] and the *market share*[94] of the top discounters and acceptors in our data set. According

[89] Chapman, *Merchant Banking*.

[90] Stein, 'Information Production'.

[91] The construction of these indicators is based on the number of drawers per acceptor and per discounter.

[92] The Herfindahl–Hirschman index is defined as the sum of the squares of the market shares of all market participants. The index ranges from 0 (in the case of a perfectly competitive market) to 10,000 (in the case of a perfectly monopolistic market).

[93] A firm's market penetration is defined as the share of potential customers it reaches. Market 'penetration' differs from market 'share' in this sense: shares cannot be appropriated by more than one firm, but any number of firms can reach the same customer(s) at the same time. The highest market penetration is the penetration of the firm that reaches the largest

to this evidence, the accepting industry did not exhibit a high degree of market concentration. There is actually much greater concentration in discounting than in accepting: the HHI index is almost four times higher for discounters than for acceptors, and the greatest market penetration is twice for discounters what it is for acceptors. Similarly, the top 15 discounters in our data set captured more than 70 per cent of the market share in discounting, whereas the top 15 acceptors accounted for only a 35 per cent market share in their activity.[95] These results suggest that the very nature of accepting activities, which required maintaining personal relationships with customers abroad, resulted in diseconomies of scale and therefore limited market concentration in the industry.

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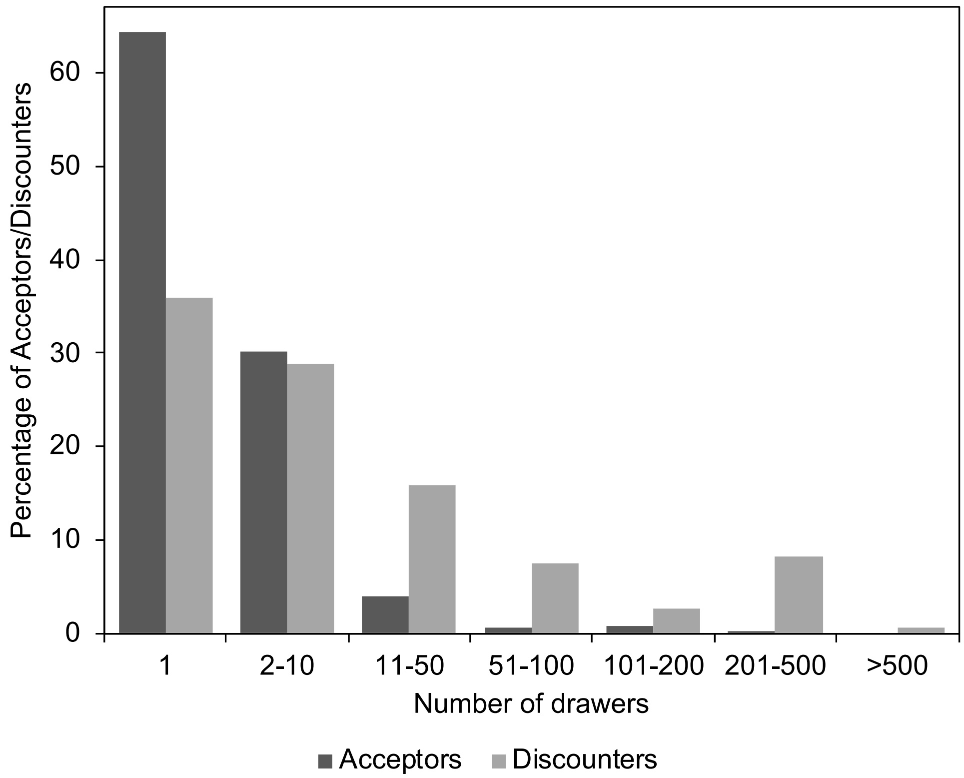
number of potential customers. This metric can range from 0 per cent (when each firm reaches only an infinitesimal share of customers) to 100 per cent (when at least one firm manages to reach all potential customers).

[94] We compute the market share by treating each drawer–acceptor and drawer–discounter relationship as the unit portion of the existing market and then computing their sum. Thus we view the accepting (resp. discounting) market as consisting of 6,075 (resp. 6,758) portions.

[95] The lower market concentration in accepting is due to the fact that a myriad of small and large acceptors coexisted on the money market apart from the most significant acceptance houses (or merchant banks). Although these houses stood among the most significant acceptors in London, they did not enjoy a dominant position in this market.

Figure 4.7: Dual structure of the accepting and discounting industries



This figure shows the frequency distribution of acceptors and discounters in terms of the number of drawers to which they were linked.

In Figure 4.7 we report the frequency distribution of acceptors and discounters with regard to the number of drawers with whom they were connected in the set of re-discounted bills. Both industries were characterised by a 'dual' market structure in that many small actors co-existed with a small number of much larger ones. Most (64.42 per cent) of the acceptors in our data set were connected to one drawer only. These small acceptors were usually trading or manufacturing firms, not financial institutions. At the other end of the spectrum, a small minority (0.83 per cent) of acceptors were connected with more than a hundred drawers. These included the main commercial banks and London acceptance houses such as Kleinwort & Co. (the largest acceptor in our data set), which accepted bills drawn by 325 different drawers.

The discounting industry also exhibited a dual market structure. Among the discounters in our data set, 35 per cent of them were connected with only one drawer and 35 per cent were connected to more than 10 drawers. Yet discounters, unlike acceptors, seem not to have faced diseconomies of scale; those that managed to grow did so to a much greater extent than did acceptors. As a result, a small number of large discounters dominated the market, while a large number of small ones undertook much more limited discounting activities. These differences in market structure explain the higher level of concentration observed in the discounting than in the accepting industry. The largest discounters included the City's leading commercial and merchant banks as well as specialised discount houses such as the Union Discount Company (the largest discounter in our data set), which purchased bills drawn by 705 different drawers.

4.5.1. The business of discounting

A consequence of the market structure just described – and of the limited market power of the large acceptance houses – was that a significant share of the bills produced in London were accepted by small, non-financial firms of modest reputation and on which little public information was available. How could bills drawn on such small acceptors end up on the money market and be brought to the final investors' portfolio?

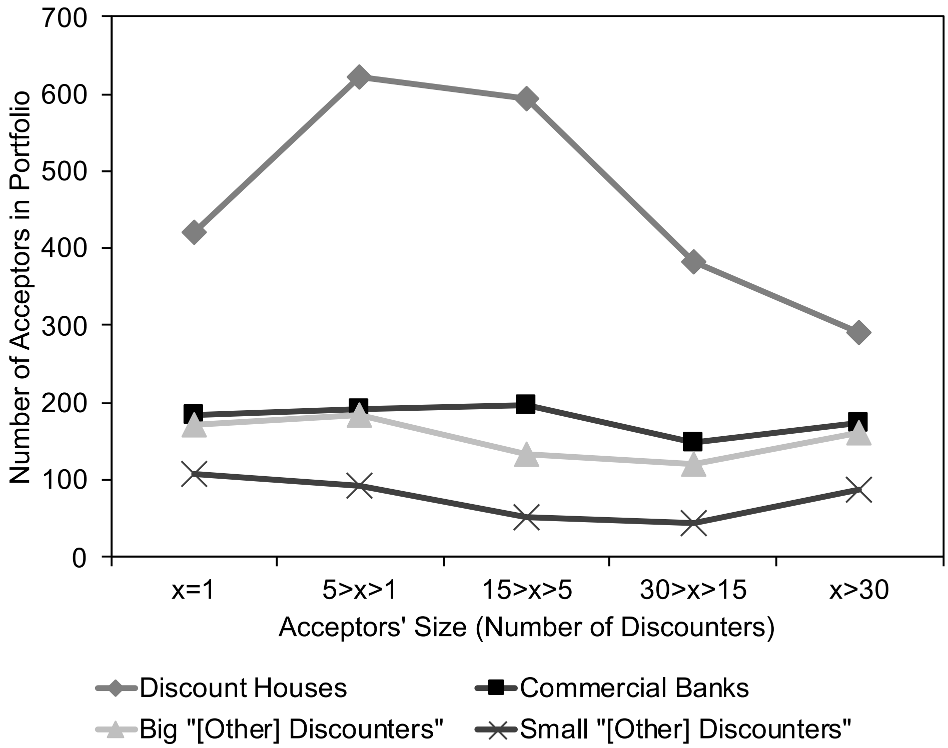
We argue that discounters played an important role in reducing the risk inherent to these bills. After being accepted, sterling bills were purchased by a discounter who then distributed them to a final investor (a re-discounter). In this process, discounters endorsed the bills and added their personal, secondary guarantee to them – that is, in addition to that of the acceptor. Thus discounters served two distinct functions on the money market: they not only distributed bills, but also rendered them more creditworthy.[96] In case the acceptor was not itself a well-known house with a solid reputation, the discounter's guarantee provided an alternative mechanism through which borrowers could sell their bills and obtain credit in London.

To investigate this mechanism, we analyse how discounters selected their bills. The Bank of England categorised discounters into three different types: 'bankers' (all commercial banks, including mostly Anglo-foreign banks), 'brokers' (discount houses), and '[other] discounters' (a mixed bag, which included a variety of UK merchant banks and trading houses).[97] Figure 4.8 shows that these three types of discounters purchased similar proportions of bills drawn on small and large

[96] All the discounters in our data set served these two financial functions. Bills recorded in the Bank of England's *Discount Ledgers* had all been endorsed (and thus guaranteed) by the discounter before being resold to the Bank (the re-discounter).
[97] Of the 145 discounters in our database, 19 were 'bankers' (including three purely domestic banks, one foreign bank, and 15 Anglo-foreign banks), 19 were 'brokers' (i.e. discount houses), and 107 were '[other] discounters'.

acceptors.[98] This means that the various discounters, whether small or large, all took part in distributing the bills accepted by the relatively less well-known, non-financial firms.

Figure 4.8: Discounters' portfolio of acceptors



This figure describes the composition of the aggregate bill portfolios of different types of discounters (discount houses, commercial banks, big '[other] discounters', and small '[other] discounters') by acceptor size. Small '[other] discounters' are those linked to fewer than 18 acceptors, and big '[other] discounters' are those linked to at least 18 acceptors. The size of acceptors (x) is defined as their total number of discounters.

That said, the different discounter types did not all obtain their bills through the same channels. First, smaller UK trading firms and houses (included in the Bank of England's 'other discounter' category) mostly discounted bills drawn or accepted by their own trading partners. They agreed to endorse those bills because they were in a business relationship with the drawers or acceptors and knew there was a sound commercial transaction behind them.

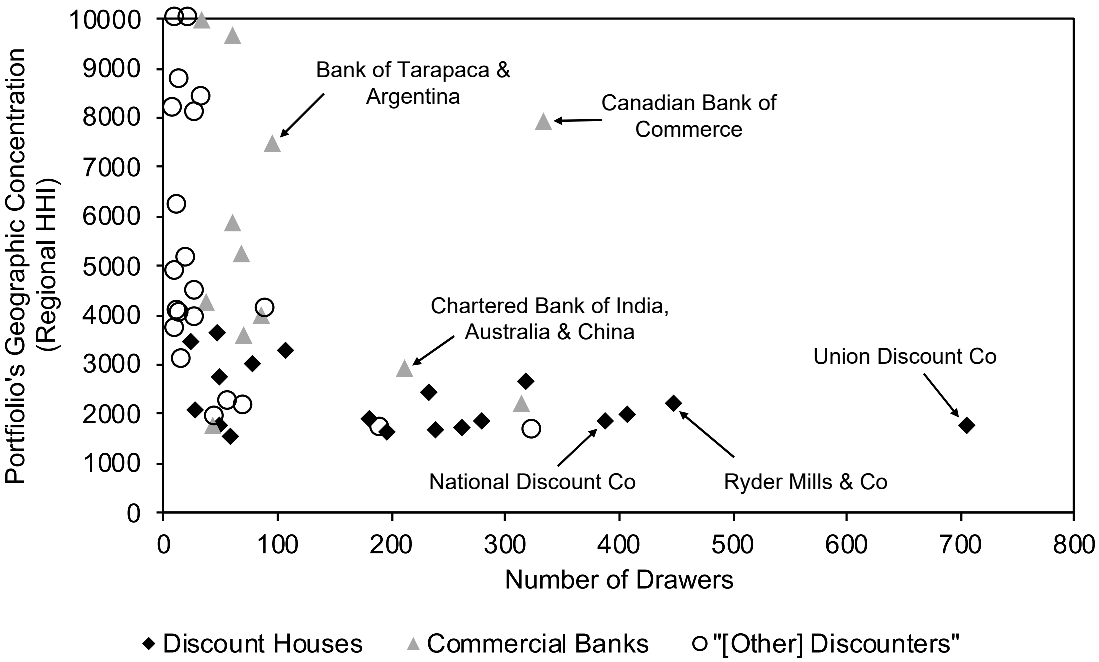
[98] There were so many acceptors that it is not possible to identify the activities in which each was involved; also, there was no geographical variation across acceptors because all of them were based in London. Hence we can classify acceptors only in terms of their size, defined as the number of discounters who had purchased their bills. We do know that most small acceptors were merchant or industrial firms, whereas most large acceptors were established financial institutions such as commercial banks and acceptance houses.

The largest discounters were (on the one hand) discount houses and (on the other hand) Anglo-foreign banks, two types that differed in how they obtained their bills. Discount houses specialised in bill trading. They were in close contact with various acceptors and remitters of bills – London acceptance houses, banks located in foreign countries, Anglo-foreign banks, and various UK importers and exporters that accepted bills drawn on them by their trading partners – and purchased bills through these agents on a daily basis.[99]

In contrast, foreign and Anglo-foreign banks did not focus exclusively on bill discounting, and their business was geographically specialised. They maintained a large network of correspondents or branches in those areas of the world where their activities were concentrated (Jones, 1993). The correspondents shipped these banks a constant stream of bills drawn by their local customers on reputable UK financial institutions and acceptance houses as well as on smaller acceptors, especially trading and manufacturing firms. Foreign and Anglo-foreign banks discounted these bills upon their arrival in London and then either kept the bills in their respective portfolios or distributed them to other investors.[100]

[99] Greengrass, *Discount Market*, pp. 62-65; Vigreux, *Crédit par Acceptation*, pp. 177-78; Truptil, *British banks,* p.126; Sayers, *Gilletts*, p. 37.
[100] Greengrass, *Discount Market*, pp. 64.

Figure 4.9: Discounters' portfolio of drawers



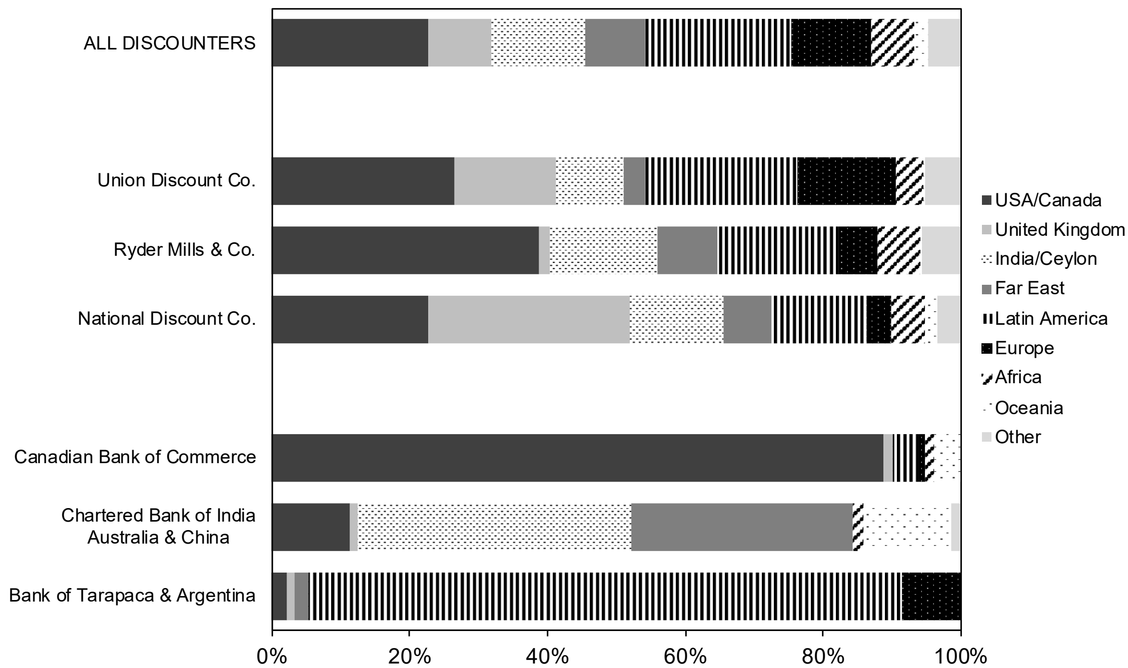
This figure plots the level of geographic concentration of each discounter's portfolio as a function of its size, defined as the number of drawers to whom the discounter is linked. The level of geographic concentration is assessed via the Herfindahl–Hirschman index, defined as the sum of the squares of the market shares of the nine regions in each portfolio; HHI values can range from 1,111 (perfect repartition among the nine regions) to 10,000 (perfect concentration in one region). The graph includes only those discounters (52 of the 145 in our data set) linked to at least 10 drawers. Regions are defined in the text.

The distinction between discount houses and Anglo-foreign banks is clearly apparent when examining bills re-discounted by the Bank of England. Figure 4.9 focuses on all discounters in our data set which had at least 10 drawers and plots the geographical concentration of their bill portfolios (as measured by the HHI)[101] against the total number of drawers with whom they were connected. The figure distinguishes between the three categories of discounters: it includes 12 'commercial banks' (including 11 Anglo-foreign banks and 1 foreign bank), 19 'discount houses', and 21 'other discounters' (merchant banks and trading houses). Our measure of geographical concentration reflects the different business models adopted by these various discounters. Discount houses purchased bills drawn on or remitted to London agents with whom they had a relationship (either directly or through a broker). These bills could be drawn from all around the world, so the

[101] The index is constructed based on the geographical distribution of each discounter's drawers. We classify drawers into nine different regions depending on the city in which they were located.

bill portfolio of a discount house was highly diversified geographically. But since Anglo-foreign banks purchased bills through their foreign correspondents, their portfolios were geographically concentrated.

Figure 4.10: Discount houses versus commercial banks' portfolios of drawers



This figure illustrates the geographical location (via colour key) of the drawers of bills discounted by three discount houses and three Anglo-foreign commercial banks as well as the extent of their representation (via the *x*-axis percentages) in each institution's portfolio. Union Discount Co. was linked to 705 drawers, Ryder Mills & Co. to 447, National Discount Co. to 387, Canadian Bank of Commerce to 333, Chartered Bank of India Australia & China to 212, and Bank of Tarapaca & Argentina to 95.

Figure 4.10 shows the geographical composition of bills discounted by six large discounters: three discount houses (Union Discount Co, Ryder Mills & Co., National Discount Co.) and three Anglo-foreign banks (Canadian Bank of Commerce, Chartered Bank of India Australia & China, Bank of Tarapaca & Argentina). We also compare the geographical composition of these discounters' portfolios with that of the Bank of England's portfolio (i.e., the aggregate portfolio for all discounters in our data set). The discount houses' portfolios did not exhibit any specific geographical bias, and their portfolios matched the distribution of all drawers in the data set. In contrast, nearly all the bills endorsed by Anglo-foreign banks originated in the regions where those banks specialised: 89 per cent of the bills discounted by the Canadian Bank of Commerce were drawn from North America, and 85 per cent of those discounted by the Bank of Tarapaca & Argentina and by the Chartered Bank of India Australia & China originated from (respectively) Latin America and Asia/Oceania.

Through their wholesale activities, then, discounters helped reducing informational asymmetries by screening a large share of the bills on the London money market; because a discounter always endorsed the bills she distributed, their creditworthiness was enhanced by that screening. Although discounters were generally not in direct contact with drawers, they could supply information on the other intermediaries involved in a bill's origination. On the one hand, discount houses endorsed bills drawn from around the world because they knew the acceptors or remitters (either directly, or indirectly through the brokers they used and trusted). On the other hand, Anglo-foreign banks discounted bills originating from specific regions because they were remitted to them by their foreign correspondents, who had previously screened the drawers. In both cases, discounters contributed to reducing the credit risks of bills. Hence, discounters' signatures allowed for a large number of bills to be sold on the money market despite being drawn on small, unknown acceptors.

4.6. Conclusions

This paper has presented new insights into the structure and industrial organisation of the London money market during the heyday of the first globalisation. The sterling bill market was a major pillar of the global financial system and lay at the root of the UK's financial hegemony during the years 1875-1914. Our aim is to uncover the foundations of the sterling bill's high liquidity and safety and to understand why the London money market remained so robust throughout this period.

We construct an original database that tracks the complete origination and distribution chains for all bills of exchange re-discounted by the Bank of England in 1906. Although bills re-discounted by the Bank only constituted a small portion (and were not fully representative) of all sterling bills issued, a detailed analysis of this sample provides new insights into the microstructure of the money market at the beginning of the twentieth century. We first show how borrowers from practically anywhere in the world could borrow on the London bill market. Then we describe the various mechanisms through which information asymmetries between borrowers and lenders were reduced on the money market. Market frictions and informational problems were solved thanks to the intervention of London agents (acceptors and discounters) who guaranteed the bills. All successive intermediaries involved in the origination and distribution of sterling bills contributed to produce information on the debts underlying them. This 'screening cascade' allowed unknown borrowers from even the most obscure parts of the globe to access money market investors in the world's financial capital.

Our analysis therefore reveals the crucial role of information collection – and of case-by-case screening by intermediaries – in transforming risky private debts into liquid and almost riskless money market instruments. The complex industrial organisation of the London discount market and its intermediaries' human capital and expertise were instrumental in positioning London as the world's money market and the UK as the dominant financial power during the first globalisation. The liquidity and safety of the London money market remained unquestioned until the position of bill-trading intermediaries, on which its functioning depended, was threatened by First World War's financial repercussions.[102]

[102] Roberts, *Saving the City*.

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A.4. Appendix A: Network simulations

This appendix provides details on the network simulations presented in Section 4.4. The purpose of these simulations is to assess whether the pattern that emerges from our data set about the number of links that drawers formed with acceptors versus discounters is not simply an artefact of the network's demography (the number of drawers, acceptors and discounters) or of the nodes' individual properties. Our data shows that drawers on the sterling bill market tended to form fewer links with acceptors than discounters. But does this pattern differ from what would have been observed if links between nodes had been formed randomly? To check this, we compare the structure of the actual network of agents with two simulated benchmarks (or null models) when link formation between nodes is randomised.

In the first benchmark, Simulation 1, we generate 100 random networks with the same number of nodes (1,361 multi-transaction drawers, 943 multi-transaction acceptors, and 119 multi-transaction discounters) and the same number of links as the actual one. We randomly recombine links between drawers on the one hand and acceptors/discounters on the other hand. This first simulation is based on a simple conditional U/L distribution[103] where the number of nodes and ties is fixed. In this scenario, each acceptor (resp. discounter) has the same likelihood as any other acceptor (resp. discounter) to form a link with a drawer. In other words, each acceptor/discounter appears on roughly the same number of bills.[104] Simulation 1 allows us to visualise the distribution of drawers' acceptor-to-discounter ratios had links between nodes been generated in a purely random fashion.

In our second benchmark, Simulation 2, we generate 100 random networks with the same number of nodes, the same number of links, and the same degree distribution (the total number of links of each node) as the actual one. Simulation 2 (known as 'degree preserving randomisation' in social network analysis) therefore better accounts for acceptors/discounters differing in their respective abilities to form links with drawers. Thus, in the language of social network analysis, we account

[103] Wasserman and Faust, *Social network analysis Methods and Applications.*

[104] In order to produce this scenario, we divide the total number of transactions involving the 1,361 multi-transaction drawers (6,715 transactions) by the number of acceptors (943) and the number of discounters (119). We then create two columns: one listing all acceptors and one listing all discounters. In the acceptors' (respectively, discounters') column, each acceptor (respectively, discounter) appears as many times as in the observed network (rounded up to the nearest integer value). Thus, since the observed drawer-to-acceptor ratio is 7.12, each acceptor appears 8 times in the acceptors' column. Since the observed drawer-to-discounter ratio is 56.43, each discounter appears 57 times in the discounters' column. We then produce simulations through a process of column building by randomly associating drawers in the original drawers' column with acceptors (respectively, discounters) in the newly-constructed acceptors' (respectively, discounters') column. Each recombination of the 6,715 rows constitutes one simulated network. We repeat this procedure 100 times in order to produce 100 different simulated networks.

for various nodes having different 'relational capacities'. In the simulated networks, each node also has the same total number of links (or degree) as in the actual data. Formally, this random model is based on a simple U/L distribution with specified in-degree and out-degree.[105] This means that each acceptor/discounter has the same likelihood of forming a link with a drawer in the simulated network as in the observed network.[106] Simulation 2 allows us to check whether the pattern we observe in the data about drawers' acceptor-to-discounter ratio does not simply arise from the fact that various acceptors/discounters had different relational capacities (total number of links).

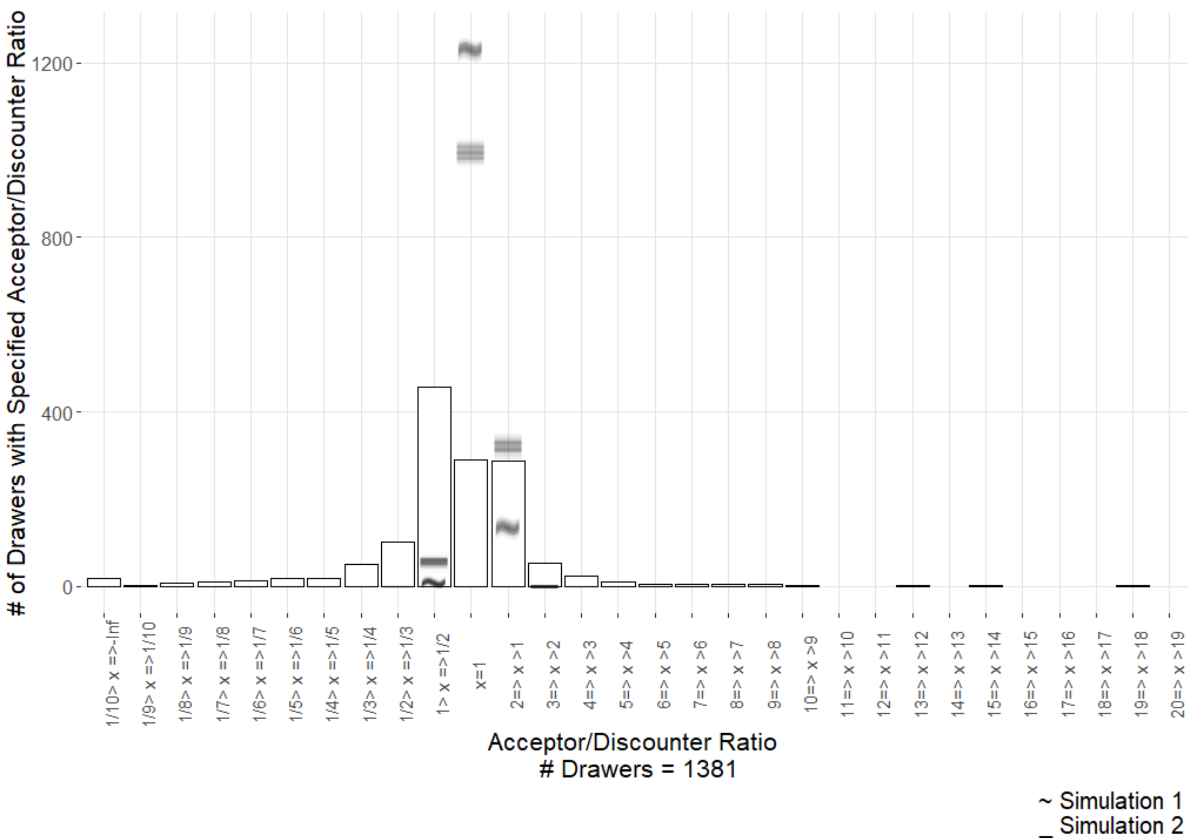
Figure 4.A.1 plots the frequency distribution of drawers' acceptor-to-discounter ratio in the actual data (white bars) together with the frequency distribution of the same variable in random networks generated according to our two simulations.[107] For each of the 100 networks generated through simulation 1 (resp., simulation 2), a grey tilde (resp., a grey line) indicates the number of drawers with a given acceptor-to-discounter ratio.

[105] Wasserman and Faust, *Social network analysis Methods and Applications.*

[106] This scenario is also produced through a process of column building. Each actor's likelihood to appear is unchanged with respect to the observed data. In order to produce a simulated network, we now simply recombine the original acceptors' and discounters' columns while keeping the original drawers' column fixed. Hence, each acceptor and discounter has as many transactions in the simulated network as in the observed one, while the pattern of these transactions is redefined randomly. We then repeat this procedure 100 times in order to produce 100 simulated networks.

[107] In order to check if the actual and simulated distributions of drawers' acceptor-to-discounter ratios are statistically-significantly different from each other, we perform a two-sample Kolmogorov-Smirnov (KS) test. The KS test is a non-parametric test which allows comparing two cumulative distribution functions under the null hypothesis that the two distributions are equal. The test compares the unaggregated frequency distribution of our actual network with the unaggregated frequency distribution of each random network we generate. For each simulated network, the test shows p-values close to 0, indicating that the frequency distributions of the actual and random networks are statistically-significantly different from each other. The KS statistic represents the maximum distance between two compared distributions. This statistic ranges from 0.4909 to 0.5018 when comparing the actual distribution of the acceptor-to-discounter ratio to the 100 distributions generated through Simulation 1. It ranges from 0.4569 to 0.4772 when comparing the actual distribution to the 100 distributions generated through Simulation 2. This indicates that all simulated distributions are far apart from the actual distribution (even though, as expected, the distance between actual and simulated distributions is smaller in the case of Simulation 2).

Figure 4.A.1: Acceptor/discounter ratios: Observed versus simulated



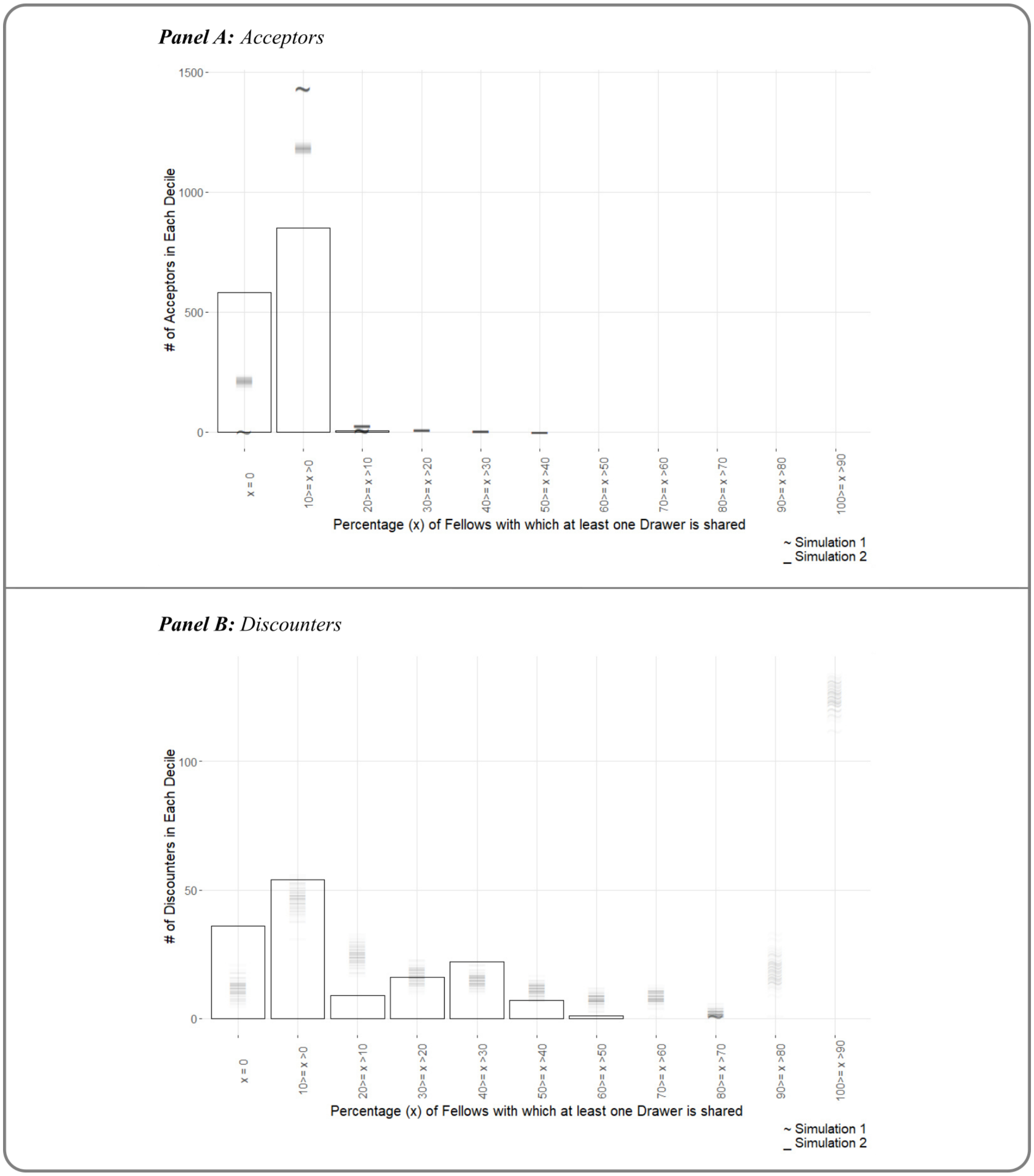
The figure plots the frequency distribution of the 1,381 multi-transaction drawers according to their acceptor-to-discounter ratio (denoted by x on the horizontal axis) in the observed network (white bars) as well as in simulation 1 (grey tildes) and simulation 2 (grey lines). Drawers for whom $x < 1$ are linked to more discounters than acceptors. Drawers for whom $x = 1$ are linked to as many discounters as acceptors. Drawers for whom $x > 1$ are linked to more acceptors than discounters. Each tilde (line) indicates the number of drawers in the corresponding decile for each of the 100 simulations (we do not report a tilde or line when there is no drawer in the corresponding decile).

In the actual network, most drawers have an acceptor-to-discounter ratio that is strictly less than 1 (i.e., they have fewer acceptors than discounters). But if links between nodes had been generated randomly, then (a) an overwhelming majority of drawers would have displayed an acceptor-to-discounter ratio of exactly 1 – that is, an equal number of acceptors and discounters – and (b) a higher proportion of drawers would have exhibited a ratio strictly greater than 1 (more acceptors than discounters) than strictly less than 1 (more discounters than acceptors). This outcome reflects that the network includes more acceptors than discounters. It is also worth noting that more outliers appear in the observed network than in the simulated ones, which suggests that the determinants of link formation behaviour varied greatly for different actors.

Finally, we investigate the extent to which acceptors (discounters) had drawers in common. Figure 4.A.2 reports the frequency distribution of acceptors (panel A) and discounters (panel B) according to the percentage (x) of fellow acceptors/discounters with whom they shared at least one drawer.[108] In each case, we report the observed distribution (white bars) in the actual network as well as the distributions in the simulated networks obtained through simulation 1 (grey tildes) and simulation 2 (grey lines).

[108] We equally perform a KS test to compare the actual and simulated distributions of these variables. For the acceptors' 'shared drawers' variable, we find p-values close to zero indicating that the actual and simulated distributions are statistically significantly different from each other; the maximum distance between the actual distribution and the 100 distributions generated ranges from 0.7400 to 0.7665 for Simulation 1, and from 0.2605 to 0.3148 for Simulation 2. In the case of the discounters' 'shared drawers' variable, p-values are again close to zero; the maximum distance between the actual distribution and the 100 distributions generated is always equal to 1.000 for Simulation 1,while it ranges from 0.2206 to 0.3379 for Simulation 2.

Figure 4.A.2: Shared drawers: Observed versus simulated



This figure plots the frequency distribution of acceptors (panel A) and discounters (panel B) according to the percentage (x) of fellow acceptors/discounters with whom they share at least one drawer in the observed network (white bars) as well as in simulation 1 (grey tildes) and simulation 2 (grey lines). Acceptors/discounters for which x = 0 do not share any drawer with any of their peers, whereas acceptors/discounters for which x = 100 share at least one drawer (not necessarily the same) with all other fellow acceptors/discounters. Each tilde (line) indicates the number of drawers in the corresponding decile for each of the 100 simulations (we do not report a tilde or line when there is no drawer in the corresponding decile).

In the observed distributions we can see that acceptors were less likely than discounters to share drawers with their peers: 40 per cent of the acceptors in our data set did not share any of their drawers with other acceptors, although more than 75 per cent of the discounters shared at least one drawer with other discounters. No acceptor shared a drawer with more than 13 per cent of the other acceptors, but a sizable group of discounters shared drawers with more than 40 per cent of their fellow discounters.

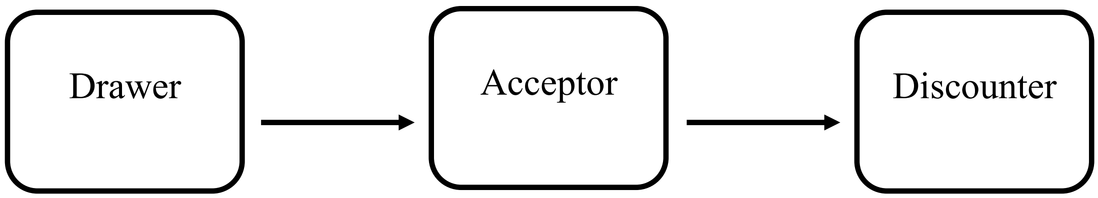
If links between drawers and acceptors had been formed randomly, then acceptors would (on average) have shared more drawers among them than they actually did (Figure 4.A.2, panel A). This means that the tendency of acceptors not to share drawers, which we observe in the data, is due not to our network's structural characteristics but rather to structural factors in the formation of links between drawers and acceptors. The low amount of sharing observed among acceptors in the actual data strongly suggests that they held private information on drawers.

In panel B of the figure we see that discounters were divided into two groups. The small discounters in our data set shared, on average, fewer drawers than predicted by the simulations; however, large discounters shared as many drawers as predicted for the case of randomly formed links between drawers and discounters. These results indicate that, unlike the acceptors, large discounters did *not* hold proprietary information on the drawers.

A.4. Appendix B: Network analysis – Descriptive statistics

This appendix provides descriptive statistics on the network of agents involved in the origination and distribution of bills re-discounted by the Bank of England in 1906. We also provide similar statistics for simulated, random networks (null models, see text and appendix A.4.A).

Figure 4.B.1: Links between a triad of nodes appearing on a bill of exchange



This figure provides a schematic representation of the links between a triad of nodes (or agents) appearing on a same bill of exchange.

As shown in figure 4.B.1, our relational unit is a *triad* involving three roles (drawer-acceptor-discounter). A bill always involves a direct link between its drawer and its acceptor as well as a direct link between its acceptor and its discounter. This means that an indirect relationship also exists between its drawer and its discounter (through the acceptor). Formally, the relation between agents forming a bill's triad is a *compound relation.* This specific feature of our network has implications for the interpretation of standard descriptive indicators used in network analysis. These indicators assume that the relational unit of analysis is a *dyad* (rather than a triad). In the case of our network, this means that standard measures do not account for the indirect relationship that exists between drawers and discounters. This makes the interpretation of standard indicators less straightforward. For example, since an acceptor always lays in the middle of each triad, descriptive measures based on the degree or paths (*geodesic distances*) will tend to overestimate the structural importance of acceptors in the network. The descriptive network measures presented below are therefore not directly comparable to those produced for modern banking networks.

Table 4.B.1: Node centrality - Summary statistics

	In-degree			Out-degree			All-degree		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Actual	0	2.10	357	0	2.10	50	1	4.20	375
Simulation 1	0	2.10	48	0	2.10	10	1	4.20	54
Simulation 2	0	2.10	357	0	2.10	50	1	4.20	375
	Closeness			**Betweenness**			**Eigenvector centrality**		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Actual	0.00	0.03	0.03	0.00	0.00	0.02	0.00	0.00	0.19
Simulation 1	0.17	0.21	0.30	0.00	0.00	0.01	0.00	0.01	0.14
Simulation 2	0.00	0.14	0.43	0.00	0.00	0.01	0.00	0.00	0.34

This table reports summary statistics of various node centrality indicators for the actual network of money market agents as well as for the random networks generated through Simulations 1 and 2 (see text and appendix A.4.A for details on the simulations). For each simulation, Min (Max) correspond to the minimum (maximum) value of the indicator across all nodes in the 100 simulated random networks and Mean corresponds to the mean value of each indicator across all 100 networks generated. By construction, each node in the networks generated through Simulation 2 has the same degree as in the actual network. *Sources*: see text.

Table 4.B.1 reports summary statistics about the importance (or centrality) of the various nodes in the network. A first measure of centrality is the *degree* which corresponds to the total number of links each node has. A node's *in-degree* is equal the total number of links received. In our network, the in-degree corresponds to the total number of dyadic relationships in which a given node plays the role of acceptor of bills drawn by another node or of discounter of bills accepted by another node. A node's *out-degree* is equal to the number of links sent. In our network, a node's out-degree is equal to the total number of dyadic relationships in which a given node plays the role of drawer of bills accepted by another node or of guarantor of bills discounted by another node.

A second way of measuring a node's centrality is through its *distance* or *path* to other nodes (the number of steps the node needs to reach other nodes in the network). There exist two standard distance-based measures of node centrality. First, *closeness* measures how close a node is from all other nodes in the network. It is defined as the inverse of the sum of the lengths of the *shortest paths* (or *geodesic distances*) between a given node and all other nodes in the network. Closeness is usually associated to the node's capacity to impact the rest of the network. A second distance-based indicator is *betweenness* which measures the extent to which a given node acts as an intermediary between other nodes in the network. It is computed by calculating the number of times a node lays on the shortest path between two other nodes in the network (as a fraction of the total number of shortest paths between all pairs of nodes in the network). Betweenness therefore measures a given node's ability to control relationships between other nodes.

Another standard indicator is *eigenvector centrality*, which measures a node's centrality through the centrality of the other nodes with which it is linked. Eigenvector centrality is a weighted degree centrality measure as it weighs a node's links according to their importance.

Table 4.B.1 reports summary statistics for each of these indicators in the actual network and in the random networkq²s generated through Simulations 1 and 2.

Table 4.B.2: Network's structural properties – Descriptive statistics

	Actual	**Simulation 1**			**Simulation 2**		
		Min	Mean	Max	Min	Mean	Max
Clustering	0.038	0.002	0.002	0.003	0.018	0.020	0.021
Closeness centralization	0.002	0.152	0.161	0.178	0.009	0.089	0.317
Betweenness centralization	0.017	0.004	0.006	0.009	0.005	0.009	0.013
Main component	99.3	100	100	100	99.7	99.9	100
Average path length	4.819	6.194	6.973	7.726	4.047	4.253	4.496

This table reports descriptive statistics on the structural properties of the actual network of money market agents as well as of the random networks generated through Simulations 1 and 2 (see text and appendix A.4.A for details on the simulations). For each simulation, the table reports the minimum, maximum, and mean value of each indicator across all 100 simulated networks. *Sources*: see text.

In Table 4.B.2, we also report additional descriptive statistics on the structural properties of the actual and random networks. *Clustering* (sometimes called *transitivity*) is an indicator of the presence of groups of nodes exhibiting relatively more dense interconnections between them. It is computed as the share of all possible sets of three nodes that actually display a complete interconnection. *Closeness* (respectively, *betweenness*) *centralization* is an indicator of the degree of inequality in closeness (respectively, betweenness) among nodes in the entire network. Centralization is computed as the sum of the differences between the most central node's centrality indicator and that of each other node in the network. The values range from 0 to 1, where values close to 0 indicate low inequality across nodes. A *component* is a set of nodes which are all connected to each other by a path. The *main component* refers to the share of nodes which belong to the largest component in the network. A main component of 100 therefore indicates that all nodes in the network are directly or indirectly connected with each other. Finally, the network's *average* *path distance* is defined as the average geodesic distance (or number of steps) between all pairs of nodes. This measure provides information about how relatively close nodes are.

Table 4.B.2 reports the value of each of these indicators for the actual network as well as for the random networks. In the case of random networks, the table reports the range and mean of each measure across the 100 generated networks. Overall, the actual network exhibits higher clustering than the random ones, suggesting that interconnections do not emerge by chance. The actual network also exhibits lower closeness centralization, but higher betweenness centralization than randomly generated networks. This suggests that there were relatively few highly central agents (in terms of closeness) on the bill market, but a few agents nevertheless exhibited strong ability to control relationships between other nodes. The actual network's main component takes a value of 99.3, indicating that only 0.7 per cent of nodes were isolated: this is only slightly lower than the values found in simulated networks. Finally, the actual network's average path length is 4.82, which is close to the average path length in random networks generated through degree preserving randomization (Simulation 2).

Chapter 5 – Bank substitutability and financial network resilience: insights from the first globalization

Abstract:

The recent literature on financial network resilience has paid relatively less attention to the dimension of substitutability than to interconnectedness. In this paper, we apply a simple technique to simulate the upper-bound effects of bank defaults on firms' access to credit at the global level during the first globalization (1880-1914). We find that, in stark contrast to today's financial networks, in the early 20th century the global network displayed considerable resilience to shocks, as the level of substitutability of all banks was relatively high. This finding has implications for regulators, as it shows that a financial network not featuring highly-systemic banks can (and did) actually exist.

Keywords: money market; bill of exchange; financial network resilience; substitutability; chain-based methodology

JEL codes: B40, E42, G23, L14, N20

This chapter is a working paper co-authored with Olivier Accominotti (London School of Economics and CEPR) and Stefano Ugolini (Sciences Po Toulouse), which will be submitted for publication in the near future. The London School of Economics has kindly provided the financial support for the collection of the data used in this chapter.

5.1. Introduction

Since the 2008 crisis, academics and policymakers have been deeply concerned with the question of the identification of *systemic actors* in financial systems. Traditionally, regulators had been mostly identifying systemic intermediaries according to their size (the "too-big-to-fail approach"), but the catastrophic effects generated by the fall of Lehman Brothers (a relatively small bank) brought to light the multidimensional nature of systemicness. In 2013, the Basel Committee on Banking Supervision (BCBS) and the Financial Stability Board (FSB) jointly published new guidelines for the assessment of systemicness, based on five different dimensions of the concept: size, interconnectedness, substitutability, complexity, and cross-jurisdictional activity (BCBS, 2013).[109] Among these five dimensions, *interconnectedness* is the one that has attracted larger academic attention in the last decade or so: many scholars have been applying network analysis and simulation techniques in order to identify "too-interconnected-to-fail" actors, thus reaching a number of important conclusions about the structural properties and resilience of modern financial networks. By contrast, *substitutability* has attracted relatively less attention to date. Assessing substitutability has however proved particularly problematic (Benoit *et al*., 2019), leading regulators to revise their guidelines under this respect (BCBS, 2018).

In this paper, we use simple network analysis and simulation techniques in order to assess more specifically the relationship between actors' substitutability and financial network resilience. Our approach is straightforward: we provide an upper-bound evaluation of network disruption due to financial shocks by looking at how many actors remain isolated once intermediaries are removed. This is an upper-bound estimation as it rests on the (very strong) assumption that no other financial relationship can exist except those that are actually observed – meaning that an agent will lose market access if the intermediaries to which she is connected do default. Applying this methodology to contemporary financial networks yields very catastrophic results: networks break down as central nodes are removed, thus pointing to the high degree of unsubstitutability of a few actors (see e.g. Pröpper *et al*., 2008). This result might be taken as a confirmation of the conclusion (a general one for studies based on contemporary data) that financial networks inevitably feature a few highly systemic actors. However, in this paper we apply this methodology to an historical

[109] *Size* is defined as the total size of the bank's liabilities. *Interconnectedness* consists of the network of contractual obligations that characterize the bank's activities. *Substitutability* (sometimes referred to as "financial institution infrastructure") is defined as the bank's importance as a provider of client services. *Complexity* consists of the business, structural, and operational complexity of the bank (i.e., its involvement in sophisticated activities such as derivatives or other off-balance-sheet exposures). *Cross-jurisdictional activity* is the geographical dispersion of the bank's activities (BCBS, 2013).

financial network and we reach very different conclusions: in our case study, node removal never generates sizable damage in the network, thus pointing to low levels of systemicness for all actors. Note that our case study does not consist of an idiosyncratic, peripheral financial market from an obscure historical epoch, but no less than the global money market at the heyday of the first globalization (1880-1914), when the international economy reached levels of interconnectedness comparable to those of the late 20th century (O'Rourke and Williamson, 2002). We are therefore able to provide, for the first time, evidence that a financial network featuring can exist and *did* actually exist globally at a time of high international integration. In our view, this finding yields potentially important implications for regulators.

The rest of the paper is organized as follows. Section 5.2 reviews the recent literature applying network analysis and simulation techniques, and highlights the originality of our paper. Section 5.3 describes our data and details our empirical strategy. Section 5.4 presents our results. Section 5.5 concludes and offers some speculations for regulators.

5.2. Literature review

5.2.1. Financial stability and network analysis: introduction

The 2008 crisis has proved that the failure of relatively small but highly interconnected intermediaries can lead to a large-scale breakdown of the financial system, generating huge economic and social costs. As a result, the study of the topology of financial systems, mobilizing network analysis techniques, has gained considerable momentum in recent years. The "macroprudential" network perspective questions the traditional "microprudential" assumption that the financial system is safe as long as each individual intermediary is safe, and highlights the importance of relational structures as a driving factor of the robustness of the system. The pioneering work of Allen and Gale (2000) has been the first to underline the role of the topology of the financial network, and more concretely its connectivity, on default contagion. Another founding block of this literature is the work of Freixas *et al*. (2000), who focused on the structural importance that some individual actors may acquire, and urged regulators to switch from the traditional "too-big-to-fail" approach to a "too-connected-to-fail" approach. Since then, the number of studies taking a network perspective has increased, addressing both the effect of network structure on the dynamics and resilience of the financial systems and the processes of network formation (Allen and

Babus, 2009). Useful surveys of this substantial research effort include Glasserman and Young (2016), Battiston and Martinez-Jaramillo (2018), Caccioli *et al*. (2018), and Iori and Mantegna (2018).

In this section, we do not aim to provide an exhaustive summary of this literature, but only to focus on the aspects that are more relevant from the perspective. The first one is the question of the availability of information about financial interlinkages – an issue that has "daunted" a large part of the research that has been conducted so far. The second one has to do with the typologies of network structures that the literature has been finding (or generating) while dealing with financial networks. The third aspect we focus on is the way in which shocks are simulated in order to test the resilience of network structures. Last (but not least), we look at the interconnection between financial and non-financial networks, in order to see how the transmission of financial shocks to the real economy has been tackled by the literature.

5.2.2. Data availability

The issue of the nature and treatment of data has been seldom addressed from a critical perspective. Most financial markets, especially interbank markets, are characterized by a high degree of opacity concerning the distribution and size of financial exposures (Espinosa-Vega and Solé, 2010; Upper, 2011; Blasques *et al*., 2015). As a natural strategy, researchers have often chosen to make estimations of the exchanges when primary data were not available, inferring bilateral credit relationships from balance sheet or payments data (Furfine, 1999; Upper and Worms, 2004; Allen and Babus, 2009; Upper, 2011). It is through this practice that it has been possible to reconstruct the structure of the interbank networks of e.g. Switzerland (Sheldon and Maurer, 1998), Austria (Boss *et al*., 2004), Belgium (Degryse and Nguyen, 2004), Germany (Upper and Worms, 2004), the UK (Wetherilt *et al*., 2010), or the US (Bech and Atalay, 2010).

Since the quality of an analysis depends on the quality of its data, these estimation practices have been criticized (Upper, 2011). Some comparative analyses have pointed to some serious problems in using estimated data. For instance, after comparing simulated and actual data on the Italian interbank network, Mistrulli (2011) concluded that simulations may overstate contagion. More recently, Anand *et al*. (2018) performed a 'horse race' between different methods for reconstructing complete interbank networks from incomplete datasets, only to conclude that no optimal method does actually exist. As a result, while relatively rare, original databases on actual network structures are naturally superior and potentially more insightful (Iori and Mantegna, 2018, pp. 651-3). This justifies the wealth of research that has been conducted on the Italian interbank network, which is the only one for which complete transaction data are actually available (see e.g. Iori *et al*., 2008; Fricke and Lux, 2015a, 2015b; Iori *et al*., 2015; Temizsoy *et al*., 2015).

Another important limitation of many of the researches in this literature is the fact that the nature of the databases they rely on is actually strictly national. Papers taking an international perspective only look at country-country linkages rather than individual linkages (Espinosa-Vega and Solé, 2010; Minoiu and Reyes, 2013; Chinazzi *et al*., 2013; Minoiu *et al*., 2015). One exception is the research conducted on syndicated loan networks (Hale *et al*., 2016; Cai *et al*., 2018), but this is based on data from a rather "niche" market whose representativeness of the broader interbank network remains unclear. As a result, to the best of our knowledge, no database on the global financial network has been available to researchers to date.

5.2.3. Network structures

Reconstructing the structural properties of financial networks is key in order to assess their resilience to shocks and its implications for policymakers. One very relevant property is the presence of a *core-periphery structure*, which can be measured through several indicators as the *degree distribution*[110] or the level of *disassortativity*.[111] The idea is to identify if there exists a small group of highly-connected actors centralizing flows and thus playing the role of "hubs". This has important implications in terms of the vulnerability of the network to shocks. As much as in the general literature on networks (e.g. Albert *et al*., 2000; Newman, 2003), in the financial literature core-periphery structures present a high degree of robustness to random shocks to individual actors, but they become extremely fragile when shocks involve actors playing the role of hubs – a situation known as the "*robust-yet-fragile*" tendency (Gai and Kapadia, 2010).

Empirical studies on modern financial networks generally found core-periphery structures (in some cases referred as *scale-free* structures)[112] with high levels of disassortativity (Craig and Von Peter,

[110] The hierarchy refers to the distribution of the nodes' degree in a network, and a network is hierarchical if a small number of actors are significantly higher than most actors in the network.

[111] The assortativity is a measure of similarity usually based on node degree correlation, and a network is assortative if nodes with high/low degree are connected to actors with also high/low degree.

[112] In theory, core-periphery and scale-free structures are not the same thing. In practice, however, it is difficult to discriminate between the two in empirical investigations. The reasons why this is the case are explained by Iori and Mantegna (2018, p. 645).

2014). This is the case of domestic interbank networks e.g. in Austria (Boss *et al*., 2004), Germany (Upper and Worms, 2004), Switzerland (Müller, 2006), the UK (Wetherilt *et al*., 2010), or the US (Soramäki *et al*., 2007). Analyses of the global country-to-country financial network (Minoiu and Reyes, 2013; Chinazzi *et al*., 2013) equally found evidence of core-periphery, disassortative networks. In the words of Fricke and Lux (2015b, p. 391), "a similar hierarchical structure […] might be classified as a new 'stylized fact' of modern interbank networks".

Only a minority of empirical studies found evidence of less hierarchical structures, featuring a weaker core-periphery structure and lower levels of disassortativity. This was viz. the case for domestic interbank networks in Italy (Iori *et al*., 2008; Fricke and Lux, 2015a), the Netherlands (Blasques *et al*., 2015), and Mexico (Martinez-Jaramillo *et al*., 2014). These findings have led some authors to criticize the use of scale-free models in the reconstruction of network structures from partial data (Martinez-Jaramillo *et al*., 2014; Fricke and Lux, 2015a; Anand *et al*., 2018).

5.2.4. Shock simulations

The network approach is a useful way to represent contagion due to externalities, but different types of mechanisms can generate financial contagion: these include defaults, distress that is not conducive to default, the common structure of assets, or the common structure of liabilities (Battiston and Martinez-Jaramillo, 2018, pp. 7-8). As the concern of our paper is with market access, we limit our review to the question of defaults. As a matter of fact, this is the issue that has been vastly dominating the literature on financial network resilience. Since the pioneering work of Allen and Gale (2000), several papers have applied shock simulation techniques (sometimes drawn from epidemiologic models) in order to understand if and how "epidemies" (cascades) of defaults might develop in financial networks (see esp. Gai and Kapadia, 2010).

Two main approaches to the modelling of default cascades can be found in the literature. The most common one has been initiated by the seminal paper of Eisenberg and Noe (2001), who modelled default cascades in the payment network as a function of interbank exposures: every node suffers a shock from its incoming links and spreads it proportionally through its outcoming links. Eisenberg and Noe's (2001) "fictitious default algorithm" has been used and developed by a number of scholars (including e.g. Müller, 2006; Battiston *et al*., 2012a, 2012b; Acemoglu *et al*., 2015; Glasserman and Young, 2015) in order to simulate "domino effects" in the interbank market. This methodology yields several advantages, but it also has some drawbacks. The first one is that it requires very restrictive assumptions on the way contagion spreads across the network: the behaviour of each node is necessarily mechanical, which casts doubts on its usefulness for policy guidance (Allen and Babus, 2009; Upper, 2011). The second drawback is that this methodology is very much demanding in terms of information, as it requires complete interbank exposures to be known. As such information is often unavailable, however, the precondition to its application is that complete interbank exposures are reconstructed from partial data through some estimation techniques (see above), which raises doubts on its adequacy to represent real-world shocks.

An alternative (and much simpler) methodology consists of merely suppressing defaulting nodes, and thus measuring the damage that such suppressions generate to the network's connectivity. This methodology is quite popular in network analysis (see e.g. Albert *et al*., 2000; Newman, 2003; Cohen and Havlin, 2010; Li *et al*., 2015), although less so in the study of financial networks (one example is Pröpper *et al*., 2008). It is obviously less sophisticated than the Eisenberg-Noe approach, but it has the clear advantage of being much less demanding in terms of information, as it only requires the general structure of the network (and not the weight of each link) to be known. In our study, we opt for this simpler methodology, which appears to be more suited for studies focused on the concept of market access and actor substitutability.

5.2.5. Bank-firm networks

The overwhelming share of the network-based literature on financial contagion has focused on interactions between financial intermediaries (bank-bank networks). Only a handful of papers have managed to go beyond this limitation, by adding to bank-bank links also bank-firm links. As a matter of fact, bank-firm relationships are essential to understanding the transmission of financial contagion to the real economy, but the availability data on such relationships has been very limited to date. The few cases for which information has been made available include Japan (De Masi *et al*., 2011), Italy (De Masi and Gallegati, 2012), and Brazil (Silva *et al*., 2018). The "stylized facts" retrieved from such empirical investigations have inspired the model of Lux (2016), which allows simulating the spillovers of financial contagion from bank-bank to bank-firm relationships.

One common feature of all these papers is the fact of representing bank-bank and bank-firm links as two different layers of the same multiplex network. This kind of representation has a number of advantages, yet the analysis of interactions between the different layers of multiplex financial networks still remains in its infancy (Battiston and Martinez-Jaramillo, 2018, pp. 11-3; Iori and

Mantegna, 2018, pp. 647-8). Moreover, representing bank-bank and bank-firm relationships as *de facto* two different (albeit interconnected) networks may obfuscate the gatekeeping role often played by financial actors. As a matter of fact, banks lending to firms are most often used to refinancing themselves from other banks, thus only playing the role of "bridges" between the borrower and the ultimate lender. In such a case, the "bridging" function implemented by gatekeepers is lost in this kind of representation (on this point, also see Bonacich *et al*., 2004). As we want to focus specifically on this function, we therefore opt not to represent our data through a multiplex network, but rather through a hypergraph (see below, Section 5.3.2). To our knowledge, we are the first ones to do so in the literature on financial contagion.

5.2.6. Literature review: summary

Our review of the network-based literature on financial contagion allows drawing a number of considerations. a) The crucial role of network structures in determining the path and extent of financial contagion is now universally acknowledged for contemporary financial systems. b) This notwithstanding, only limited information on the complete structure of financial networks is available to date, and scholars have been forced to reconstruct such structures through estimation techniques that present some inconveniences; moreover, most papers have had to take a strictly national perspective, as very limited information exist on global financial networks. c) Based on the above-mentioned reconstructions, most papers have tended conclude that financial networks inevitably assume hierarchical core-periphery structures characterized by a high level of disassortativity; only a minority of papers have nuanced (albeit only partially) this very stark view. d) Simulations of "default cascades" have mostly been based on a number of restrictive assumptions, which may limit their ability to represent real-world crises. e) Only a handful of papers have been concerned with the transmission of financial contagion from bank-bank to bank-firm relationships; in all cases, the two types of relationships have been represented as different layers of a multiplex network, yet this does not allow appreciating the "bridging" role (between borrowing firms and lending banks) actually played by some banks.

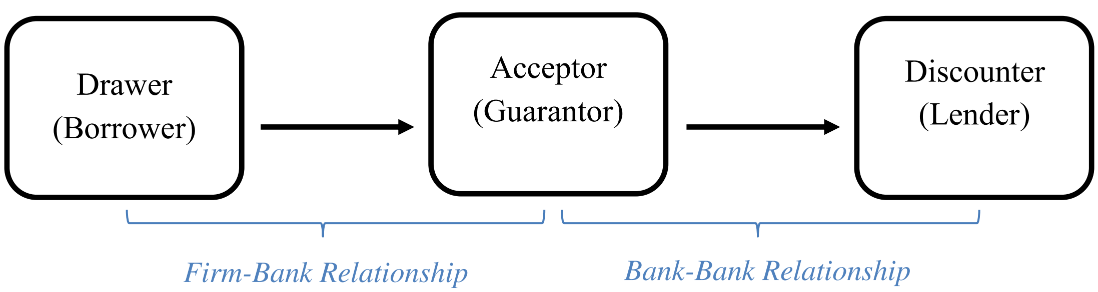
Our paper is therefore original under many respects. a) To the best of our knowledge, this is the first paper to investigate the role of network structures in financial contagion from an historical perspective. b) It is based on observed data on actual financial connectivity rather than on estimated data; moreover, it features data on the global financial network rather than national data. c) In contrast to the findings of the literature on contemporary systems, we evidence the existence of a financial network with a rather weak core-periphery structure and low levels of disassortativity. d) Finally, our data features information not only on bank-bank relationships, but also on bank-firm relationships; moreover, we are the first to focus specifically on the gatekeeping role of banks by representing bank-bank-firm relationships as continuous chains (see below, Section 5.3.2).

5.3. Empirical strategy

5.3.1. Data

Our empirical analysis is based on an original database of global financial interlinkages at the time of the first globalization (1880-1914). In those times, London was the unrivalled global financial centre and the sterling-denominated *bill of exchange* was the staple international money market instrument (Accominotti and Ugolini, forthcoming). Painstakingly hand-collected from archival sources, our dataset includes information on 23,493 bills of exchange issued on the sterling money market during the calendar year 1906. A detailed discussion on the nature and representativeness of these data can be found in our historical companion paper (Chapter 4).

Figure 5.1: The origination and distribution chain of a bill of exchange



As illustrated by Figure 5.1, the origination and distribution of a bill of exchange always involved at least three fundamental actors: one borrower (the "drawer", a firm), one guarantor (the "acceptor", an intermediary), and one lender (the "discounter", generally a bank or a money market fund). As our archival source provides systematic information on all three roles for each bill, we are therefore able to track all borrower-guarantor ("firm-bank") and guarantor-lender ("bank-bank") relationships: this allows us drawing the complete network of interlinkages for the core global money market of the time. We end up with a static network of 4,970 nodes: of these, only 1,680

(33.80%) were located in London, while the rest was spread throughout the five continents (Chapter 4).

5.3.2. Chains

As said (see above, Section 5.2.5), all of the papers studying the effects of financial contagion on the real sector have treated firm-bank and bank-bank relationships as two different layers of a multiplex network. In this paper, we make a different choice. In order to keep the unity of the borrower-guarantor-lender relationship, we treat each bill as a *three-unit chain* or *triad* (drawer-acceptor-discounter), which is a *hyperedge* of a *hypergraph* (forming a *hyperstructure*)[113]. (Criado *et al*., 2010). More formally, within a population of individuals *V*, a bill is a chain C_i defined as a non-empty set $(i, j, k) \in V$ where it exists a borrower-guarantor relationship (iTj) and a guarantor-lender relationship (jUk)[114]: so $C_i = (iTjUk)\ \forall \{i, j, k\} \in V \wedge \{T, U\} \in R$. Additionally, we define a network of chains as a hypergraph $H=(V, E)\ /\ \forall\ C_i\ \exists\ E_i$, or in other words, every chain C_i corresponds to an edge or hyperedge E_i. Representing chains as hyperedges of a hypergraph (forming a hyperstructure) allows preserving the unity and configuration of the chains. Additionally, hypergraphs provide a flexible analytical framework that allows using simple social network measures that cannot be applied to multilayer networks without further adjustments, as e.g. several types of degree centrality (see below).

We are not the first ones to use hypergraphs as a way to preserve supra-dyadic structures. Bonacich *et al*. (2004), Estrada and Rodríguez-Velázquez (2006), and Battiston *et al*. (2020) all stressed that traditional dyadic-based graphs do not provide a complete description of complex real-world systems, and recommended the use of hypergraphs to study "higher-order" (i.e., supra-dyadic) systems. However, common hypergraph approaches (including the ones mobilized in the three above-mentioned works) do not allow preserving the internal configuration of supra-dyadic structures, because they do not reproduce the links existing between individuals and the positions occupied by nodes within such structures. This problem can be solved through the introduction of hyperstructures, as suggested by Criado *et al*. (2010). To illustrate their intuition, these authors give

[113] A *hypergraph* is a generalization of a graph in which an edge (called *hyperedge*) groups one or several nodes, and every node is related to a hyperedge. A *hyperstructure* is an association between an adjacent matrix – which indicates every dyadic link between nodes – and a hypergraph – which groups one or several nodes of the adjacent matrix by hyperedges. Thus, a *hyperstructure* is a hypergraph which includes every dyadic link between nodes.
[114] Note that nodes' specialization is not absolute: in theory, each actor can play all three roles. In our data, however, "hybrid" nodes are relatively rare (see below, Section 5.4.2).

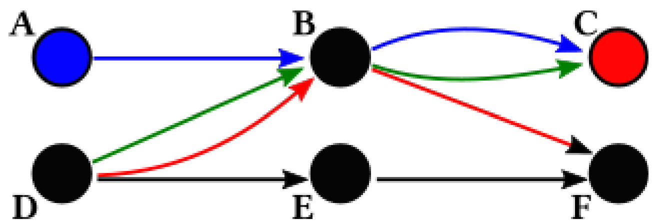
the example of a subway network. This network is composed by the subway stations (the nodes) and the trunks between them (the links). Stations and trunks are grouped as subway lines, which can be considered as substructures of the subway network. Two stations may be separated by the same number of trunks, but a traveller moving between the two will face quite a different situation if the stations are on the same line or not. In order to take this into account, it is convenient to consider the whole subway network as a hypergraph and the single subway line as hyperedges. Then, the hyperstructure will consist of the combination of an adjacency matrix (representing all the stations and the trunks between them) and a hypergraph (where each hyperedge is a subway line, grouping all its stations and branches). Criado *et al*. (2010) only considered hyperstructures with symmetric (non-oriented) relations. Our contributions extend their original intuition by considering hyperstructures with directed (oriented) relations.

5.3.3. Shock simulations in chains

In order to test the resilience of the resulting financial network to shocks, we opt for simple node removal simulations (see above, Section 5.2.4). Specifically, we alternatively simulate the removal of individual *upstream* nodes (guarantors or lenders, i.e. the nodes situated in position 2 or 3 of each chain), and we examine the impact of the suppression in terms of loss of market access for *downstream* nodes (borrowers and guarantors, i.e. the nodes situated in position 1 or 2 of each chain).[115] Thus, the structural relevance of each removed node is measured as the number of downstream actors who are strictly dependent on it in order to obtain market access (i.e, to be connected to an upstream actor). A downstream actor is considered as independent if it is connected to other nodes providing it with access market (i.e., if it has other paths to reach an upstream actor). The number of downstream actors losing market access in case of the removal of an upstream actor is thus taken as the indicator of the degree of substitutability of the latter.

[115] Note that in using the terms "upstream" and "downstream" we do not refer to the direction of links as represented in Figure 5.1 (going from borrowers to lenders through guarantors), but rather to the direction of credit (flowing from lenders to borrowers through guarantors). This is due to our focalization on market access: under this respect, borrowers are actually "downstream" as they depend on market access provided by "upstream" lenders.

Figure 5.2: A fictive example of four different chains connecting six agents



The example provided in Figure 5.2 helps clarifying the rationale of our methodology. The figure visualizes four different chains (i.e. four different bills of exchange, each one represented as a coloured series of arrows). Each chain involves one borrower (position 1 from left to right), one guarantor (position 2), and one lender (position 3). In this example, nodes A and D are specialized as borrowers, nodes B and E are specialized as guarantors, and nodes C and F are specialized as lenders. If we remove node C (a lender), node A (a borrower) loses market access as no alternative upstream path exists for it. In other words, if node C disappears, all the chains in which it is involved (blue and green arrows) also disappears, and this includes the link between A and B, thus making borrower A isolated. By contrast, the suppression of lender C has no impact on market access for borrower D, as the latter is linked to another lender (i.e. node F) via a compound relationship through guarantor E (represented by the red arrows). Notice that if we had implemented a traditional node removal without paying attention to the compound nature of the relationship, the suppression of lender C would have had no impact on the connectivity of borrower A. This, however, would have been oblivious of the reality of market access: as a matter of fact, in reality lender F is unwilling to lend to borrower A, and this path is therefore actually unavailable to A. This underlines the importance of preserving the integrity of actual chains while simulating shocks.

Concretely, we proceed as follows. In our network defined by the hypergraph $H=(V, E) \,/\, \forall C_i \, \exists E_i$ of chains $C_i = (i,j,k)$ defined by $(iTj \cup jUk)$, consider an element $x \in (jUk)$ (i.e., an upstream actor, acceptor or discounter). Any element $y \in C_i \wedge y \neq x$ has an alternative access to the market if $\exists C_j : x \notin C_j \wedge y \in C_j$. On other words, we first identify all the chains in which the given element plays the upstream role of acceptor or discounter (we call it the reference set for this element), and we single out all the other actors involved in these chains. Then we check if each of the individual downstream actors of the reference set is present in any other of the chains in our dataset. If an actor is already present in at least one other chain, we consider it as having an alternative market access: thus, the node is not strictly dependent on the upstream element, as it does not get isolated when the latter disappears. To the contrary, if the actor is not present in any other chain, we consider it as not having any alternative market access: thus, the node is strictly dependent on the upstream element, as it gets isolated when the latter disappears.

5.4. Results

5.4.1. Results: Introduction

In order to test our network's resilience to individual defaults, we proceed as follows. In Section 5.4.2, we provide some descriptive statistics on the network and its structure. In Section 5.4.3, we first apply the methodology described above (Section 5.3.3) and measure the absolute impact of the suppression of individual nodes – viz., the number of nodes that remain isolated following the default of each intermediary. We find that the systemic damage generated by the suppression of individual nodes is always relatively limited, which points to a low degree of unsubstitutability for all nodes. This is our baseline result. In the subsequent sections, we perform a number of robustness checks.

In Section 5.4.4, we ask whether some nodes might have displayed some "local" systemicness: to tackle this question, we measure the relative impact of the suppression of individual nodes – viz., the share of the total downstream nodes that remain isolated. We find that some nodes did display some local unsubstitutability, yet this was mainly the case for nodes with low rather than high absolute impact.

In Section 5.4.5, we measure the "group" systemicness of some (exogenously-defined) groups of intermediaries that are recognized to have played an extremely relevant role in the global financial system. We find that, even in the most catastrophic scenarios (in which an entire segment of the financial sector defaults), our network does not break down completely – which points to relatively low levels of unsubstitutability even for crucial segments of the financial sector.

In Section 5.4.6, we ask whether some nodes might have displayed some "geographic" systemicness – viz., if their removal would leave some geographic locations cut off from the global financial network. We find that some nodes did display some local unsubstitutability, yet this was mainly the case for nodes with low rather than high absolute impact.

Finally, in Section 5.4.7 we measure the degree of vulnerability of geographic locations throughout the world to the default of financial intermediaries in London. We find that on average most cities displayed a relatively limited level of vulnerability, and that such a level was insensitive to city size.

Therefore, all robustness checks are consistent with our baseline result, suggesting that the early-20th-century global financial network displayed a high degree of resilience to individual defaults and was not prone to the "robust-yet-fragile" tendency.

5.4.2. Descriptive statistics

In this section we provide some descriptive statistics concerning the population of our network, and present its macro structure by comparing its degree distribution to simulated both random and free-scale degree distributions.

As explained above (see Figure 5.1), each chain is formed by the sequence of the three roles, where acceptors and discounters may be located only in London, while drawers may be located anywhere in the world (including London). While most individuals are specialized in one role, some take several roles (we call them "hybrids"). Table 5.1 shows the distribution of individuals by role and location, as well as the proportion they represent with respect to the total population and to the population of actors located in London.

Table 5.1: Individuals' specialization and location

Specialization	Population	% of All	% of Londoners
Pure Drawer (outside London)	3,290	66.20%	NA
Pure Drawer (in London)	145	2.92%	8.63%
Pure Acceptor	1,326	26.68%	78.93%
Drawer+Acceptor	64	1.29%	3.81%
Pure Discounter	61	1.23%	3.63%
Drawer+Discounter	35	0.70%	2.08%
Acceptor+Discounter	29	0.58%	1.73%
Drawer+Acceptor+Discounter	20	0.40%	1.19%
TOTAL	*4,970*	*100.00%*	*100.00%*

The table shows an unequal distribution of roles: drawers (borrowers) are the most important group, followed from afar by acceptors (guarantors) and, further, discounters (lenders).[116] Note that 61.71% of drawers (2,193) only appear in one single chain, while this proportion is reduced to 40.47% for acceptors (641) and 17.93% for discounters (26). This distribution suggests a "funnel-shaped" structure, where at each step of the chain the "universe" of individuals potentially playing the role is drastically reduced. On the basis of such demography, it would be reasonable to expect the network to exhibit a core-periphery structure, in which drawers form the periphery that is connected, through the intermediation of acceptors, to the core formed by the discounters. "Hybrid" individuals complexify the structure, since they connect different chains at different levels.

A common way to study the macro properties of a real network is to analyse its *node degree distribution*, and to compare it to the node distribution of "null" networks expressly simulated in order to display some specific properties. This methodology allows unveiling both the macro structure of the real network and the relational dynamics that drive its link creation (e.g. Craig and Von Peter, 2014; Martinez-Jaramillo *et al*., 2014). We follow this standard procedure and compare

[116] Note that the "discounters" in our dataset were *wholesale* lenders (commercial banks, investment banks, money market funds), which in turn played an intermediary role by refinancing themselves from investors and savers. Also see Section 5.4.5 below.

the node degree distribution of our observed network to the degree distribution of 100 simulated random (Erdös-Renyi) networks and 100 simulated scale-free networks displaying the same demography of the observed ones. On the one hand, because in random networks any two individuals have the same probability to be linked to each other, simulated *random networks* are used as baselines (e.g. Iori *et al*., 2015; Chinazzi *et al*., 2013) in order to unveil the existence of any relational dynamics (i.e. any kind of biases) guiding link creation and the formation of the macro structure of the network. On the other hand, simulated *scale-free networks* are used as baseline in order to unveil the existence of one specific relational dynamic – viz., the preferential attachment dynamics, which is conducive to core-periphery macro structures (e.g. Martinez-Jaramillo *et al*., 2014; Iori and Mantegna, 2018). Following the preferential attachment principle, individuals tend to connect preferentially to well-connected actors rather than to poorly-connected ones: this generates core-periphery structures, where most of the population connect to a small group of well-connected individuals. As said above (Section 2c), empirical investigations have mostly found core-periphery structures in modern interbank systems.

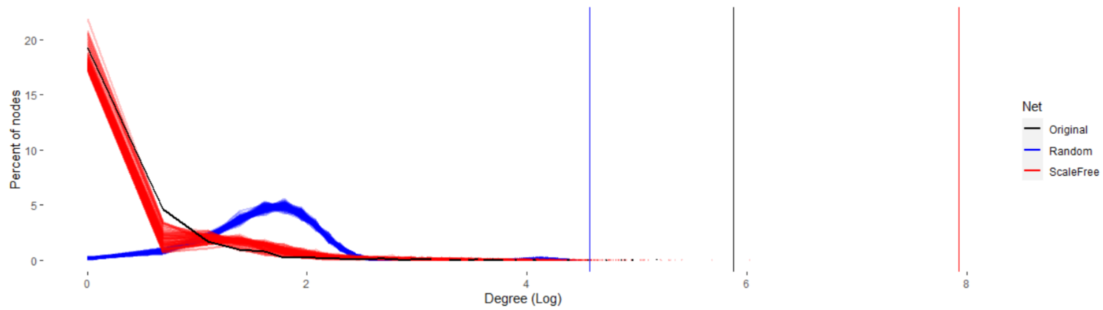
Hypergraphs allow for great flexibility in the definition of network measures, including the node degree (Battiston *et al*., 2020; Kapoor *et al*., 2013). In order to properly describe the macro structure of our network, we use three different definitions of node degree: 1) the node's *in-degree*, defined as the number of its adjacent nodes linked by an input-arc; 2) the node's *hyperedge degree*, defined as the number of node's incident hyperedges – i.e., the number of hyperedges (in our case, chains) in which an individual is involved; and 3) the node's *hyperedge's adjacent nodes degree*, defined as the number of nodes that belong to the same hyperedge (chain).

To build the simulated networks, we keep the original drawers-bills distribution (i.e., we consider that the bills' origin does not change, so each drawer preserves its original number of bills) as well as the original number of individuals in the acceptor and discounter roles. Consequently, simulated networks preserve the same demography and number of chains of the observed network.

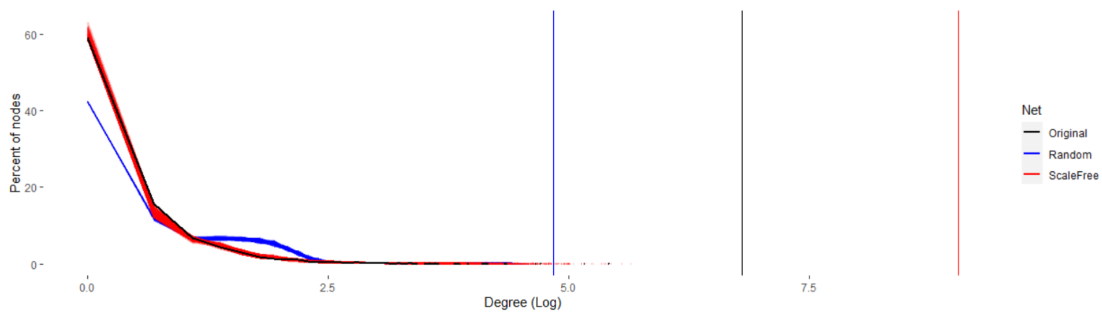
Figure 5.3a-c compares (for each of our three definitions of node degree) the degree distributions of our observed network, 100 simulated random networks, and 100 simulated scale-free networks.

Figure 5.3: Degrees distributions of observed and simulated networks

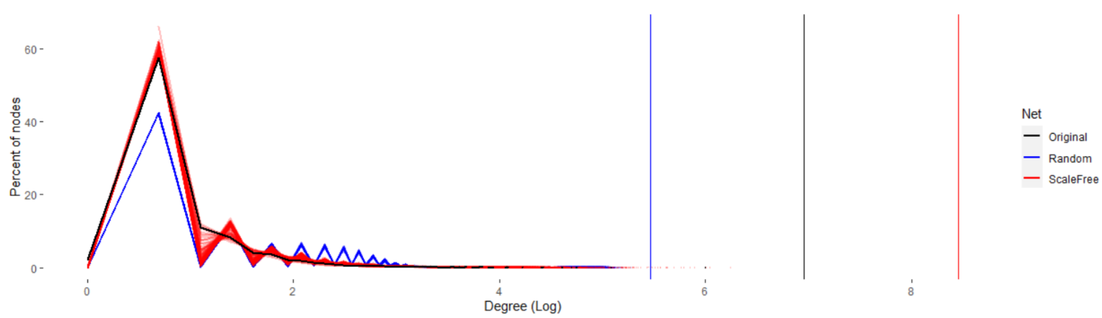
a) In-degree distributions



b) Hyperedge degree distributions



c) Hyperedge's adjacent nodes degree distributions



For each of our three definitions of degree (see text), the figures show the degree distribution of our observed network (black lines), of 100 simulated random networks (blue lines), and of 100 simulated scale-free networks (lines). The x axes represent the degree value through a natural logarithmic scale. The y axes correspond to the percent of individuals sharing the same degree value. Vertical lines (in blue, black, and red) represent the highest degree value for (respectively) random, observed, and scale-free networks. Since all drawers have in-degree 0, they have been removed from Figure 5.3a.

Three features emerge from Figure 5.3a-c. First, the degree distributions of our observed network are very different from those of random networks, which highlights the presence of some kind of relational dynamics in link creation. Second, the degree distributions of the observed network are more similar to, yet still somewhat different from those of free-scale networks. Third, regarding the highest degree for each type of distribution (vertical lines), the ones of the observed network is situated between those of random and those of free-scale networks. These elements suggest that, although there do exist some relational dynamics determining the link creation behaviour, these dynamics do not perfectly follow a preferential-attachment rule, which would be conducive to a core-periphery macro structure.

Some interesting features emerge from a more detailed observation. Hyperedges' adjacent nodes degree distributions exhibit irregular shapes (peaks), esp. in simulated networks (see Figure 5.3c). The first peak is formed by the first three degree values and is common to all types of networks. The first value (corresponding to degree 1) represents an atypical situation in which an individual is involved in chains (usually, one single bill) that include only one other individual – i.e., the chain has one individual appearing twice in two different roles. This is due to the existence of "hybrid" individuals intervening at different steps of the same chain.[117] The presence of this type of behaviour is higher (2.11% of individuals) in the observed network since some intentionality, and not only a statistical probability, is required for this kind of combination to occur. The degree value 2 (top of the peak) is very common (57.56% of individuals in the observed network), and represents a situation where the individual is involved in one or several chains with two other individuals. This situation is typical for drawers, especially those involved in one only transaction. Higher degree values necessarily require the individual to be involved in several chains. The situation where several chains link the individual to three other ones (degree 3) is very unusual in the simulated networks but not in the observed network. This is also the case for higher degree values.

To sum up, the demography of our network would, a first sight, suggest the existence a core-periphery macro structure (as modern interbank networks). Although at this stage we cannot completely reject the "null" hypothesis that link formation in our network is dictated by a preferential attachment rule, the presence of very highly interconnected nodes (represented by the highest degree values) is much lower in our observed network than in simulated free-scale networks with the same demography. This suggests that the sort of "mega-hubs" found in present-day

[117] In our data, this situation occurs in case the same individual plays at the same time the role of drawer (borrower) and discounter (lender) of the same bill. This apparent paradox is due to the fact that discounters were wholesale lenders, and used bills as collateral for refinancing their operations with retail lenders: in some cases, some discounters "created" bills in order to refinance themselves under the guarantee of an acceptor (Chapter 4).

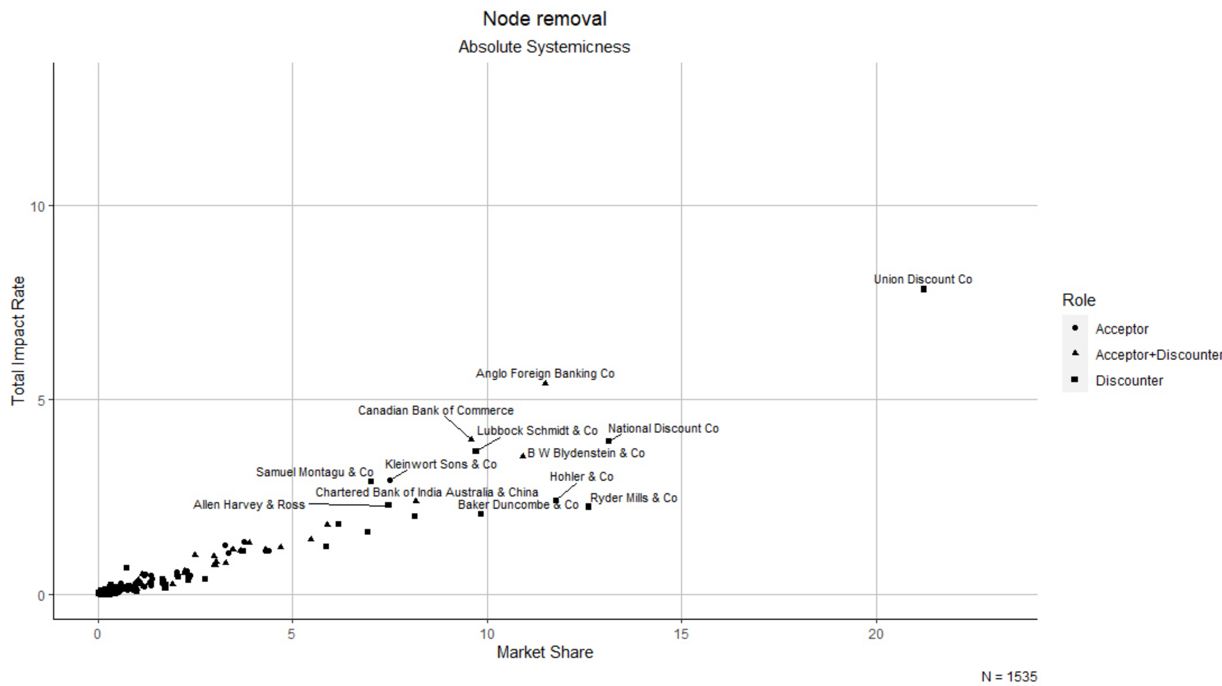
interbank networks did not exist in the early-20th-century global financial network. In what follows, we will address this question more specifically.

5.4.3. Absolute systemicness

As explained in Section 5.3.3, our methodology assumes that removal from the network of one individual implies that the operations (bills) in which it is involved cannot be performed, and the impact of this removal is measured by the number of individuals who strictly depend on those very chains for their market access. As said, this is an upper bound estimate of the degree of unsubstitutability of upstream actors, as it rests on the assumption that downstream actors will not have any chance to connect to any other upstream actor – which is a very restrictive assumption indeed. Thus, in order to assess the *absolute systemicness* of individuals, we remove them one by one from the network, we identify the chains that are impacted, and we count how many individuals are left isolated. We only focus on the absolute systemicness of individuals playing the upstream role of acceptor (guarantor) and/or discounter (lender), which means a total of 1,535 individuals. We do not consider individuals playing the role of drawers (borrowers): since they are located in the beginning of chains, their systemicness is by construction equal to zero.

For each individual i, we compute: (a) the Acceptor Impact $AImp_i$, which is the number of individuals who remain isolated when the individual i is removed from her acceptor role; (b) the Discounter Impact $DImp_i$, which is the number of individuals who remain isolated when the individual i is removed from her discounter role; (c) the Total Impact $TImp_i$, which is the number of individuals who remain isolated when the individual i is removed from her acceptor/discounter role; (d) the Total Impact Rate $TImpR_i = (TImp_i / (n-1))*100$, which is percent of all actors n of the network who remain isolated when the individual i is removed; and (e) the Market Share $MS_i = (n_i / (n-1))*100$, which is the share of all the actors in the network (n) who are involved in the same chains as individual i (n_i).

Figure 5.4: Node removal – Absolute systemicness



Market Share (x axis) and *Total Impact Rate* (y axis) of the 1,535 individuals playing the upstream role of acceptor and/or discounter. The names of the individuals displaying a Total Impact Rate higher than 2% (13 individuals) are reported.

In Figure 5.4, we compare the *Total Impact Rate* and the *Market Share* of all 1,535 upstream actors. Two main features emerge from the picture. The first and most important one is that the Total Impact Rate is low for all actors: only two actors do impact more than 4% of market participants if they are removed (i.e. Union Discount Co with 7.83%, and Anglo Foreign Banking Co with 5.41%), while as many as 597 upstream actors have no impact at all. Table 5.2 provides more details on the 31 individuals who have a Total Impact Rate exceeding 1%. As also shown in Figure 5.4, Union Discount Co is by far the biggest actor in the network, with a market share of 21.23%. However, its removal impacts only 7.83% of the network (389 actors), which is relatively low. The following five individuals in the ranking are either pure discounters or hybrids who mainly play the role of discounters. The most systemic pure acceptor, Kleinworth Sons & Co, only comes seventh in the general ranking, with an Absolute Impact Rate of 2.92% in spite of a market share of 7.51%.

Thus, the ranking appears to be dominated by discounters, and esp. by discount houses (money market funds). We shall come back to this issue in Section 5.4.5.

Table 5.2: Descriptive statistics of the 31 most systemic individuals

Rank	*Name*	*Acceptor Impact*	*Discounter Impact*	*Total Impact*	*Total Impact Rate*	*Market Share*	*Category*
1	Union Discount Co	0	389	389	**7.829**	21.232	DH
2	Anglo Foreign Banking Co	4	265	269	**5.414**	11.491	AF
3	Canadian Bank of Commerce	8	192	197	**3.965**	9.600	AF
4	National Discount Co	0	195	195	**3.924**	13.141	DH
5	Lubbock Schmidt & Co	0	182	182	**3.663**	9.720	MB
6	B W Blydenstein & Co	9	167	175	**3.522**	10.928	MB
7	Kleinwort Sons & Co	145	0	145	**2.918**	7.507	MB
8	Samuel Montagu & Co	0	143	143	**2.878**	7.024	MB
9	Hohler & Co	0	119	119	**2.395**	11.773	DH
10	Chartered Bank of India Australia & China	9	109	118	**2.375**	8.171	AF
11	Allen Harvey & Ross	0	113	113	**2.274**	7.466	DH
12	Ryder Mills & Co	0	111	111	**2.234**	12.618	DH
13	Baker Duncombe & Co	0	102	102	**2.053**	9.841	DH
14	King & Foa	0	99	99	**1.992**	8.151	DH
15	Roger Cunliffe Sons & Co	0	89	89	**1.791**	6.178	DH
16	Baring Bros & Co Ltd	61	27	88	**1.771**	5.897	MB
17	Haarbleicher & Schumann	0	79	79	**1.590**	6.943	DH
18	Huth & Co, F	57	13	69	**1.389**	5.474	MB
19	Brown Shipley & Co	66	0	66	**1.328**	3.763	MB
20	Ruffer & Sons	65	0	65	**1.308**	3.884	MB
21	Lloyd's Bank	62	0	62	**1.248**	3.260	CB
22	Brightwen & Co	0	60	60	**1.207**	5.876	DH
23	London & Hanseatic Bank	42	19	59	**1.187**	4.689	AF
24	Bank of Tarapaca & Argentina	27	31	57	**1.147**	4.307	AF
25	Parr's Bank	57	1	57	**1.147**	3.461	CB
26	Brandt's Sons & Co, William	55	0	55	**1.107**	4.307	MB
27	Lazard Bros & Co	25	31	55	**1.107**	3.663	MB
28	Schroder & Co, J H	55	0	55	**1.107**	4.387	MB
29	Alexanders & Co	0	54	54	**1.087**	3.723	DH
30	London City & Midland Bank	53	0	53	**1.067**	3.341	CB
31	Wallace Bros	23	29	50	**1.006**	2.495	MB

Acceptor Impact, Discounter Impact, Total Impact, and Market Share for the 31 most systemic individuals (see text). Note that the *Total Impact* may not be equal to the sum of *Acceptor Impact* and *Discounter Impact*, because although the same drawer may be impacted twice by the suppression of the upstream individual on whom she depends both as an acceptor of her bills and as a discounter of her bills, she would not show up twice in the Total Impact of the upstream individual. For each of the 31 most systemic actors, we also indicate the category it belongs to: discount house (DH), Anglo-foreign bank (AF), merchant bank (MB), or clearing bank (CB). More on these categories in Section 5.4.5.

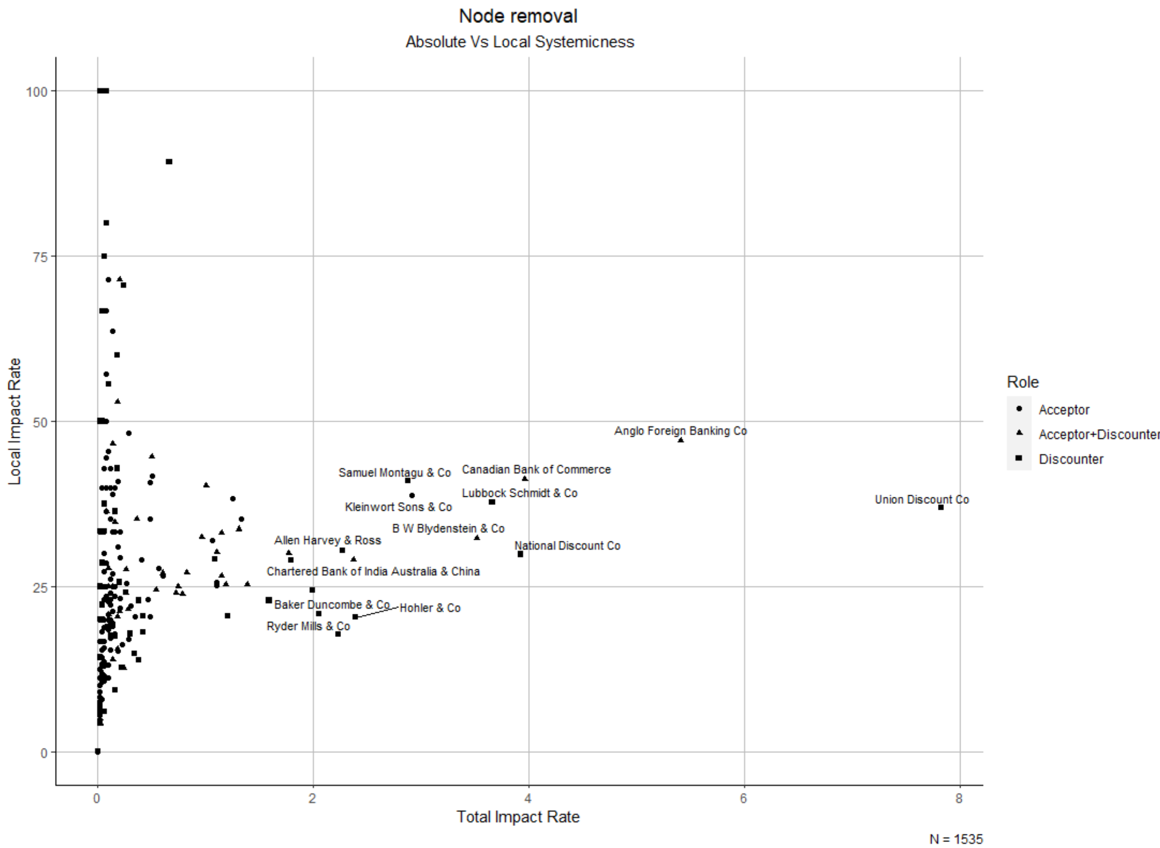
Therefore, our upper-bound estimates of the degree of unsubstitutability of actors in the early-20th-century global financial network suggest that, contrary to nowadays' interbank networks (Gai and Kapadia, 2010), the system was not prone to the "robust-yet-fragile" tendency, as it did not feature any "mega-hub". This is our baseline result.

The second feature emerging from Figure 5.4 is that the vast majority of dots are situated well below the diagonal of the graph: only individuals with very low Market Share values are close to the diagonal. Individuals are plotted on the diagonal when, following their removal, 100% of their downstream actors lose market access: the farther the dots are from the diagonal, the lesser the degree of dependence of their downstream actors. The figure suggests that most upstream individuals "punch well below their weight" in terms of their unsubstitutability for their downstream actors. We investigate this issue in Section 5.4.4.

5.4.4. Local systemicness

We define *local systemicness* an individual's degree of unsubstitutability for the downstream actors who are connected to it through one or more chains. We compute for each individual i: (a) the Acceptor Local Impact Rate $ALocImpR_i = AImp_i / (An_i - 1)$, where $AImp_i$ is the Acceptor Impact and An_i is the number of partners (number of actors involved in the same bills) of i when i plays the role of acceptor; (b) the Discounter Local Impact Rate $DLocImpR_i = DImp_i / (Dn_i - 1)$, where $DImp_i$ is the Discounter Impact and Dn_i is the number of partners of i when i plays the role of discounter; and (c) the Local Impact Rate $LocImpR_i = TImp_i / (n_i - 1)$, where $TImp_i$ is the Total Impact and n_i is the overall number of partners of i.

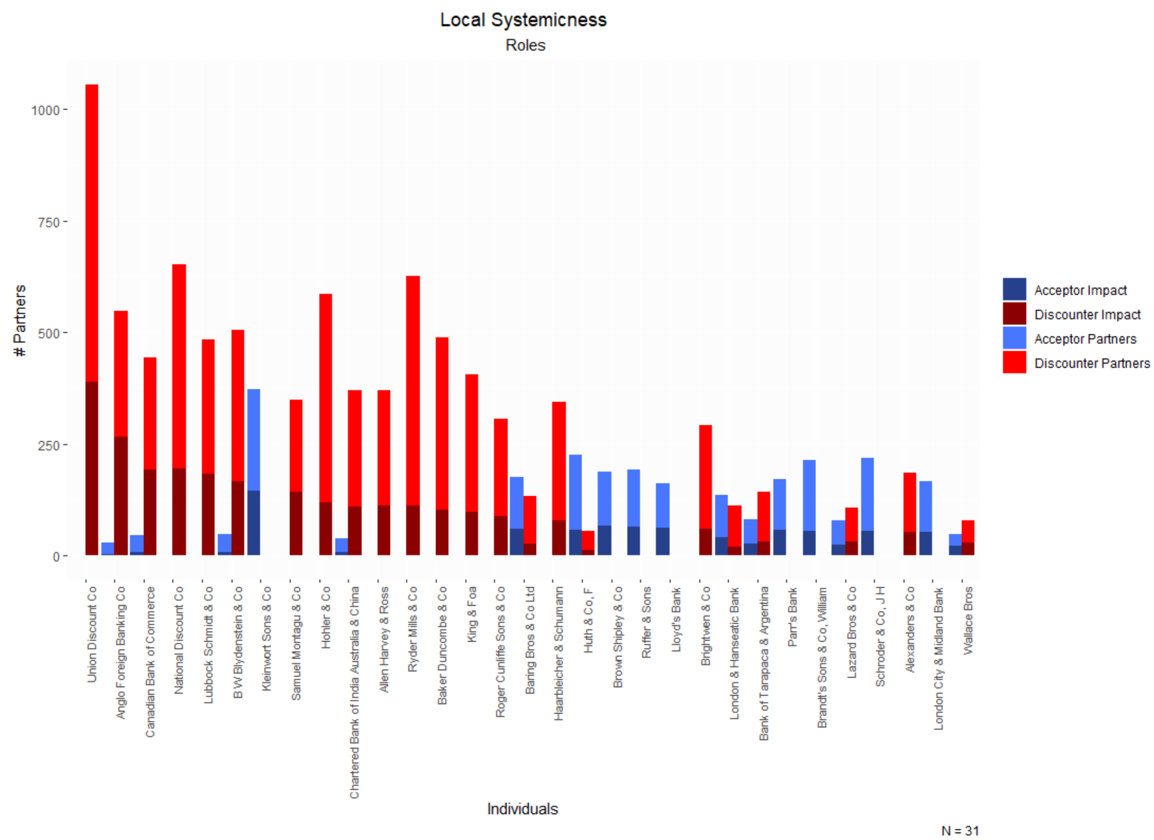
Figure 5.5: Node removal – Absolute vs Local systemicness



Total Impact Rate (x axis) and Local Impact Rate (y axis) of the 1,535 upstream actors.

Figure 5.5 shows that on average, local systemicness tends to be roughly stable (24.93%) across levels of absolute systemicness. Unsurprisingly, there is a lot of dispersion in local systemicness for low levels of absolute systemicness. This is because these actors are involved into a limited number of chains, so there is a size effect on the rate. A simple illustration is provided by the case of a discounter involved into one only bill: the discounter's absolute systemicness is always very low (because a maximum of two downstream actors are impacted by her removal), but if both drawer and acceptor lose market access her local systemicness will be equal to 100% – while it will be only equal to 0% if none of the two is impacted. Interestingly, in Figure 5.5 actors involved in the accepting business appear to display, on average, higher levels of local systemicness than pure discounters. It is therefore legitimate to ask whether in the accepting business (i.e., in bank-firm relationships), downstream actors' level of dependence on upstream ones might have been higher than in the discounting business (i.e., in bank-bank relationships).

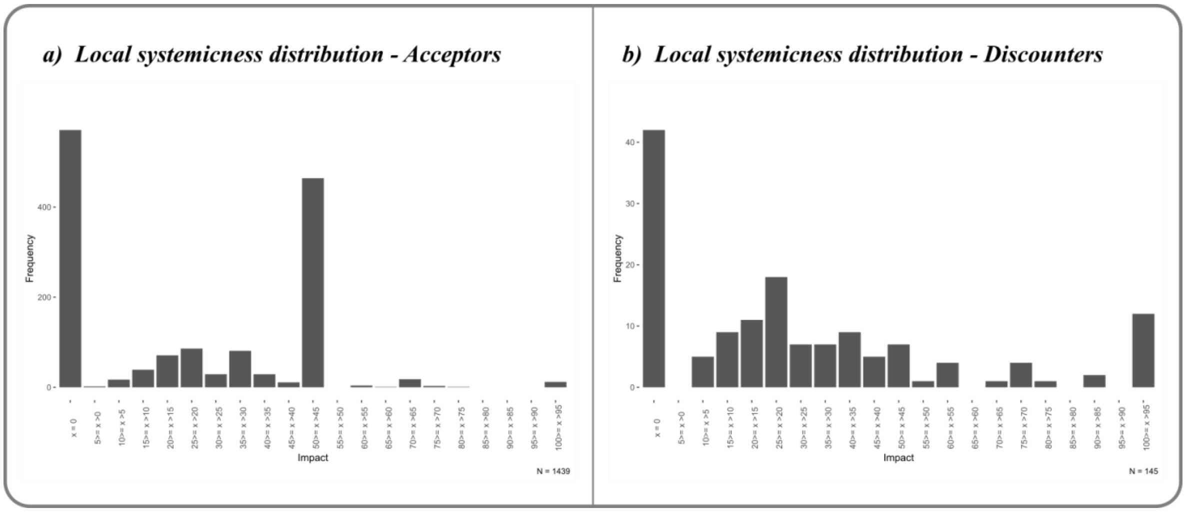
Figure 5.6: Local systemicness by acceptor-discounter roles



Number of partners as acceptor (light blue), Acceptor Local Impact (dark blue), number of partners as discounter (light red), and Discounter Local Impact (dark red) for the 31 individuals with a Total Impact Rate exceeding 1% (ranked according to their Total Impact).

In order to answer this question, Figure 5.6 compares the Acceptor Local Impact and the Discounter Local Impact for the 31 actors with highest absolute systemicness (see Table 5.2). In general, the Acceptor Local Impact Rate is actually higher than the Discounter Local Impact Rate. Thus, downstream actors appear to have displayed a relatively higher level of dependence on acceptors than on discounters. However, some exceptions did actually exist. For instance, we can see in Figure 5.6 that the two individuals with the second and third highest absolute systemicness, Anglo Foreign Banking Co and Canadian Bank of Commerce (two hybrid actors), both displayed an Acceptor Local Rate that was lower than their Discounter Local Rate.

Figure 5.7: Frequency distribution of Local Impact Rate – Acceptors and discounters



Frequency distribution of Local Impact Rate values for acceptors (Figure 5.7a) and for discounters (Figure 5.7b).

To delve deeper into this question, Figures 5.7a and 5.7b provide the frequency distribution of Local Impact Rate values for acceptors and discounters. Figure 5.7a shows that a significant share of acceptors displayed a Local Impact Rate that was close or equal to 50%, yet only a handful of them surpassed the 50% threshold. On the contrary, Figure 5.7b shows that most discounters displayed a much lower Local Impact Rate, yet a more sizable share of them surpassed the 50% threshold. However, it must be noted that all of these locally-systemic discounters were very small. Within the 25 discounters whose Local Impact Rate was higher than 50%, the mean size (defined as the number of chains in which they were involved) was equal to 6.36 and the median size was equal to 2.

To sum up, not only absolute systemicness, but also local systemicness was generally low for all actors, except for some very small actors. This suggests that the failure of any actor would have produced limited damage not only to the general architecture of the financial network, but also to single regions of it. Local systemicness tended to be higher in the accepting business than in the discounting business, whereas absolute systemicness was generally higher for discounters than for acceptors.

5.4.5. Group systemicness

Table 5.2 revealed that no single actor in our network displayed high levels of absolute systemicness. However, it also unveiled the high occurrence of some specific categories of market participants (esp. discount houses) within the list of the relatively less substitutable actors. This might mean that even though no single actor was systemically important *per se*, a shock affecting one group of similar actors (which is often the case in real-world financial crisis) might have broken down the entire system nonetheless. In order to test this hypothesis, we now examine the cumulative absolute systemicness of four exogenously-defined groups (representing entire segments of the financial sector) which may be suspected to have played a crucial role in the network: we remove entire groups from the network, and check whether their removal causes the breakdown of the whole network as a result.

On the basis of qualitative historical evidence, we single out four groups of potentially highly-systemic actors: 1) the twenty *discount houses* eligible for rediscount at the Bank of England – i.e., money market funds of the time, investing big amounts of their clients' funds into bills (Chapter 4); 2) the forty-five *Anglo-foreign banks* eligible for rediscount at the Bank of England – i.e., UK-based multinational commercial banks (Jones, 1993); 3) the top ten *merchant banks* or "acceptance houses" – i.e., the globally-renowned investment banks which were market leaders in the business of guaranteeing bills (Chapman, 1984); and 4) the eleven top *clearing banks* which dominated the domestic commercial banking business in the UK (Sykes, 1926).

Table 5.3: Total impact, impact by roles and market share

Groups	*Acceptor Impact*	*Discounter Impact*	*Total Impact*	*Total Impact Rate*	*Market Share*
Discount Houses (N=20)	17	2095	2094	**42.141**	65.656
Anglo Foreign Banks (N=45)	389	867	1053	**21.191**	40.609
Top10 Merchant Banks (N=10)	554	49	569	**11.451**	22.258
Clearing Banks (N=11)	284	1	281	**5.655**	11.554

Acceptor Impact, Discounter Impact, Total Impact, and Market Share for 4 exogenously-determined groups of top specialized financial intermediaries (see text).

The results of our simulations are reported in Table 5.3. They confirm that money market funds (discount houses) overwhelmingly dominated the population of discounters, with a market share of 65.66%. The upper-bound estimate of the nodes becoming isolated in the (highly unlikely) catastrophic scenario of a total destruction of this crucial segment of the financial sector is equal to 42.14%. This is quite a significant damage, but it falls short of breaking down the entire backbone of the financial network. All other groups display a much lower Total Impact Rate: 21.19% for Anglo-foreign banks, 11.45% for the top ten merchant banks, and 5.65% for the clearing banks. Unsurprisingly, a linear relation appears to exist between Market Share and Total Impact Rate. On the whole, even the removal of entire segments of the financial sector does not entail the collapse of the network.

5.4.6. Geographic systemicness

Assessing the *geographic systemicness* of upstream actors is yet another way to study the resilience of a system. Financial intermediaries in London might have been specialized along geographic lines, and this might have been conducive to some form of dependence for some regions on some specific actor to access to the market. Thus, if drawers from a region or a city were used to access the market only via one acceptor and/or one discounter specialized in that particular region or city, the failure of these actors would have implied the loss of the access to the London bills market for this part of the world.

In order to test for this particular variant of local systemicness, we use the drawers' location data to test the dependence of cities around the world (617 in our database, including London itself) on individual upstream actors to access to the London bill market. Similarly to previous analyses, we identify the number of drawers who lose market access when an individual playing the role of acceptor and/or discounter is removed. Naturally, all cities which are connected to London only through one single chain are very vulnerable (257 cities), because they have an absolute dependence on one acceptor and one discounter. Table 5.4 gives the frequency distribution of our 617 cities according to the number of drawers they feature. It shows that

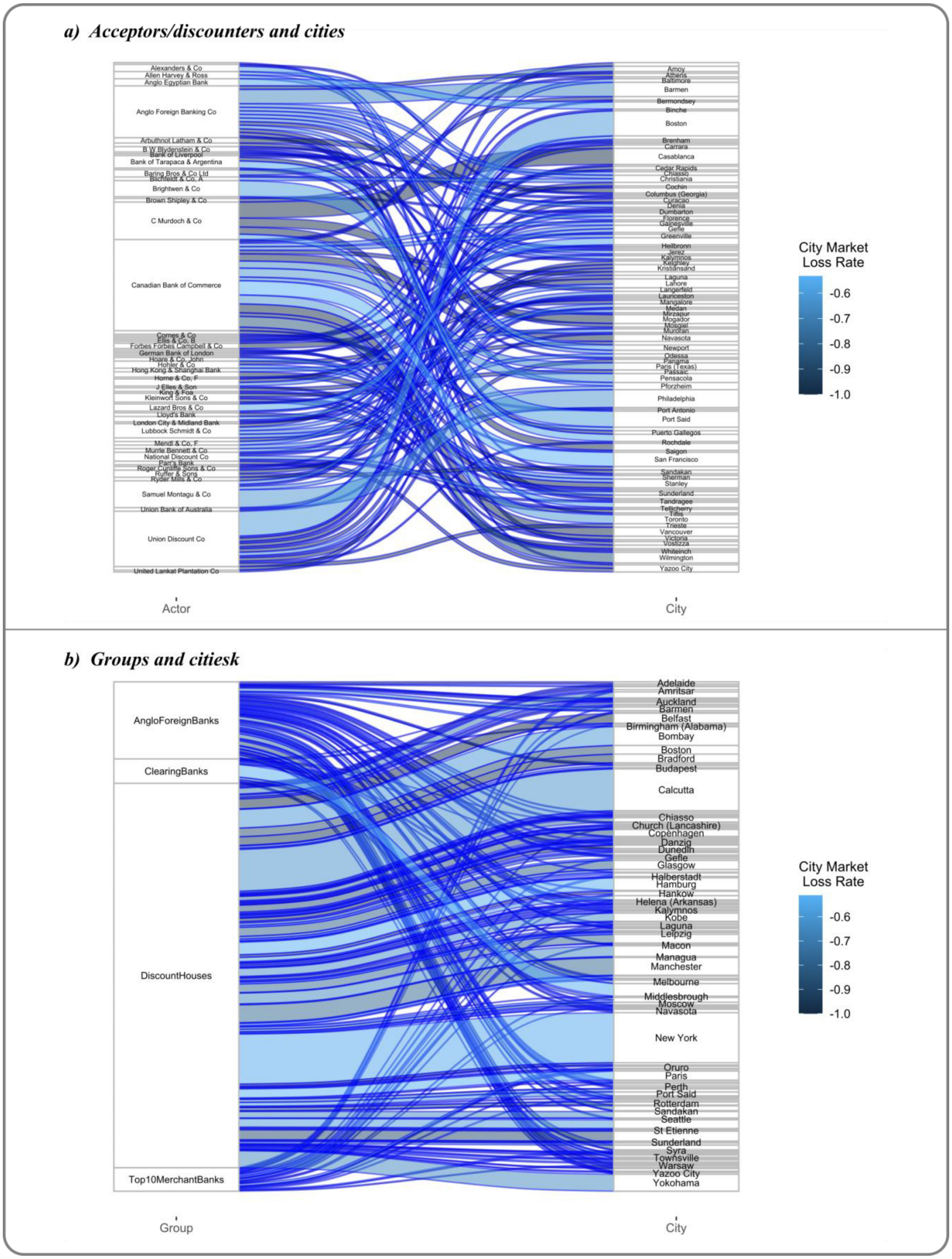
Table 5.4: Frequency distribution of cities according to their number of drawers

# Drawers	*# Cities*	*Examples*
1	331	Aarau; Athens (Georgia); Bayonne; Birmingham (Alabama); Botosani; La Plata; Munich; Ravilloles; Saigon; Toowoomba; etc.
2-5	172	Alicante; Barcelona; Chiasso; Coimbatore; Florence; Managua; Odessa; Potosi; Tangier; Wellington; etc.
6-10	50	Antofagasta; Bilbao; Casablanca; Foochow; Guayaquil; Marseille; Moscow; Paris (Texas); Surabaya; Zurich; etc.
11-50	52	Berlin; Cairo; Chicago; Glasgow; Manila; Melbourne; Montreal; Rangoon; Rio de Janeiro; Valparaiso; etc.
51-100	9	Alexandria; Bombay; Buenos Aires; Colombo; Hamburg; Manchester; Memphis; New Orleans; Yokohama
101-200	1	Calcutta
>200	2	London; New York

For each acceptor and discounter, we compute the City Market Loss Rate $CMLR_i$, which is the proportion of drawers in a city who lose market access when their acceptor or discounter is removed. Formally, $CMLR_i = DrwcImp_i / nDrw_c$ where Drw_cImp_i is the number of drawers in a city c impacted by the removal of and individual i and $nDrw_c$ is the overall number of drawers in a city c. We arbitrarily fix a threshold equal to 50% of the drawers of a city losing market access, beyond which we consider the upstream actor to be geographically systemic for the given city

We find that the cases upstream actors whose removal impacts more than one half of the drawers located in a city are 63; as some of these upstream actors are systemic for more than one city, the total number of geographically systemic bilateral relationships is equal to 126. This means that out of all actual 2,750 bilateral relationships between one upstream actor and one city connected through more than one chain, only 126 relations (i.e. 4.58% of the total) pass our proposed threshold of geographical systemicness.

Figure 5.8: Impact of individuals and groups removal on cities



The figures show on the left the acceptors or discounters, and on the right the cities impacted by their removal. The width of flux between individuals and cities represents the number of drawers who lose market access, and the colour darkening the proportion of these drawers with respect to the total population of drawers in the city. Figure 5.8a illustrates the 126 geographically systemic bilateral relationships between single upstream individuals and cities. Figure 5.8b illustrates the 208 geographically systemic bilateral relationships between groups of upstream individuals (i.e. segments of the financial sector) and cities (see text).

The 126 geographically systemic actor-city relationships are represented in Figure 5.8a. The figure shows that, for instance, if Alexanders & Co (who is connected to 3 out of the 5 drawers in Newport) is removed, this city loses 60% of its access to the London market. Union Discount is the most systemic actor for Boston, since 60% of the drawers depend on it. Similarly, Union Discount Co is the most systemic actor of other cities like Curaçao or Trieste, since all drawers of these cities depend on it. Some cities, like Yazoo City, are dependent on both an acceptor and a discounter, and the removal of one of them makes the city lose access to the market. Figure 5.8a shows that in some cases, some upstream actors played a geographically systemic role for some cities. This was esp. the case for some actors who were specialized in financing trade with some specific regions of the globe. For instance, the Anglo-foreign banks Anglo Foreign Banking Co and Canadian Bank of Commerce appeared to play a systemic role for middle-sized (in terms of number of drawers) cities located in Continental Europe and North America respectively, while the merchant bank C Murdoch & Co appeared to play a systemic role for middle-sized cities located in Africa. However, such cases of geographical "niches" appear to be the exception rather than the rule. Interestingly, despite their huge market share, individual discount houses like Union Discount Co "punch below their weight" in terms of geographic systemicness.

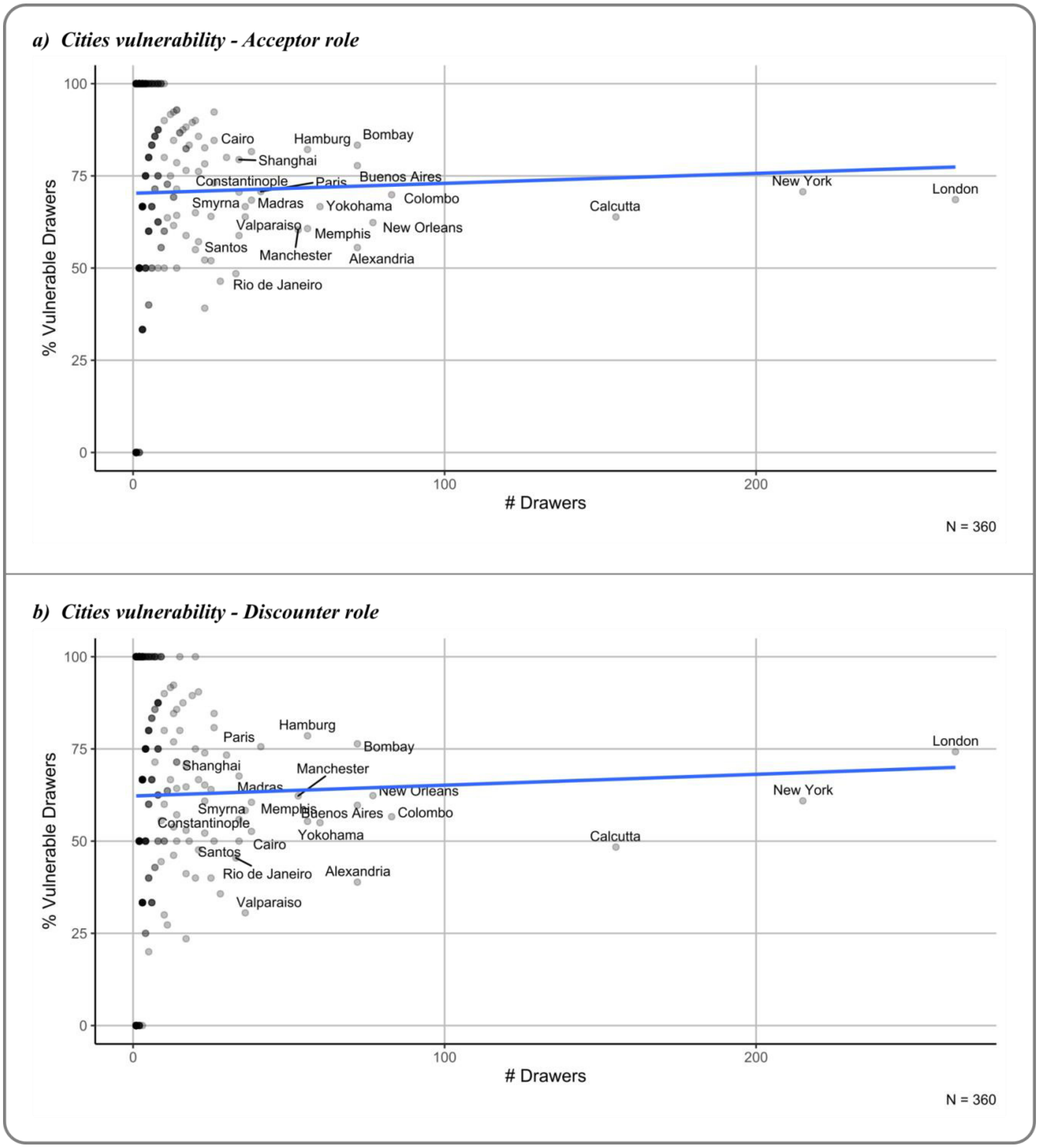
To further investigate this question, we also assess the geographic systemicness of the groups of actors defined in Section 5.4.5 (i.e., the exogenously-defined crucial segments of the financial sector). The results are presented in Figure 5.8b: they confirm the findings of Figure 5.8a. On the one hand, in view of the presence of a number of individual geographical specialization niches, Anglo-foreign banks and top merchant banks are systemic for many small-sized (in terms of number of drawers) cities, but not for bigger ones. On the other hand, the removal of discount houses as a group has a significant impact on 112 cities around the world, be them small, middle-sized (such as Paris where it impacts slightly more than 50% of drawers, Manchester with more than 75%, or Belfast with 100%), or big (such as New York where they impact 53.48% of drawers, or Calcutta with 61.93%). This means that only 45.16% of the bilateral relationships between the group and one city can be seen as geographically systemic. In view of the large market share of discount houses (65.66% of bills), this result is not particularly impressive. Even in the (highly unlikely) catastrophic scenario in which the whole segment of money market funds had disappeared, most cities would still have been able to keep their access to the core of the global financial network.

5.4.7. City vulnerability

The last robustness check we perform consists of turning the question of geographic systmicness on its head, and computing a measure of the degree of vulnerability of each city to shocks in London. *City vulnerability* is a drawer-focused measure. We consider a drawer to be vulnerable if her market access depends on one acceptor or on one discounter only. If, on the contrary, the drawer can access the market through several acceptors and discounters, we consider that she has alternative ways for accessing the market in case one of her acceptors or one of her discounters does fail. Consequently, all drawers involved in just one chain are vulnerable by construction, since they depend entirely on one single acceptor and one single discounter. And the vulnerability of drawers involved in several chains depends on the fact of being connected to more than one acceptor and more than one discounter. For example, in the case of a drawer belonging to five different chains involving two different acceptors but one discounter, we consider that the de not vulnerable regarding the acceptor role but vulnerable regarding the discounter role.

Thus, we define the vulnerability of a city as the proportion of vulnerable drawers located in the city. Formally, $\mathrm{Vul_c} = \mathrm{VulDrw_c} \,/\, \mathrm{nDrw_c}$ where $VulDrw_c$ is the number of vulnerable drawers in a city c and $nDrw_c$ is the overall number of drawers in the city c. Since cities involved in one single chain are vulnerable by construction, we restrict our sample to the 360 cities involved in more than one chain.

Figure 5.9: Cities vulnerability by acceptor and discounter roles



Each dot represents one city; its darkness reveals the presence of several cities with same values; the names of the cities featuring more than 30 drawers is provided. The x axis represents the number of drawers in city, and the y axis the percent of vulnerable drawers. A regression line (blue) has been included in the figure.

Figure 5.9a shows the vulnerability of cities with respect to acceptors' shocks. In our sample of 360 cities, we consider as small cities those with 10 drawers or less (i.e., a total of 296 cities). All of the

144 cities having 100% of their drawers vulnerable to an acceptor belong to this category: this represents 48.65% of all small cities. 88 small cities have half or less of their drawers vulnerable: 50 of them have no vulnerable drawer at all (most of them have only one drawer involved in several chains with several acceptors). Figure 5.9a also shows that no city with more than 10 drawers is completely vulnerable, and the percent of vulnerable actors tends ≈ 70% as the size of the city increases.

Figure 5.9b shows the vulnerability of cities with respect to discounters' shocks. It shows that in general, cities' vulnerability with respect to discounters is lower than their vulnerability with respect to acceptors. On the one hand, the number of cities that are 100% vulnerable to discounters' shocks is lower than for acceptors', as it is equal to 115. However, 2 of these 115 cities (Port Said and Amsterdam) are middle-sized cities with more than 10 drawers (15 and 20 respectively). On the other hand, the number of cities with no vulnerable drawer grows to 60 (most of them have one only drawer involved in several chains with several discounters). Another interesting fact is that 20 cities with one single drawer are resilient to acceptors' shocks but vulnerable to discounters' ones. Similarly, among the 64 cities with more than 10 drawers, 12 exhibit more vulnerability to discounters' shocks than to acceptors': this is esp. the case for cities located in the UK, such as London, Manchester, Belfast, or Bradford.

These findings confirm that in spite of the high concentration of the discounting business (in which 20 discount houses detained a market share of 65.66%), the degree of unsubstitutability of discounters (i.e., wholesale lenders) was lower than expected. Drawers (i.e., borrowing firms) could generally pass through many alternative paths in order to access the London market; often, they displayed a greater degree of dependence on acceptors (i.e., guarantors), whose market share was nonetheless generally much lower than discounters' (see above, section 5.4.3). In a sense, a sort of trade-off existed in the banking system: on the one hand, guarantors had a relatively higher degree of unsubstitutability for their customers, but this was compensated by a lower market share; on the other hand, wholesale lenders had far bigger market shares, but this was compensated by a relatively lower degree of unsubstitutability for their customers. This trade-off appears to have stemmed from the fundamentally different characteristics of the accepting and discounting businesses (Chapter 4). The result was that, in spite of a "funnel-shaped" demography, the macro structure early-20th-century global financial network did not feature the sorts of "mega-hubs" found in present-day interbank networks, and were therefore not prone to the "robust-yet-fragile" tendency.

5.6. Conclusions

We use a new database (hand-collected from archival sources) allowing to reconstruct the complete network of financial interlinkages in the global sterling-denominated money market during the calendar year 1906 (at the heyday of the first globalization). This database is valuable under many respects: it consists of truly observed (and not estimated) linkages; it is one of the very first historical databases on financial networks; to the best of our knowledge, it is the first one to cover a core global money market; and it is one of the very few available databases covering both bank-bank and bank-firm relationships. We apply very simple shock simulation techniques (node removal) to obtain upper-bound estimates of the unsubstitutability of intermediaries in the network. In contrast to the multilayer approach adopted by the literature in order to analyse the interaction between bank-bank and bank-firm networks, this methodology allows us keeping track of actual chains and of the role of gatekeepers in connecting borrowing firms with lending banks.

When applied to contemporary financial networks, this kind of simulation leads to a breakdown of the network's connectivity as central nodes are removed (Pröpper *et al*., 2008), thus pointing to a high level of unsubstitutability of a few systemic actors. In stark contrast, we find that in no case the removal of any node leads to major damages to the network structure, as only very few actors get isolated. This result is robust to several specifications of the shock simulations. All this allows us concluding that, in stark contrast to today, during the first globalization no intermediary had high levels of unsubstitutability in the global financial network. This means that a financial network deprived of systemic actors can exist and did actually exist at one of the highest times of international economic development.

This conclusion has important implications for regulators. In our historical companion paper (Chapter 4), we explain that the specific characteristics of the monetary instruments that was at the basis of the global financial system (the bill of exchange) provided incentives for gatekeepers (guarantors) to engage into information-production activities, and this generated diseconomies of scale in their business, which was akin to relationship banking (Boot, 2000; Stein, 2002). On this basis, we speculate that the low systemicness of intermediaries was the outcome of the specific design of the money market instruments used in those times. As a matter of fact, 19th-century regulators were indeed adamant about the superiority of bills of exchange from a supervisory viewpoint (Ugolini, 2017). If regulators want to escape the "too-unsubstitutable-to-fail" trap, they should therefore start from the microstructure of financial market and try to design instruments providing disincentives to concentration. As always, the devil is in the details.

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General conclusions

The main objective of this thesis was the development and application of innovative analytical tools for the study of hybrid organizations – the "strange animals" (Ménard, 2013) that play a crucial role in the interplay between individual action and aggregate outcomes. We have focused on two discrete types of "hybrid" organizations – horizontal and vertical – which we have associated to affiliation and supra-dyadic interaction structures, respectively. We have proposed two novel methodologies to study these "hybrid" organizations (the "place-based methodology" and "chain-based methodology", respectively) and we have applied them to two different domains: innovation studies and financial economics.

Although the "place-based methodology" had been used previously, this thesis has provided some contributions. First, we have pointed out for the very first time the suitability of this methodology in order to overcome artificial clustering problem and the analytical and interpretative problems associated to. Second, we have introduced this methodology to economics, and more specifically on innovation studies. Third, we have combined this tool with the cohesive blocks methodology, and showed that the combination of the two provides a useful meso-approach for the study of community structures in networks, sometimes not visible since having no formal institutional borders, and which provides information on both micro dynamics and macro structural properties.

Contrary to the "place-based methodology", the "chain-based methodology" as we design it in this thesis has never been used before, and therefore constitutes one fully original contribution of our work. The use of hypergraphs for the study of supra-dyadic interaction units is an emerging field, to which scholars from many different disciplines– such as physics, mathematics, or sociology – are currently contributing (Battistion *et al*,. 2020). However, while the methods that are commonly used preserve the unity of supra-dyadic entities, their internal substructure is lost. The hyperstructure approach is little known, and provides a complete solution for the study of supra-dyadic interaction networks. This works has pointed to the usefulness and simplicity of hyperstructures for the study of supra-dyadic relational units, and provided a relevant application case in the domain of financial economics. Additionally, to the best of our knowledge, this contribution is the first one to introduce the use of hyperstructures to oriented substructures. Indeed, hyperstructures had previously been used for symmetric or non-oriented relations: we have been the first ones to show the flexibility of this tool by adapting it to the analysis of oriented relations.

In sum, this thesis has highlighted the importance of considering hybrid organizations for a better understanding of economic phenomena, and more broadly of social phenomena. It has also provided methodological solutions that, to the best of our knowledge, were little known (if all) in economics.

Several future developments may be envisaged for the issues covered in this thesis.

A number of developments can come out of our original work on places and its application to innovation studies (Chapters 2 and 3). Certainly, the "place-based methodology" provides a useful and well-established way to study structural equivalence in affiliation networks. However, this methodology uses a "hard" definition of structural equivalence, since every two actors in a place have to connect in the very same way to the rest of the network. Some applications or research questions may require a "softer" conception of structural equivalence. For instance, suppose the case of two authors who have co-authored ten publications, but one of whom also has one paper with a third author: in fact, it might perhaps be legitimate to consider that the two authors are structurally equivalent even if they did not co-author exactly the very same papers. To provide some flexibility to the concept of places, we have developed the concept of *k-places*. We define it as a place which allows a maximum divergence of *k* sets that define the place. A *beta* version of the algorithm is included in the R-package *places* that we have authored,[118] and it should be useful in further applications of structural equivalence analysis in affiliation networks.

The study of horizontal hybrids organizations and their structure by the combination of places and cohesive blocks methodologies should be developed with a better measure of the relative importance of "peaks". As discussed briefly in Chapter 3, the importance of a peak mainly depends on (a) its relative cohesion level (with regard to bottom blocks which also host other communities), and (b) the number of peaks hosted in a common parent block. The development of new measures and indicators to better asses the relative importance of each peak should provide a more accurate view of the community structure of networks.

The application of the "place-based methodology" in Chapters 2 and 3 evidences micro dynamics unveiling proximities that go beyond the individual attributes of actors. Some combinations, often repeated in several projects/consortia, can be unexpected in view of individual attributes (as e.g. industrial classifications codes), but make sense in a collaborative context involving other actors. This reveals the importance of forms of proximity that are not based on direct dyadic interaction,

[118] "Places: Structural Equivalence Analysis for Two-mode Networks", Lucena-Piquero, D., 2017.

but on common objectives and collaboration with third parties. A close view of the dynamics involved in these complex substructures can provide a better understanding of micro dynamics in innovation.

The impact of R&D policies, and more specifically diversification policies, on innovation networks remains a domain that requires further research (Mewes and Broekel, 2020). While this thesis did not aim to dress an evaluation of R&D policies, its results highlight the need for more "surgical" measures to attain their objectives (taking into account the particularities of innovation activities, as e.g. their sectors of composition), as some policies can have a significant impact on the achievement of the objectives of other ones.

Finally, collaborative R&D projects are just one example of "horizontal" hybrid organizations. Many other economic phenomena can be conceptualized as affiliation relations and, consequently, be studied using the proposed methodological approach. Chapter 1 provides some examples of possible empirical applications, but also exposes the under-exploitation of this approach and its analytical advantages. A larger application of the "place-based methodology" should provide a better understanding of "horizontal" hybrid organizations, as well as of the opportunities and limits of this analytical tool.

A number of developments can equally come out of our original work on chains and its application to financial economics (Chapters 4 and 5). As mentioned above, a multidisciplinary effort has emerged in recent decades to study complex phenomena as supra-dyadic units. A "higher-order" (beyond pairwise interaction) approach seems to be a promising way to acquire a better understanding of complex real-world phenomena. Although the use of hypergraphs has spread and developed in recent times, it is still little used, and greater coordination and consensus in the community is required.[119] In this scenario, we advocate the promising potential of the hyperstructure approach, in the sense of Criado *et al*. (2010). We consider that it is important to preserve the interaction substructures existing in supra-dyadic units. From here, much remains to be done, from developing new network metrics to exploring new application cases. While this work has focused on one simple type of supra-dyadic structure (the relational chain), other more complex types of substructures can be considered in social sciences – e.g. tree structures or valued subnetworks. In particular, the development of standardized metrics is an issue that needs to be tackled in this emerging field.

[119] Potts (2000) is an example of this lack of consensus, as his definition of hyperstructure is different from the one commonly adopted in the literature: actually, he defines hyperstructures as nested-hierarchical systems (or nested sets of connections among components).

This thesis has shown the suitability of the supra-dyadic approach through hyperstructures to the study of an historical financial network. The study of current financial markets through this approach can contribute to their better understanding, and thus to improve regulation policy design. Of course, finance is just one of the many possible cases of application. As we have pointed out, several types of "vertical" hybrid organizations can be observed in the economy. For example, supply chains can be studied in this way, thus overcoming some of the analytical biases discussed in Chapter 1. This approach seems to meet the concerns of some scholars, who consider supply chains as more than the sum of pairwise relations (Choi and Wu, 2009).

Finally, this thesis has operated a strict association between (on the one hand) "horizontal" hybrid organization and affiliation networks and (on the other hand) "vertical" hybrid organizations and interaction networks. This association responds to an analytical strategy, but it does not mean to be exclusive. Indeed, the study of some hybrid organizations can focus on both the shared objectives/properties (from group membership) and the interaction substructure (from supra-dyadic units) of collective action. For example, collaborative R&D projects have been studied here as affiliation networks, and we argued in Chapter 3 that this kind of relation does not always inform about the internal interaction structure of groups. Consequently, interpreting affiliation networks in terms of interaction can lead to misinterpretations. However, in some cases participation into the R&D activity can take the form of well-defined roles – e.g., in case some developments require specific forms of interactions implying dependencies or complementarities – thus becoming much more similar to a supply chain. This means that, in a sense, the methodologies proposed in this thesis may be seen as somewhat complementary, and their scope of application may potentially be much more generalized than what has been proposed here. Many fascinating avenues for future research are open before us.

References of the conclusions

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List of figures

List of tables

Table of Contents

Au-delà de l'Approche Dyadique dans l'Analyse des Réseaux Sociaux : Applications aux Études sur l'Innovation et à l'Économie Financière

Au cours des dernières décennies, l'Analyse des Réseaux Sociaux est devenue de plus en plus populaire en économie. Cette thèse se concentre sur les structures méso-économiques "horizontales" et "verticales", que nous associons respectivement aux réseaux d'affiliation et d'interaction. Dans le chapitre 1, nous discutons de la pertinence de la méthodologie des places pour l'étude des méso-structures "horizontales" dans les réseaux d'affiliation, tandis que les hyperstructures sont un outil approprié pour l'étude des méso-structures "verticales" dans les réseaux d'interaction. Ces idées sont en suite mises en œuvre dans deux applications empiriques concernant l'innovation et la finance. Les chapitres 2 et 3 s'inscrivent dans le domaine des études de l'innovation, et traitent de l'effet des politiques de R&D sur les réseaux d'innovation collaboratifs (qui représentent des relations d'affiliation) en utilisant la méthodologie des places, qui repose sur l'équivalence structurelle. L'approche de l'équivalence structurelle permet d'identifier les agents partageant la même position structurelle (c'est-à-dire les agents soumis aux mêmes ressources et contraintes relationnelles) et d'obtenir ainsi le "squelette" des réseaux d'affiliation. Cela nous permet de surmonter certains biais et certaines limites de l'analyse classique et de fournir de nouvelles perspectives sur l'innovation en tant qu'action collective. Les chapitres 4 et 5 s'inscrivent dans le domaine de l'économie financière, et étudient la structure du réseau financier mondial pendant la Première Mondialisation. Nous nous concentrons sur les chaînes d'origine et de distribution des instruments du marché monétaire (qui représentent les relations d'interaction), et nous montrons que l'interdépendance des rôles joués par les agents dans les chaînes a permis de surmonter les asymétries d'information et de générer un système financier très résilient. Afin d'étudier les chaînes en tant que structures supra-dyadiques, nous utilisons des hypergraphes : cette approche originale nous permet de surmonter les erreurs d'interprétation potentiellement induites par les méthodologies classiques (comme les réseaux simples ou multi-niveaux) et de souligner ainsi les propriétés structurelles du réseau financier mondial.

Mots clés : réseaux sociaux, structures méso, systèmes d'innovation, réseaux financiers

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Beyond the Dyadic Approach in Social Network Analysis: Applications to Innovation Studies and Financial Economics

In the recent decades, Social Network Analysis has become increasingly popular in economics. This thesis focuses on “horizontal” and “vertical” meso economic structures, which we associate to affiliation and interaction networks respectively. In Chapter 1, we argue that the place-based methodology is a convenient tool for the study of "horizontal" meso-structures in affiliation networks, while hyperstructures are a convenient tool for the study of "vertical" meso-structures in interaction networks. These insights are henceforth put to work in two empirical applications, relating to innovation and finance respectively. Chapters 2 and 3 situate themselves within the field of innovation studies, and address the effect of R&D policies on collaborative innovation networks (which represent affiliation relationships) using the place-based methodology, which builds on structural equivalence. The structural equivalence approach allows to identify agents sharing the same structural position (viz., agents under the same relational resources and constraints) and thus to obtain the “skeleton” of affiliation networks. This enables us to overcome some biases and limitations of classical analysis and to provide new insights on innovation as collective action. Chapters 4 and 5 situate themselves in the field of financial economics, and study the structure of the global financial network during the First Globalisation. We focus on the origination and distribution chains of money market instruments (which represent interaction relationships), and show that the interdependence of the roles played by agents in chains helped overcome information asymmetries and generate a highly resilient financial system. In order to study chains as supra-dyadic structures, we use hypergraphs: this original approach allows us to overcome the misinterpretations potentially induced by classical methodologies (as e.g. simple or multilayer networks) and thus to underscore the structural properties of the global financial network.

Keywords: social networks, meso structures, innovation systems, financial networks