The dynamics of and on networks: an introduction

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1 Introduction

Over the past decades, network research has started to be used in a variety of fields. The reason for this is straightforward. Many real-world systems, including socio-economic systems, can be described as a set of nodes and relationships between these nodes. In this special issue, we focus exclusively on socio-economic networks. A closer look at the literature reveals a broad thematic spectrum including, for example, inter-bank networks, friendship networks, supply networks, inventor networks, corporate ownership networks, co-authoring networks, and inter-organisational innovation networks. The developments in network research have been fuelled by the recognition of complex systems as a subject of scientific inquiry, rapid progress in theory building, and methodological advances in areas such as quantitative network analysis, networks, game theory, agent-based modelling, and econometrics.

The rich body of network literature that has emerged in economics, sociology, and management science has enhanced our understanding of the antecedents and consequences of network embeddedness, actors' strategic positioning and pattern formation processes at higher aggregation levels. Today, we know that the overall network topology itself matters in several ways. However, we still face more questions than answers when it comes to the *dynamics* of and on networks. The explicit consideration of *time* opens up an entirely new and rich set of research questions such as: how do innovation networks form and evolve? Which mechanisms are responsible for their characteristics? How do networks affect the stability of the systems they are part of? What are the consequences of tie formations or terminations and entries or exits of organisations into the network for the structural stability of the system? Which processes can be used to model dynamics? How do networks affect, for instance, technological economic dynamics? And, conversely, how do technological and economic dynamics shape the networks? How can we model and analyse network diffusion processes? How do diffusion processes affect the performance of the actors involved?

This special issue addresses the tip of the iceberg at best. Nonetheless, it contains a collection of papers that contribute to an understanding of two dimensions of network dynamics. On the one hand, a number of papers focus on the 'dynamics *of* networks' by studying how and why networks evolve over time. In particular, an in-depth understanding of endogenous and exogenous drivers of network change as well as of the institutions guiding the behaviour of the actors involved plays a crucial role in these contributions. On the other hand, a number of papers focus on the 'dynamics *on* networks' by studying exchange processes and flows on *existing* network structures such as, for instance, knowledge transfer in innovation networks. Given the complexity of the topics, a variety of methods are used, including statistical analyses, simulations, case studies, etc.

The rest of this introduction is structured as follows: Section 2 provides a brief overview of theoretical arguments, empirical findings, and network models in economics and related fields; Section 3 highlights different methodological approaches in the fields discussed in Section 2. The papers of the special issue are summarised in Section 4.

2 Short overview

While both network modelling and network analysis were already a featured in the toolkit of social sciences during the mid-twentieth century (see e.g., Borgatti et al., 2009), the adoption of these methods as research instrument in economics is relatively recent. While *innovation* and *financial* networks are the main focus of this special issue, we acknowledge that economists also study business networks, production networks, demand-side diffusion networks, and many others in a similar manner. There are two main reasons for why financial networks – aside from our primary focus on innovation networks – have a prominent place in this special issue: first, financial networks are of prime interest for academics, but also for practitioners and policy makers. This is evidenced by the research undertaken by central banks and private companies. Second, the datasets for financial networks are available in exceptional quantity and quality, facilitating the application of statistical tools. Thus, the area of financial networks is likely to be one in which theoretical and methodological innovations are likely to occur.

Here we define an innovation network as a set of actors that are interconnected and exchange, recombine, and generate new knowledge, often with the purpose of developing new products or services to meet customer needs or general market demand (see Cantner and Graf, 2011; Brenner et al., 2011; Kudic, 2015). Knowledge exchanged in such networks (i) may have tacit, hard-to-explicate components (Polanyi, 1967), (ii) require face-to-face communication (see e.g., Nonaka, 1994), and (iii) call for collaborative rather than competitive relationships (Grant, 1996). The first seminal works with an innovation network perspective on technological change appeared in the early 1990s (cf. Freeman, 1991; DeBresson and Amesse, 1991).

Here we provide a short overview over four interlocking theoretical constructs, which, in our view, form the pillars of present-day innovation network research:

i firms have specialised technological knowledge and innovation requires cross-fertilisation with complementary knowledge possessed by other agents

ii competition between firms co-evolves with industry dynamics and ultimately culminates in the innovation of products, services, and processes, and thereby in collaboration

iii technological change occurs in a multifaceted context with systemic, geographical, and institutional factors

iv due to both market failure as it pertains to knowledge, and the transient nature of exploration and exchange relationships, the selection of collaboration partners and the governance of relationships – and thereby the network structure and dynamics – is, in part, driven by non-economic rationales such as trust, reputation, etc.

These pillars emerged from relaxing (mostly neoclassical) assumptions on economic rationales.

Firstly, until the 1980s, scholars in the prevailing neoclassical economic theory of the firm and industrial organisation modelled (a) firms as making perfectly rational decisions, (b) competition to revolve around price/costs, quantity, or entry timing, and (c) relationships between firms as game-theoretic market transactions. However, people rarely behave perfectly rational, because of a lack of information and intellectual capabilities to make optimal decisions (cf. Simon, 1955). Arguably, this bounded rationality holds for technological development in particular, which features many sources of fundamental uncertainty (cf. Rosenberg, 1996). Moreover, firms do not merely optimise price/costs, quantity, and/or entry timing, but ultimately, when profit margins have eroded, seek to develop and market new products, services, or processes. During the 1980s and 1990s, scholars in the field of strategic management advocated the resource (see e.g., Barney, 1991), capabilities-based view of the firm (see e.g., Hamel and Prahalad, 1994), and the knowledge-based view of the firm (see e.g., Kogut and Zander, 1992; Grant, 1996). The latter view focuses on a specific resource particularly relevant for innovation and argues that firms (and other economic agents) are to be viewed as holders of (distinct) technological knowledge stocks. Given this specialisation, fragmentation, and distribution of knowledge, firms need to access the knowledge stock of other agents (firms, universities, etc.) to create new combinations of technological knowledge, to develop new products and services, to enhance production processes, and to reduce the time-to-market (cf. Hagedoorn and Schakenraad, 1990; Freeman, 1991). Given the significance of access to complementary knowledge, the *relationship* between containers of these knowledge stocks is particularly valuable (cf. Dyer and Singh, 1998).

Secondly, in the 1970s and early 1980s, the evolutionary economics and strategic management literature disputed the neoclassical economic perspective according to which markets are in equilibrium and technological changes can be considered to be mere exogenous shocks. I was emphasised that competition ultimately forces firms to develop new products, services, and business models, there is endogenous technological change driving industry dynamics. Arguably, product markets cycle through stages in which (i) small entrepreneurs focus on product innovation and (ii) scale-intensive producers focus on price competition, cost saving, and process innovation (Utterback and Abernathy, 1975; also see Anderson and Tushman, 1990; for related life-cycle models). However, the organisation and governance forms of (research and development) activities also vary from stage to stage (e.g., Afuah, 2001; Jacobides and Winter, 2005). Moreover, during early stages, firms are part of volatile networks engaged in exploration and experimental product innovation, while, in later stages, networks become more stationary, focused on production, and engaged in incremental innovation (cf. Rosenkopf and Tushman, 1998).

Thirdly, technological change is driven not only by firms creating and exploiting opportunities to serve their commercial interests, but also by a range of other actors interacting in an ‘innovation system’ (Lundvall, 1992), and, generally, by the interaction of industry, government, and academia in a ‘triple helix’ (see e.g., Etzkowitz and Leydesdorff, 1995), or, even more broadly, by the institutional environment with social and cultural factors. The innovation system literature serves as a general conceptual basis for both industry evolution and network dynamics and allows for conceptual specifications, such as national (e.g., Lundvall, 1992; Nelson, 1992), technological (Carlsson et al., 2002), sectoral (Malerba, 2002), and regional innovation systems (Cooke, 2001). For over a century, scholars intermittently focused on the geographical dimension of industrial activities, and notably the tendency to cluster due to so-called Marshall-Arrow-Romer externalities (cf. Glaeser et al., 1992), and whether regional specialisation or rather diversification were commendable for regional innovativeness (see e.g., Van der Panne, 2004). Either way, given that innovation involves the recombination of knowledge that may have tacit, hard-to-explicate components (see notably Polanyi’s work in the 1960s), face-to-face communication is required (see e.g., Nonaka, 1994). Given that the innovation potential of the knowledge exchange and recombination processes may get exhausted, it could be that fresh, 'alien' knowledge is introduced into any innovation network's collective knowledge base. Regionally dense networks may seek to import knowledge through 'pipelines' and subsequently absorb and exploit that knowledge in a 'local buzz' (Bathelt et al., 2004), e.g., by gatekeepers (Graf, 2010). Arguably, however, geographical proximity is neither necessary, nor sufficient for network ties to exist, as technological (cognitive), organisational, institutional, and social proximity matters also (see Boschma, 2005). That said, the actual transfer, exchange, and cross-fertilisation of technological knowledge may require (temporary) geographical co-location. However, once technology has crystalised and knowledge is codified, co-location is no longer required (Ter Wal, 2014; Audretsch and Feldman, 1996). The initial ideas for and preliminary assessment of the innovative potential of the recombination of different knowledge stocks may occur between agents in different regions, though. Over time, however, proximity may increase the geographical density of networks, even though increasing codification allows long-distance exchange, and despite the fact that this (unintentionally) induces technological lock-in and hampers path-breaking innovation (cf. Boschma and Frenken, 2010).

Fourthly, sociology has contributed key insights to innovation network research both by highlighting non-economic factors that affect the existence of particular dyadic relationships, as well as by emphasising the influence of an existing network structure on the diffusion and adoption of knowledge and thereby the general innovativeness of individual agents as well as of the network. Firms rely on research collaborations with incompletely specified contracts under prerequisites such as trust, reputation, or triadic closure. Moreover, the formation of new relationships has been shown to be affected by the firm's existing position in the network (Powell et al., 1996). Consequently, a particular network's structural features may be conducive to diffusion, adoption and innovativeness, examples being the existence of weak and strong ties (Granovetter, 1973), social capital and structural embeddedness (Granovetter, 1985; Coleman, 1988, 1990), structural holes (Burt, 1995), and several other properties. Longitudinal social network analysis reveals that, at an early stage, an innovator network develops based on social capital and network replications, while over time redundancies are removed to give the network its sparse form characterised by structural holes (Walker et al., 1997; Hite and Hesterly, 2001). During exploration, the network evolves subject to preferential attachment-based technological capabilities, research proficiency, and the owned technological portfolio (cf. Gilsing and Duysters, 2008).

In innovation economics, generally, networks are perceived as evolving based on the interaction of local decisions. The fields of industrial marketing & purchasing and strategic network management share several premises from innovation economics, e.g., the resource-based perspective and the importance of the relationships of actors to access complementary resources. However, in the latter two fields, the central perspective is that (powerful) actors seek to explicitly manage (parts of) the network or that actors in the network pursue a collective goal. The literature focuses main on issues such as network evolution (e.g., Halinen and Törnroos, 1998), network description tools (e.g., the actor-resource-activity framework, see Håkansson and Snehota, 1989, 1995), network types (e.g., Kambil, 2008; Harland et al., 2001), network development (Halinen et al., 1999) and network management challenges (e.g., Möller and Svahn, 2003; Ritter et al., 2004).

Network theory is now regularly used in finance to study the credit-relationships among firms. In this case, firms correspond to the vertices, and the credits correspond to the edges. A primary motivation to study such inter-bank networks is the need to better account for systemic risk, the risk created by the banking system and its structure, rather than the individual banks themselves. While a single illiquid bank usually does not constitute a significant problem for an economy, the collapse of the entire banking sector does. In modern economies, banks are closely connected and provide liquidity to one another using overnight loans and other instruments. Depending on the network structure, however, the bankruptcy of a single bank may result in a cascade of subsequent bankruptcies of other banks. Studies of inter-bank networks strive to characterise the inter-bank network empirically, to understand the systemic risks, and to develop policies to reduce it. Previous studies suggest that inter-bank networks often exhibit a core-periphery structure (e.g., Gabrieli and Georg, 2014; Lux, 2016). A large number of studies exist on systemic risk in inter-bank networks and bankruptcy cascades (e.g., Allen and Gale, 2000; Battiston et al., 2007; Roukny et al., 2013; Poledna et al., 2014; Caccioli et al., 2014) as well as on mediating or aggravating the effects of designed features of the systems such as central clearing parties (e.g., Cont and Minca, 2016).

3 The methodological richness of network research

As highlighted in the previous section, the field of network research maintains a plurality of approaches and methods. This plurality should be thought of as a strength rather than a weakness. Especially in emerging fields, there are considerable trade-offs in model design. After all, there is no 'perfect model' (Teller, 2001), but, depending on the purpose of inquiry, different modelling formulations are preferable. This is what we see reflected more generally, even in this very special issue.

Graph theory is used and applied in a variety of fields such as mathematics, computer science, physics, chemistry, biology, and sociology. Each field has its particular (conceptual) interpretations of what the vertices and edges are, as well as an interest in certain comparative properties of particular vertices or of the graph as a whole. In social sciences, vertices often are individuals or companies (generally: agents) and edges signify the existence of some form of connection, e.g., an exchange or transfer. In social sciences, there is a vast range of metrics quantifying properties of (i) particular nodes, such as the 'centrality' or whether a node is a 'structural hole' (see Burt, 1995), (ii) particular vertices, such as its 'strength' (Granovetter, 1973), or the likelihood of ties to form based on other existing ties, cf. 'social capital' (Coleman, 1990; Portes, 1998). For an extensive reference work, the reader is referred to Wasserman and Faust (1994). In the knowledge-based perspective of innovation economics, however, the agents are heterogeneous, notably in the knowledge and capabilities at their disposal, as their dissimilarities in particular may provide a competitive edge. Ties between agents are actively created by agents themselves for the purposes of temporary exchange and the cross-fertilisation of knowledge. As such, the ties in an innovation network change endogenously and are related to the properties of agents. Any quantification of the dynamics of innovation networks is thus involved and bound to relate to particularities of the vertices and the competitive interests both of the individual agents and of the industry as a whole. The previous section provides a few references to hypotheses on innovation network dynamics over the industry life-cycle.

Innovation network dynamics itself are studied using real-world relational data such as inventor co-patenting in patent data, patent citation information, firm and research institute cooperation in publicly funded research projects, licensing and purchasing information in business transaction data, customer databases of consultants, etc. In devising claims (and ultimately theories) on innovation network dynamics, it is instructive to use descriptive statistical methods relating to these data. Statistical exercises may focus on node properties such as centrality, betweenness, etc. as well ties' properties such as knowledge spanning, regional gatekeeping, etc. The tie properties are ideally related to node properties such as age, size, knowledge portfolio, (geographical) proximity, etc. Studying the network dynamics in real-world datasets thus gives rise to theories on innovation network dynamics, which can subsequently be tested with different datasets using inductive statistical methods.

Moreover, abductive research approaches are possible by using both stochastic-actor oriented modelling (SAOM) and agent-based modelling (ABM) to operationally define the behaviour of agents such as tie formation heuristics as well as control agents' covariates (e.g., knowledge and capital endowments), pre-existing network ties, etc. and subsequently study the emerging dynamics in computer simulations. As such, both ABM and SAOM are research instruments designed to discover and formulate hypotheses on the behaviour of real-world agents that render particular empirical realities (cf. Brenner and Werker, 2007; Snijders et al., 2010). In addition to this, (many conceptualisations of) the real-world can be modelled in a largely unabridged manner and can potentially also be calibrated by using empirical data such that the computer model offers facilitated policy evaluation and experimentation (cf. Vermeulen and Pyka, 2016).

SAOM (see e.g., Snijders, 1996; Snijders et al., 2010) is a method used in studying the dynamics of social networks where the agent decisions and other processes that drive these dynamics can conveniently be represented by 'objective functions' (capturing the value attached by this actor to the overall network configuration) and 'rate functions' (capturing the timing and frequency of an actor's tie formation processes). Among the areas of application are both the study of innovation networks and the analysis of social networks.

ABM (see e.g., Macal and North, 2010; Tesfatsion, 2006; Axelrod, 1997) is a method to study interacting heterogeneous agents in models that may include multiple types of entities and of interactions and large numbers of agents. In particular, the structure of interactions and relationships among these entities can evolve endogenously and could be calibrated to match stylised facts. ABM has been employed in both innovation network research, e.g., the investigation of collaboration in knowledge creation, and in financial network research, e.g., the investigation of systemic risk and stress testing in finance. A great deal is known about interbank lending, trading, and exposure networks – they are core-periphery networks, have heavy-tailed degree distributions and the central nodes (intermediaries) tend to control much of the trading and lending activity of the sector. Investigations into the stability of the sector and the dynamics that would ensue in a potential collapse (bankruptcy cascades etc.) have to consider both the properties of the network and those of corporate strategies and decision making. ABM as a technique is well-suited to tackle this problem.

4 Overview of papers in the special issue

Here we provide a short summary of the papers, which also reflects the diversity of current network research both in terms of the types of networks considered, the types of dynamics, as well as the research methods used.

Table 1 Overview over the papers in the special session

Authors	*Type of networks*	*Type of dynamics*	*Method*
Cantner et al.	R&D networks based on patents	Dynamics of networks	Econometrics: descriptive stats
Rothgang and Lageman	Collaboration networks	Dynamics of networks	Qualitative: surveys and interviews
Vermeulen	Inventor networks	Dynamics of and on networks	Econometrics: descriptive stats
Hain et al.	Funding/R&D/networks	Dynamics of networks	Econometrics: SAOM
Schaffrin et al.	Multilevel social network	Dynamics of and on networks	Conceptual
De Caux et al.	Banking network	Dynamics of and on networks	ABM
Bogner et al.	Social/Innovation networks	Dynamics on networks	ABM

Cantner et al. provide an indicator measuring innovation cooperation and furthermore study the changing innovation networks in East and West Germany since 1990. By paying particular attention to the dynamics of the innovations networks and by using patent data for their empirical exercise, the authors are able to identify important differences in the developments of East and West Germany after the formal re-unification. The authors show that the dynamic of innovation cooperation within East German regions is much higher than in the West. They explain this with the tremendous re-structuring and adaptation processes in the former German Democratic Republic.

Rothgang and Lageman exemplify the methodological pluralism of the research on innovation networks: their analysis of innovation networks is explorative and uses qualitative data. The authors conducted surveys and interviews with the innovation clusters that were picked as winners in the German 'Leading-Edge Clusters Competition' (LECC, Spitzencluster-Wettbewerb), a policy program that seeks to foster innovation cooperation among businesses. Their comparative study of the various innovation clusters reveals a number of interesting patterns, but they also highlight the specificity of every single innovation cluster. Aside from their concrete findings, which are interesting in themselves, their detailed description of the actors involved in the innovation networks highlights the more general importance of a multi-level analysis of innovation networks: single actors in their study, such as small firms or huge enterprises, are themselves economic systems consisting of a number of individuals and relations among them, and can themselves be analysed via network theoretic concepts (see @ Claudius....! for a meta-theoretical treatment of the multi-layeredness of economic systems).

Vermeulen uses descriptive statistics to analyse forward citation graphs of breakthrough patents. He finds indications that, early on in technological trajectories, inventors tend to collaborate mostly locally yet cite knowledge sources found more remotely, while, later on in technological trajectories, inventors collaborate over greater distances yet cite more local knowledge sources. As such, there exists a progressive globalisation of inventor networks, whereas knowledge sources are used increasingly locally in follow-up inventions.

Hain et al. use a stochastic actor-oriented model (SAOM) to analyse the role of exogenous firms' attributes (notably size, age) and endogenous structural effects in explaining network evolution. They calibrate their model to empirical data on the relationships of firms in the German automotive industry. They find that firm level attributes marginally contribute to explaining network change (particularly as it regards 'patenting experience'), while structural network characteristics (degree centrality, triads, alter popularity) are highly significant.

The paper entitled 'How to find a needle in a haystack?: a theory-driven approach to social network analysis of regional energy transitions' by Schaffrin et al., provides a rich conceptual framework which can be used to structure and guide the data gathering process and the empirical analysis of complex dynamics in a regional context. The authors substantiate the framework by drawing on theoretical considerations from sociology, economics and political science. This multi-disciplinary perspective allows for formulating hypotheses on different transition pathways. The authors exemplify the applicability of their framework by discussing the case of a local and regional energy transition in Germany. This case study demonstrates that the proposed framework provides a highly differentiated guiding system and points at the same time towards new directions for identifying and analysing system-inherent dynamics within social transition processes.

De Caux et al. investigate systemic risk in banking with an agent-based model. They analyse the frequency and size of cascades in a market with a single asset and interbank lending subject to liquidity requirements and an investment strategy. The investment strategy defines the utilisation of funds – how much to invest in assets, how much to make available for interbank lending. It is subject to endogenous evolution; banks adapt it slowly depending on their relative profits. The lending-network is also endogenous. Results include Minsky-type cycles with periodic bankruptcy cascades. The authors further find that the profile of cascades depends on the volatility characteristics of the simulation run.

Bogner et al. use an agent-based model to study knowledge diffusion in social networks where diffusion success is determined by cognitive distance. They study diffusion speeds, variance of diffusion, and resulting knowledge levels with five different network structures. The authors choose to use static networks for the purpose of this paper. Investigated network structures include one that was empirically measured for German federally funded R&D collaborations in the energy sector as well as several standard network topologies (Erdös-Renyi, Watts-Strogatz, Barabasi-Albert etc.). The authors find that average path length and clustering coefficients are much less important in determining the results than the characteristics of the skewed degree distribution.

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