Towards an Interdisciplinary Theory of Networks

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Abstract

Research problems in ICT networks often comprise coordination problems of information infrastructures and require state-of-the-art methods of coping with complex system dynamics. Especially, relevant economic network analysis is increasingly challenged to transcend "reductionist economic agendas" and incorporate findings from other disciplines. Recent trends of trying to bridge existing theoretical gaps in disciplinary research approaches by integrating the findings of other scientific disciplines reinforce the role of IS in establishing a sound theory of (social, economic) networks.

Based upon efforts towards extending an economic view on networks, in this paper the paradigm of agent-based computational economics is proposed as a possible methodological path towards developing a unified perspective on network research.

Keywords:

Network analysis, interdisciplinary network theory, agent-based computational economics

1. Introduction

Network is a widespread metaphor describing structures of interrelated elements as e.g. in corporate Intranets, supply chains, economies or other social systems. Expected network benefits result from improved coordination designs and generally include - depending on the particular problem domain - optimized business processes, more advantageous allocations, enhanced availability of information and other resources as well as decreased information costs or increased revenues.

But even when focusing on information and communication (ICT) networks (see section 2.1) the dynamics governing these networks are not yet sufficiently understood. Inherent in networks, the commonality property of network agents deriving from the need for compatibility implies coordination problems. From a theoretical perspective, the existence of network effects as a form of externality renders efficient neo-classical solutions improbable. The externality property deriving from network effects (and thus the multifaceted dynamics behind diffusion processes in networks) challenges traditional economic theories. Examples include monopoly and policy issues (Lemley 1996) (Braunstein & White 1985), societal infrastructures (Carlton & Klamer 1983) and market efficiency (Katz & Shapiro 1985) (Farrell & Saloner 1985). From a practical perspective, a virulent lack of theoretically sound and yet applicable methods for controlling networks leaves substantial efficiency potentials unused. Examples include software vendor strategies (Varian 1999) (Bakos & Brynjolfsson 1999) (Wiese 1990) and integration and standardization problems in business networks (Weitzel, Wendt & Westarp 2002).

Accordingly, a key challenge is to propose a theoretical foundation for ICT network analysis. Since there is literally no area in the social and economic world unaffected by the recent advancements of ICT, a relevant network theory needs to pursue an interdisciplinary research approach. That is why in this paper from the perspective of IS researchers a methodological path towards a unified theory of networks is proposed. After a brief summary of the problems associated with approaches from economics, network effect theory and diffusion theory, possible extensions towards considering elementary findings from other disciplines like especially the social sciences are discussed and incorporated. It becomes clear that incorporating findings from sociology and geography like network topology and density and various institutional and individual informational assumptions can offer more sophisticated views on social and technical networks. The role of IS is seen in bridging methodological problems by providing building blocks common to many effected established disciplines.

The main results presented in this paper also represent key experiences gained in one of the most interdisciplinary research programs hitherto funded by the German national science foundation (DFG). The authors are indebted to the DFG for funding the project.

2. Some Economics of Networks

2.1 Network Effect Theory

Networks started to draw public and academic interest after the Second World War when optimization focus shifted from improving national productivity (to obtain production side economies of scale) to compatibility and associated demand side economies of scale. This new dynamic first peaked with the release of the papers of McGowan and Fisher concerning the antitrust lawsuits versus IBM in the 1970s (Fisher, McGowan & Greenwood 1993). Building on this, the influential works of Farrell and Saloner and Katz and Shapiro (Katz & Shapiro 1985; Farrel & Saloner 1985) established the concept of network effects as the underlying particularity in networks which can be said to have opened network problems as an area of research of its own aimed at explaining typical behavior found in networks (like instability, excess inertia, excess momentum, installed base effects, etc.) (Farrell & Saloner 1985; 1986, Katz & Shapiro 1985; 1986; Arthur 1989; Besen & Farrell 1994). *Network effects* have been defined as "the change in the benefit, or surplus, that an agent derives from a good when the number of other agents consuming the same kind of good changes" (Liebowitz & Margolis 1995; see Thum 1995, 5-12 for different sources of network effects).

The externality property implies coordination problems in markets subject to network effects, which are said to be endemic in high tech industries in particular "and that such industries experience problems that are different in character from the problems that have, for more ordinary commodities, been solved by markets" (Liebowitz & Margolis 1995). Common results found in the literature on network effects are the following:

- In many cases, the existence of network effects leads to Pareto-inferior results in markets (i.e. unfavorable network behavior).
- Particularly, excess inertia can occur as no actor is willing to bear the overproportional risk of being the first network participant (start-up problem, lock-in, stranding). Also, excess momentum can occur, e.g. if a sponsoring firm uses low prices in early periods of diffusion to attract a critical mass of adopters.
- Positive network effects imply multiple equilibria and the (tippy) market will finally lock-in to a monopoly situation.

In Weitzel, Wendt and Westarp (2000) it is argued that traditional approaches addressing network effects offer great insights into general network phenomena like start-up problems but that they fail to explain the variety of diffusion courses in today's dynamic ICT markets. The main drawbacks of traditional network effect theory are:

- No sufficient distinction between direct and indirect network effects is made in the models although it can be shown empirically (Weitzel 2003) and analytically (Katz & Shapiro 1994) that they have different economic implications.
- No explication of cost and benefit development: If optimum networks under network externalities are monopolies, "all networks are too small". This hypothesis only holds where there are constant or falling costs when adding new members to a network. The costs of network size are ignored in almost all models.
- No consideration of individuality: Another limiting assumption is that of similar and agent independent valuations of networks and the growth of network effects. Heterogeneity can have substantial impact on the evaluation of different networks as well as on the value assigned to new actors. Heterogeneous preferences increase the chance of the efficient coexistence of networks.

2.2 Diffusion of Innovation Theories

While the theory(ies) of positive network effects analyze the specific characteristics of markets for network effects goods (such as software products) models of the diffusion of innovations focus on explaining and forecasting the process of the adoption of innovations over time. The term diffusion is generally defined as "the process by which an innovation is communicated through certain channels over time among the members of a social system" (Rogers 1983, 5). In particular, the question of which factors influence the speed and specific course of diffusion processes arises (Weiber 1993). Traditional diffusion models are based on similar assumptions: Generally, the number of new adopters in a certain period of time is modeled as the proportion of the group of market participants that have not yet adopted the innovation. Most of the traditional approaches aim at revealing the relationship between the rate of diffusion and the number of potential adopters according to the nature of the innovation, communication channels, and social system attributes (Mahajan & Peterson 1985, 14). The three most common types of diffusion models (Weiber 1993; Lilien & Kotler 1983; 706-740, Mahajan & Peterson 1985, 12-26) are exponential (assumes that the number of new adopters is determined by influences from outside the system, e.g. mass communication), logistic (assumes that the decision to become a new adopter is determined solely by the positive influence of existing adopters; e.g. word of mouth) and semilogistic (considers both influences) diffusion models. A famous example of the latter is the Bass model, which has been used for forecasting innovation diffusion in various areas such as retail service, industrial technology, agricultural, educational, and pharmaceutical markets (Bass 1969; Mahajan, Muller and Bass 1990, 2).

For modeling the diffusion of network effect products, three areas of deficit are eminent: critical mass phenomena are not sufficiently analyzed, real life diffusion processes cannot be explained, too, and the interaction of potential adopters within their socio-economic environment is not sufficiently elaborated (Schoder 1995, 46-50). Therefore, logistic and semilogistic approaches are primarily found in areas where innovations have only small consumer interdependencies, where the acceleration of the adoption is characteristically slow, and where the diffusion function is similar to normal distribution.

A long, mostly empirical, research tradition exists in the area of *network models of diffusion of innovations*. Network analysis in this context is an instrument for analyzing the pattern of interpersonal communication in social networks (for geographical network analysis see Haggett, Cliff & Frey 1977; for sociological network analysis see Jansen 1999). Two early studies can be seen as the starting point for network diffusion analysis (Valente 1995, 4-15). Collecting network and diffusion data in 1955/6 Coleman, Katz, and Menzel studied the diffusion of a drug innovation (tetracycline) in four towns (Coleman, Menzel & Katz 1957). With the aim of determining the role of social networks, the doctors were asked to name doctors from whom they most frequently sought discussion, friendship, and advice, respectively. For example, the diffusion of the new drug was faster among doctors with an integrated position in the network than among isolated doctors. In general, network diffusion models can be divided into *relational models* and *structural models*. Relational models analyze how direct contacts between participants in networks influence the decision to adopt or not adopt an innovation. In contrast, structural models focus on the pattern of all relationships and show how the structural characteristics of a social system determine the diffusion process.

3. Alternatives to an Economic Analysis of Networks

The analysis has shown some theoretical approaches addressing systems subject to network effects that make network problems challenging for traditionally established scholarly systems, especially neo-classical analysis. Beneath the externality property, there are other shortcomings of the neoclassical framework when ICT systems (and their contents like information products) are the basic unit of analysis. Hence, after identifying these drawbacks, a possible methodological path is proposed to bridge some of the major problems identified.

3.1 General Drawbacks of the Neo-Classical Paradigm

From an economic perspective, the network effect property associated with network agents' activities is a form of externality that disturbs the automatic transmission from local to global efficiency. Neoclassical analysis is based on a set of premises that need to be fulfilled in order for the "fundamental theorems of welfare economics" (Hildenbrand 1976) to be valid and thereby to reach a Pareto-optimal allocation of goods. The ability of the market mechanism to accomplish this task depends on the validity of the following implicit assumptions (for an extensive discussion see Weitzel, Wendt & Westarp 2000):

- Absence of externalities (see below*)*
- Complete rationality of the homo oeconomicus (see below)
- Exclusion principle (unique possession and ownership of goods)
- Consumption paradigm (utility derived from consumption of goods)
- Separation of consumers of producers
- Divisibility of resources
- Concave utility function (no complementarities)
- No transaction costs

The approaches towards network analysis presented above mostly focus on the first premise in accepting the relaxation of the no externality premise.

3.2 Extensions to an Economic Framework of Analysis

In earlier definitions, an externality was considered to be present whenever the utility function $U_i(.)$ of some economic agent *i* includes real variables whose values are chosen by another economic agent *j* without particular attention to the welfare effect on *i*'s utility. Three principal solutions to the problem of externalities have been proposed. Pigou (1920) suggests a tax imposed by a regulator. This Pigovian tax "corrects" the externality if the regulator knows its correct level (although then he could also just regulate the optimal level of the underlying problem). In the context of positive network effects this implies negative taxes, i.e. subsidies. A problem is that the Pigovian tax is only "right" in equilibrium and the theory does not say much about the optimal (intertemporal) price path (Wiese 1990, 5).

Another solution is shown by Coase (1960). He argues that the market mechanism may overcome some of these problems by adding well-defined "property rights" as tradable goods to the economy. Agents can then reach efficient outcomes by negotiation (given transaction costs are zero) the structure of which remains open, though. Accordingly, Arrow (1970) suggests setting up a market for the externality as the institution providing a negotiation structure. Therefore, nowadays an externality is said to be present whenever there is insufficient *incentive* for a potential market to be created for some good and the non-existence of this market leads to a *non-Pareto-optimal equilibrium*. So far, the absence of externalities is the only premise network effect literature – as discussed above – is trying to relax.

Network effect literature often relies on the neo-classical assumption that all agents not only know their own action space and utility function but likewise have a complete and realistic model of all the other agents' current allocation, action spaces and utility functions as well. In a pure neo-classical "exchange economy" this assumption may be relaxed and even when we only bargain with our direct neighbors the decentralized exchange still leads to a unique and Pareto-optimal equilibrium, but unfortunately only if there are no network externalities or indivisibilities. But for "real world" individuals, parametric and strategic (or strategic and statistical (Williamson 1985)) uncertainty imposes constitutional bounds to the knowledge their decisions can be based upon (Hayek 1937; 1994, 171). Additionally, heterogeneous institutional and structural environments influence the decisions of individual socio-economic agents. A frequent sociological argument for applying non-economic methodologies (i.e. surpassing the notion of a homo oeconomicus) is that "social patterns of human interaction transcend reductionist economic agendas" (Alstyne 1997). The procedural setback is associated with the concept of a methodological individualism associated with a homo oeconomicus that is "a generic individual distinguished not by sex, ethnicity, religion, age, or any other social characteristic" (Biggart & Hamilton 1993, 480) while the "pursuit of economic goals is typically accompanied by (such) non-economic (goals) as sociability, approval, status, and power… Economic action is socially situated and cannot be explained by reference to individual motives alone" (Granovetter 1993, 25). In this context, a market derived price seems to be not only too little dimensioned to capture network effects but also to be a simplification failing to capture the intricacies and complexity of human interaction (Powell 1990, 112).

3.3 Towards an Interdisciplinary Theory of Networks

As could be shown in the previous sections, a general theory of networks will have to consider several aspects that go beyond traditional analytical economic analysis. Due to the deficiencies of the neoclassical paradigm the question of whether there are alternative theoretical foundations arises. An extensive survey of the network metaphor ("network organization") comparing views and trying to identify commonalities from the points of understanding of network as a computer metaphor (coordinated problem solving), a rational agent metaphor (or economy metaphor; motivating self-interested parties to achieve mutually satisfactory Pareto-efficient outcomes) and a society metaphor (social patterns of human interaction) is presented by Alstyne (1997). In the field of institutional economics (or more general institutionalistic theories in the social sciences) the critique outlined above is widely supported (Hodgson 1993). In general, "institutions" are considered to reduce uncertainty and thereby coordination costs between agents and can be, for example, property rights, contracts, or traditions. In economic theories of institutions, a commonality is the shared criticism concerning parts of the notion of the homo oeconomicus. In particular, the consideration of bounded rationality and opportunistic behaviour is deemed crucial for explaining socio-economic systems. In Institutional economics, assumptions concerning agent behaviour are crucial: "Since institutional economics is behavioristic, and the behavior in question is none other than the behavior of individuals while participating in transactions, institutional economics must make an analysis of the economic behavior of individuals" (Commons 1931, 654). The central assumptions about agent behavior are bounded rationality, opportunistic behavior, and utility maximization. Nevertheless, institutional economics as an extension to the neoclassical theory is based on a methodological individualism (social processes and institutions as pillars of the social world can, in principal, be explained by individual behaviour). Among others, new institution economics has faced criticism concerning the fact that, particularly due to path dependencies, agents with bounded rationality cannot possibly determine optimum institutions (North 1990).

In the social sciences, institutionalistic approaches have been successfully applied in the past 15 years when analysing questions like why different countries (or regions) react differently to technical and economic developments and why similar actions take different effects. For an overview of recent institutionalistic research approaches in the social sciences and disciplinary particularities see Esser (1999). In the context of network analysis, institution theories from disciplines like sociology focus on analogous important phenomena such as the importance of the socio-economic and institutional environment in that the social embeddedness of all deciding agents is a major determinant of system behavior (e.g. economic institutionalism (Williamson 1985; North 1990; Hodgson 1988; Dosi et al. 1988; Nelson 1993), political neo-institutionalism (Hall & Taylor 1996; Peters 1999) and institutional organization sociology (Granovetter 1985; Powell & DiMaggio 1991), see also Hall and Taylor (1996) for differentiating "historical institutionalism", "rational choice Institutionalism" (social phenomena are explained by individual decisions according to the methodological individualism), and "sociological institutionalism"). For the concept of social embeddedness see Veblen (1919), Polanyi (1944), Granovetter (1985); Granovetter and Swedberg (1992); Hodgson (1996). In contrast to the economic branch of institution theories, in sociology the complexity deriving from the social embeddedness of the agents and the impossibility of separating agents from their environments (among others due to path dependencies) has led many sociologists to neglect all micromodels of agent environments; from a theoretical point of view the notion of a homo oeconomicus and especially the associated methodological individualism is supposed to be inappropriate to describe a complex socio-economic reality.

Thus, a necessary condition for developing an operable view on networks that can be accepted by economists as well as researchers from social sciences is to incorporate the concepts of

- bounded rationality
- uncertainty and incomplete information
- social embeddedness.

Within this framework, the primary challenge is to overcome disciplinary differences concerning methodological individualism (homo oeconomicus) and a sociological macro perspective (homo sociologicus). Nevertheless, no common methodology has yet been developed. From an economist's perspective, the main reason is the refusal to explicitly model behavioral assumptions as needing to be used within models of social systems consisting of interacting agents. Naturally, game theory offers a rich ground for analyzing systems subject to interdependencies like network effects. Using game theory instead of decision theory is an important step leading away from a methodological individualism and into the direction of rather focusing on the interdependencies between particular decisions. Moreover, the differentiation between micromodels and macromodels vanishes in game theoretic models. Additionally, considering frictions resulting from incomplete contracts, asymmetric information etc. makes the models more realistic (SFB 2000, 14-15). Unfortunately, most traditional game theory still strives for analytical solutions, which neglects the complexity deriving, among others, from network effects. An exception is parts of the evolutionary branch of game theory aimed at describing the evolutionary dynamics that are demanded by sociologists and political scientists (SFB 2000, 15).

These approaches together with recent contributions in the area of complex adaptive systems inspired a new research field which focuses on using computer-based models for understanding emergent system behavior. The paradigm of agent-based computational economics (ACE) rejects the complete rationality of the homo oeconomicus in favor of a learning individual (Vriend 1999; 1996). "Agent-based computational economics is the computational study of economies modeled as evolving systems of autonomous interacting agents" (Tesfatsion 2002). Although, as outlined above, in disciplines such as sociology, research approaches based on micromodels are often considered to be inappropriate for modeling complex social networks due to the proposed impossibility of modeling the social embeddedness of agents and the emergence of institutions, ACE might be a common way for conducting descriptive network analyses: "One principal concern of ACE researchers is to understand why certain global regularities have been observed to evolve and persist in decentralized market economies despite the absence of top-down planning and control (…). The challenge is to demonstrate *constructively* how these global regularities might arise from the bottom up, through the repeated local interactions of autonomous agents" (Tesfatsion 2002). This methodological approach thus focuses on how structures (or institutions) *emerge* in decentralized networks (bottom-up) rather than being explicitly planned and rationally implemented (top-down).

For normative network analysis, which is the second principal concern of ACE researchers, we can use "computational laboratories within which alternative socioeconomic structures can be studied and tested with regard to their effects on individual behavior and social welfare" (Tesfatsion 2002). Also, central to social network research, learning and the evolution of social norms are prevalent ACE research areas making this approach interesting for future research on various kinds of socioeconomic networks. Notably, in an early simulation study, Wiese (1990) proposes pricing, product, and communication strategies for network effect goods vendors using elaborate simulations. He analyses problems indicative of the three stages of market development: market creation (start-up problem in a not-yet-existing market), market entry (installed base) and oligopoly battle.

3.4 Application to an Interdisciplinary Framework for Network Analysis

Due to the existence of multiple equilibria and the evolutionary dynamics in networks, we have proposed using computer models for network analysis. Using game theory to explicitly model the individual incentives responding to their individual informational and social environments eventually allows to create bottom up economies, i.e. overall system behavior results from individual decisions without having been explicitly controlled on a central level. But how can we learn from and incorporate findings from other scientific disciplines?

Incorporating the influence of opinion leadership (Coleman, Menzel & Katz 1957), group membership (relevance of intra-group pressure towards conformity), personal network density (interconnectedness of an individual's network) and personal network exposure (how intensely is an individual exposed to network innovations) by modeling respective network topologies can substantially improve the explanatory power of recent network models. Also, in the literature, various centrality measures exist for individuals and for the whole network (Freeman 1979, Bolland 1988) that have so far not found their way into economic network analysis. An interdisciplinary approach using these geographic and sociological proximity measures as parts of a computer-based network model has been successfully applied to model the diffusion of innovations in the software market and to develop vendor pricing strategies based upon the model. Most notably, in doing so the actual market structure of U.S. and German EDI, office software, and ERP markets can be explained quite precisely (Westarp 2003). In (Weitzel 2003) based on a game theoretical equilibrium analysis using computer simulations, the findings of the existing theory (section 2) can be described as special cases of a network framework at particular constellations of the main network determinants like especially price, network structure (topology and density), number of alternative technologies, agent size and choice sequence and installed base effects. Using the proposed approach, phenomena like the coexistence of incompatible products despite strong positive network effects, quite different installed-base effects and inefficiencies could be well explained. An imminent challenge for future research is the further combination of physical and social networks and the disclosure of their interdependencies. Ultimately, one might think of a generic model common to e.g. automotive supply chains and social networks like societies in generically modeling scarce resources and ways of optimizing their allocation by synchronizing these various networks.

4. Conclusion

An economic theory of networks faces challenges resulting from the complex dynamics deriving from the existence of network effects and the social and institutional embeddedness as well as the bounded rationality of the network's agents. Using important findings from social, political and geographical sciences regarding network topology and proximity measures to model the social emdbeddedness of agents combined with computer-based simulation models to master at least parts of the virulent evolutionary complexity in these systems might offer new insights into the dynamics behind networks and provide a step towards befriending the homo oeconomicus and the homo sociologicus.

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