ON SOCIAL NETWORK ANALYSIS IN A SUPPLY CHAIN CONTEXT

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The network perspective is rapidly becoming a lingua franca across virtually all of the sciences from anthropology to physics. In this paper, we provide supply chain researchers with an overview of social network analysis, covering both specific concepts (such as structural holes or betweenness centrality) and the generic explanatory mechanisms that network theorists often invoke to relate network variables to outcomes of interest. One reason for discussing mechanisms is facilitate appropriate translation and context-specific modification of concepts rather than blind copying. We have also taken care to apply network concepts to both "hard" types of ties (e.g., materials and money flows) and "soft" types of ties (e.g., friendships and sharing-of-information), as both are crucial (and mutually embedded) in the supply chain context. Another aim of the review is to point to areas in other fields that we think are particularly suitable for SCM to draw network concepts from, such as sociology, ecology, input-output research and even the study of romantic networks. We believe the portability of many network concepts provides a potential for unifying many fields, and a consequence of this for SCM may be to decrease the distance between SCM and other branches of management science.

Keywords: social network analysis; supply chain management

[1] Acknowledgements: We would like to thank Goce Andrevski, Dan Brass, Tom Goldsby, Joe Labianca, and Ajay Mehra for their important help with various aspects of this manuscript. Contact information: Gatton College of Business and Economics, University of Kentucky, Lexington, KY 40506. Email address for Steve Borgatti: sborgatti@uky.edu. Email address for Xun Li: xli@uky.edu

INTRODUCTION

In most social science fields, including management science, the default mode of explanation up through the mid-twentieth century has been based primarily on individual attributes. Whether the individuals were persons or firms or any other kind of entity, the standard approach has been to explain one attribute of the entity – e.g., an outcome of some kind -- as a function of other attributes of the entity, representing inherent characteristics of the entity. For example, at the person level, sociologists have explained a person's status as a function of their gender and education. Similarly, at the firm level, organizational theorists in the Weberian tradition have explained the success of an organization in terms of its use of certain processes and structures, such as documentation of procedures, promotion based on qualifications, unity of command, and so on.

Over time, however, most of the social sciences (and, indeed, physical and biological sciences as well) have shifted to a more relational perspective that takes into account the environment around the actor in addition to internal attributes. For example, in the earliest days of contingency theory, attributes of an organization's structure (such as whether the organizational chart was deep and narrow or flat and wide) were seen as a function of other attributes internal to the organization, such as its size and its technology (Woodward, 1958). Over time, however, contingency theory began to shift its emphasis to the organization's environment, supposing that successful organizations would adapt to their environments, often in a mimetic fashion so that, for example, organizations in highly differentiated environments would develop highly differentiated organizational structures (Lawrence and Lorsch, 1967).

In these early views of an organization's environment, the environment was monolithic – a single "thing" characterized by attributes such as complexity or turbulence. However, starting with Evan (1966) researchers began to see an organization's environment as consisting of multiple individual players, interacting separately with the focal organization. Thus resource dependence theory is concerned with the response of one organization to dependency on another (Pfeffer and Salancik, 1978), and some forms of institutional theory have seen organizations as influencing each other to adopt practices and structures (DiMaggio and Powell, 1983).

With respect to this evolution, it could be said that supply chain management (hereafter, SCM) has had the jump on other fields, because it has long conceived of its subject in relational or dyadic terms. Moreover, SCM has not been just dyadic, as, say, most of resource dependency has been, but has -- through the notion of chains -- implicitly considered paths through a network of firms. Of course, for the most part, the focus has been on chains of just two links: supplier to focal firm, and focal firm to customer. Still, the concept of suppliers of suppliers and customers of customers and so on has always been there, and now the imagery and terminology of a supply network is beginning to supplant that of a simple chain. Furthermore, supply chain researchers are now actively importing concepts from the (primarily) sociological field of social network analysis (e.g., Carter, Ellram and Tate, 2007; Autry and Griffis, 2008). As a result, the time is right for a general review of key concepts in social network analysis that could be useful to supply chain researchers in further elaborating the potential of the network concept. This is the purpose of the present paper.

We organize the paper as follows. First, we give an overview of social network theory, as developed in a number of social science fields, including social psychology, anthropology and sociology. We take the opportunity to integrate several threads of network research into a small number of coherent bodies of theory. Next, we turn to how network theory might be applied to the SCM.

It should be noted that supply chain management has both "hard" (i.e., technical) and "soft" (i.e., people) aspects, reflecting the fact that the field is at the intersection of many disciplines, such as marketing, procurement, management, operations research, logistics, and so on. It might be supposed that social network analysis – originating as it does in social psychology – would have its greatest and most natural application on the soft side of SCM, helping to understand how patterns of personal relationships translate to competitive advantage through diffusion of information, social control of opportunism, coordination and aid, and so on. In truth, however, social network analysis can be fruitfully applied to both sides of the equation, and, to the extent that this hard/soft distinction translates into different kinds of ties (such as movement of supplies versus personal friendships), this will be reflected in this paper, which sketches out how social network concepts might be applied to both resource flows and less tangible relations.

KEY CONCEPTS IN SOCIAL NETWORK ANALYSIS

The objective of this section is to provide a short introduction to the key concepts and perspectives in social network analysis.[2]

The network perspective views any system as a set of interrelated actors or nodes. The actors can represent entities at various levels of collectivity, such as persons, firms, countries, and so on. The ties among actors can be of many different types, such as friendship, competition and so on, and can be characterized along multiple dimensions, such as duration, frequency and the like. Figure 1 shows a simple typology of ties commonly studied among individual persons.

At the top level, the typology divides ties into two basic kinds, continuous and discrete. Continuous ties are those that are always "on" for the duration of the relationship, such as being the spouse of someone. Another way to think of continuous ties is as relational states. In contrast, discrete ties are based on a series of discrete events, which we might count up, such as the number of times X sends Y an email, or the number of bits of information transferred from one place to another.

[2] This section is based on Borgatti, Mehra, Brass and Labianca (2009).

At the next level, the typology divides ties into four major groups: similarities, social relations proper, interactions, and flows.

The *similarities* class refers to dyadic conditions that might be said to be "pre-social" – things like co-membership in groups, or co-location in space. Actors that co-occur in organizations or locations or activities don't necessarily even know each other, but have heightened opportunity to establish other kinds of ties. A classic article in social network analysis using this kind of data is the Davis, Gardner and Gardner (1941) study of Southern women. They collected data using the newspaper's society pages on who went to which social events. The study documented the existence of separate social circles based on class issues.

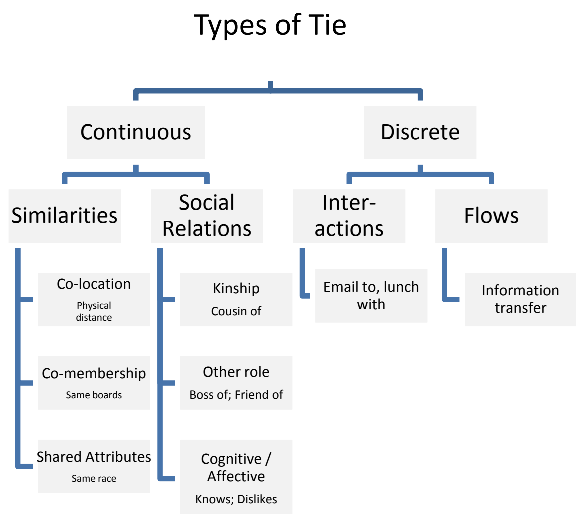

Figure 1*. Typology of types of ties among persons studied in the social networks literature.*

The *social relations proper* class refers to (a) continuously existing ties such as kinship relations, (b) other role-based relations such as 'is the friend of' or 'is the boss of', and (c) cognitive-affective relations like 'knows' or 'trusts'. Much of network theorizing and imagery is focused on these kinds of ties.

Interactions differ from social relations proper in consisting of discrete events that are (typically) counted up over a period of time, such as 'talked to over the last month' and 'sent email to'. In empirical analysis, we often assume that interactions imply the existence of some kind of underlying relation, so that the number of emails between two actors serves as a proxy for the strength of some kind of social relation between them. At the same time, we typically assume that social relations facilitate interactions, so that, to some extent, measuring one measures the other.

Finally, *flows* consist of the content that (potentially) moves between actors when they interact, such as ideas or money or stocks of inventory. In principle, flows are often the most important kinds of tie. But, in practice, flows are rarely measured and are instead assumed from interactions or social relations. For example, one of the most common concepts in knowledge management research is information and knowledge transfer, although actual transfers are rarely measured. Instead, a proxy like frequency of communication or strength of affective relationship is usually measured (see, for example, Borgatti and Cross, 2003).

Ties among collective actors, such as firms, can be classified along the same four dimensions as ties among individuals. However, in addition, it is useful to make a cross-cutting distinction between ties among actors as collective entities, and ties that exist through the personal relationships of their members. Table 1 shows examples of inter-firm relationships cross-classified by these two dimensions.

Type of Tie	***Firms as Entities***	***Via Individuals***
Similarities	***Joint membership in trade association; Co-located in Silicon valley***	***Interlocking directorates; CEO of A is next-door neighbor of CEO of B***
Relations	***Joint ventures; Alliances; Distribution agreements; Own shares in; Regards as competitor***	***Chief Scientist of A is friends with Chief Scientist of B***
Interactions	***Sells product to; Makes competitive move in response to***	***Employees of A go bowling with employees of B***
Flows	***Technology transfers; Cash infusions such as stock offerings***	***Emp of A leaks information to emp of B***

Table 1. *Examples of inter-organizational ties cross-classified by type of tie (rows) and type of entity involved (columns).*

At the top left of the table ("similarities" row) we have "proto-ties" among firms as collective entities, such as joint memberships in trade associations (Human and Provan, 2000), or co-location in industrial districts (Marshall 1920; Saxenian, 1994). At the top right we have co-affiliation ties through organizational members, as when scientists from different companies attend the same conferences. These kinds of ties have figured prominently in the interlocking directorate literature (Mizruchi, 1996).

In the second row of the table we have continuous relations among firms. At the firm level proper we have such ties as joint ventures, distribution agreements, ownership of, and competition with. These kinds of ties have been a staple in firm-level research on knowledge and innovation (Powell, 1996). In the category of inter-organizational ties through individual members we have such things as friendships between employees of different companies. Such ties have been seen as important in the procurement literature (Reingen, 1987) and the embeddedness literature (Uzzi 1996).

In the first cell of the interactions row of the table we have market transactions between firms such as when one firm makes a sale to or a purchase from another firm (Williamson, 1975), or interactions of other kinds, such as when one firm makes a competitive move against the other firm (Ferrier, 2001). In the second cell of the interaction row we have interactions among organizational members, as when employees of one firm play sports with employees of another firm.

Finally, in the flows category, we have transfers of materials and ideas from firm to firm, either at the firm level proper, as when a company acquires the technology of another, or through individuals, as when an employee leaks information to another company, whether inadvertently or as an act of espionage. The flows are the consequences of the other kinds of ties – physical access, personal relationships, interactions, and so on. A classic example in the inter-organizational literature is the diffusion of practices like poison pills and golden parachutes from firm to firm via board interlock ties (Davis, 1991; Davis and Greve, 1997).

It is understood that among any given set of actors, any or all of the ties described above can exist simultaneously, a property known as *multiplexity*. For example, actor A can be friends with actor B, but the pair can also be coworkers, and both actors can have myriad other relations with others. One way of analyzing social networks is to consider different kinds of ties as being like separate layers of relations, or, to put it another way, as separate networks based on the same actors. Thus, given a set of actors, we can examine the 'who talks to whom' network and, separately, examine the 'who dislikes whom' network, which may or may not be negatively correlated. It is important to realize that these different networks can have very different structures, and may have different logics and implications for the actors. Being central in the 'who talks to whom' network could be fun and enlightening, but being central in the 'who dislikes whom' network, could be painful and constraining. Another way to analyze networks is to look at each dyad in its totality of types of tie. Hence, a firm that sells to another firm may also have equity in that firm, as well as common memberships in trade associations. In addition, the individuals in the two firms may have a complex collection of personal relationships with each other.

It is worth noting that type of tie can be seen as a parallel concept to that of actor attribute. Actor attributes are variables that measure different characteristics of each actor. A given actor has a certain profile of characteristics that identify them. For example, a person may be male, age 24, and Republican. Similarly, types of tie can be seen as variables that measure different characteristics of a dyadic relationship. A given dyad has a particular bundle of types of tie that characterize it. For example, the relationship between Bill and Mary may be characterized as involving friendship, 6 years of knowing each other, and advice-giving. Thus, the key difference between actor attributes and types of tie is the unit of data, which is the actor in the former case and the dyad or pair of actors in the latter case.

It is a fundamental characteristic of network analysis that the basic unit of data is the dyad. However, this is not what makes network analysis unique. Many fields take the dyad as a fundamental unit. For example, psychologists study the "mother-daughter" relationship and the "patient-therapist" relationship. These are dyadic, but the approach differs from network analysis in that the dyads are conceptually independent of each other – they do not link up to form a network. As a result, to study the mother-daughter relationship empirically, a psychologist can recruit mother-daughters pairs at random. If by chance two dyads were connected (e.g., subject A is the mother of subject B and subject B is the mother of subject C) this would be ignored or treated as a nuisance to be controlled for in the statistical analysis.

In contrast, in network analysis, the idea is that, given a set of nodes and a set of relational types of interest (say, friendships), we systematically consider the relationships among all dyads (pairs of nodes) in our frame. The key consequence of this conceptually is that dyads link together into chains or paths that vary in length and may indirectly connect all actors with all others. These paths provide avenues through which actors unknown to each other can influence each other, and through which position in the network as a whole can be theorized to have consequences for the node.

Given this distinction between a purely dyadic perspective and the network perspective, it may be surprising to learn that in practice many studies that draw on the network theoretical perspective do not actually take into account the full network. Instead, they utilize only what is called the *ego network*, which consists of (a) a focal actor, known as ego, (b) the set of actors with any kind of tie to ego (known as alters), and (c) all ties among the alters and between the alters and the ego (see Figure 2).

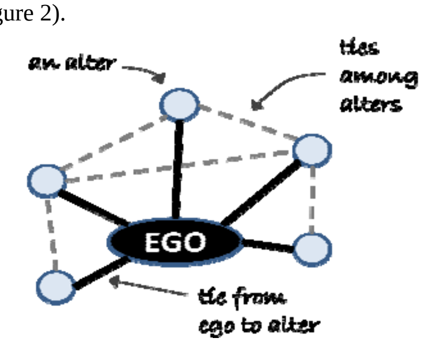

Figure 2. *An ego network. Ties between egos and alters are indicated by solid lines. Ties among alters are shown with dotted lines.*

An example is provided by the well-known work of Ron Burt (1992) on social capital. In a nutshell, Burt proposes that nodes whose ego networks are sparse (i.e., few ties among alters, a property known as structural holes) will enjoy a variety of benefits as compared to nodes whose ego networks are dense. According to his more recent work (Burt, 2005), the main benefit of structural holes is the availability of (non-redundant) information. If a node's alters are connected to each other, then the information that one alter possesses may also be possessed by another of ego's alters, which would suggest that a tie to both of them would be redundant – and therefore unnecessary. Hence, an ego network of similar size but with fewer ties among alters is likely to provide ego with more non-redundant information.

The main reason to restrict attention to the ego network is, in principle, the belief that more distal connections are not relevant to the specific mechanisms at hand. Of course, it is also much more convenient to collect ego network data than full network data, and if the ego network provides a reasonable proxy for position in the larger structure, there is little reason to collect the whole network.[3]

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KEY THEORETICAL PERSPECTIVES

A fundamental axiom in network analysis is the notion that actors are not independent but rather influence each other. There are many aspects of and mechanisms for this, but perhaps the mostly commonly invoked is the mechanism of direct transmission or flows. For example, if two nodes are friends, they will interact and, in so doing, ideas and information will be transmitted from one to the other.

The transmission mechanism is the kernel of a general theory of how network variables have consequences for nodes and for the network as a whole. For example, taking information as an illustrative focus, if information is obtained through ties then the transmission mechanism suggests that having more ties (a property known as degree centrality) implies having more information. That is, nodes with more ties will have more information and, to the extent that information has an impact on things like performance, better performance. Furthermore, if even a few nodes in a network have a great many ties, then it is easy for all nodes in the network to search out information held by the network – they need only ask the central nodes which, by virtue of their knowledge of who knows what, can refer the seeker to the appropriate node. This also leads to the proposition that nodes that are connected to well-connected nodes (a property known as eigenvector centrality) will have even more information than nodes that are connected to an equal number of less connected others.

At the same time, if an ego's alters have an information-sharing tie with each other, then some of the information that ego might obtain through these ties will be redundant. Hence, an ego would do better to allocate their relational energy to alters that are unconnected to each other and therefore more likely to possess independent information or points of view. Thus, having unconnected alters (or, as mentioned before, structural holes) should lead to more information and, ultimately, better performance (Burt, 1992). Taking this a bit further, we might note that a person's strong ties are more likely to have ties to each other than a person's weak ties. For example, if actor A is married to actor B, it is likely that B knows most of A's other friends, especially their close friends. If so, an ego network composed of weak ties will likely have more structural holes than an ego network of strong ties, and therefore can be expected to enjoy more information benefits. Thus we can hypothesize that weak ties have performance benefits (Granovetter, 1973).

Continuing with other branches of the transmission-based general theory, consider that if it takes time for things to be transmitted from person to person, then nodes that are a short distance from most other nodes (in the sense of short path lengths) will, on average, receive information sooner than nodes that are far away from most others (a property known as closeness centrality). In addition, networks that are highly centralized in the sense of having a node that is close to all others are likely to perform well in tasks that require integrating information. This is the well known result of the MIT experiments by Alex Bavelas and Harold Leavitt (Bavelas, 1950; Leavitt, 1951). If short paths are important, then we also hypothesize that nodes that lie along many short paths between others (a property known as betweenness centrality) are structurally important nodes that are well positioned to (a) control and possibly filter or color information flows, and (b) become over-burdened bottlenecks that slow the network down.

For the purposes of expository convenience, we have illustrated the flow theory entirely in terms of information flows. More generally, however, it is obvious that resources of all kinds may flow through social ties. This is the basis of one important stream of social capital research, known in the past as social resource theory, (Lin, 1981). Through social ties, actors such as entrepreneurs can avail themselves of resources that they don't possess, such as funding, materials, labor, expertise and so on.[4] Thus, the generic hypothesis in this social capital literature is that actors with 'strong' ego networks (in the sense of providing access to valuable resources) will have higher rates of entrepreneurial success or career rewards.

All of the above hypothesizing can be seen as parts of a single general theory because it is all based on the same fundamental explanatory mechanism, which is that things flow from one node to another along social ties. Underlying this theory is a metaphor that sees ties as pipes or roads along which traffic flows. However, by this definition, it is not the only theory in social network analysis, as there are other fundamental mechanisms of consequence.

Another body of theory emerges from the mechanism of coordination or bonding. Here the underlying metaphor is one that sees ties as girders or bones or chemical bonds that create a unified structure out of otherwise autonomous agents. A bureaucratic organization, with its backbone of who reports to whom, is an example of such a unifying, coordinating structure, as is a molecule or a biological organism.

Like the notion of ties as pipes, the notion of ties as bonds has a number of implications that generate an elaborate theory. For example, if coordination or unification results from bonding, then we can hypothesize that the stronger the tie, the stronger the unification, and the greater the commonality of fates. Tightly coupled markets sink or swim together. Tightly coupled suppliers and buyers prosper or founder together (Ford plan).[5] Another implication is that structural holes will have autonomy and power benefits in addition to the information benefits discussed earlier (Burt 1982, Burt 1992). An actor that is negotiating with several alters that are

[3] For example, in the case of structural holes, if two alters have no tie to each other then it is at least possible that they belong to different social circles and may connect to different nodes beyond the ego network. Indeed, Everett and Borgatti (2005) find extremely high correlations between a centrality measure calculated on the ego network and the same measure calculated on the network as a whole.

[4] For firm-level work in this tradition, see Gulati, Nohria and Zaheer (2000).

[5] "Because our industry is an interdependent one, with broad overlap in supplier and dealer networks, the collapse of one or both of our domestic competitors would threaten Ford as well,"

unconnected will have a much easier time of it than an actor whose alters are in communication and actively coordinating with each other. For example, a con man can tell different life stories to different marks, as long as they don't compare notes. A police interrogator can play suspects off each other if they are kept in isolation. An organization has greater power in negotiating salaries with individuals than with a union.

Another branch of the bonding theory is found in work on network governance and social control. For example, at the firm level, Jones, Hesterly and Borgatti (1997) argue that ties between organizations serve as social mechanisms of control, enabling the emergence of so-called network organizations. Similarly, at the individual level, the bonding mechanism predicts that individuals who are less embedded in the network around them will be capable of greater deviance, a proposition that has been borne out empirically as far back as Bott (1957) and Mayhew (1968).

A more distant branch of bonding theory is concerned with the effects of network location on bargaining position. In the experimental exchange tradition of social network analysis (Cook, Emerson, Gillmore and Yamagishi, 1983; Markovsky, Willer and Patton, 1988), researchers have subjects bargain with each other to distribute points between them, where the goal is to amass as many points as possible. The subjects are placed in networks designed by the experimenters, and can only negotiate with people they have been given links to. In each round of the experiment, subjects are required to divide up 24 points with another person. Initially, subjects tend to make even trades of 12 and 12. Over time, however, subjects in certain network positions are able to command more favorable terms, such as 13-11, 14-10, and eventually, 23-1. For example, in Figure 3a, node X has all the power.

Initially, it was thought that centrality was the underlying principle (Cook et al, 1983). However, it was soon discovered that in the network shown in Figure 3b, the most central node had none of the power. Instead, it was the Zs that had the power. The reason is simple: even though X has at least as many potential trading partners as the Zs, the Zs have one partner (a Y) that is in a very weak position, whereas X only has powerful partners to trade with. Why are the Ys weak? Because whenever their Z makes a deal with someone else, the Y is excluded from that particular round. In effect, every deal between a pair of players temporarily creates a single unit out of them, and the network can be analyzed in terms of all the different blocks that can be created by different combinations of possible deals (Markovsky et al, 1993). The advantage that Zs have is that no matter who strikes a deal with whom, there is always someone they can trade with in a given round. They can never be excluded.

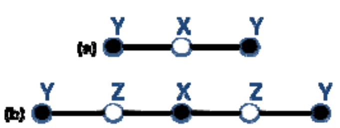


Figure 3. *Two experimental exchange networks. Light-colored nodes have more power.*

An increasingly popular elaboration of the bonding theory is the perceptual perspective advocated by Kilduff and Krackhardt (1994) at the micro level and Podolny (2001) at the macro level. The perspective is drawn from the image management literature and says that people are judged by the company they keep, and so one of the functions of ties is to associate a person with another, and particularly to associate them with the attributes of the other. The principle is well illustrated by the story recounted by Cialdini (1989) regarding a time when the financier Baron de Rothschild was asked for a loan by an acquaintance. Reportedly, the Baron said "I won't give you a loan myself, but I will walk arm-in-arm with you across the floor of the Stock Exchange, and you soon shall have willing lenders to spare." (Cialdini, 1989, pg 45). The underlying mechanism here is that the observed social tie creates for the observer a reified entity out of the pair of nodes that are tied, much as the Gestalt researchers of the 1920s found that similarity, physical proximity, and common fate led to perceivers reifying collections of stimuli into single objects.

A third basic theory is based on what we will call the adaptation mechanism. The fundamental notion is that actors adapt to their environments, and similar environments lead to similar adaptations. In biology, for example, there is a phenomenon known as convergent forms, which is where phylogenetically unrelated species evolve similar characteristics in response to the same environments, such as the aquadynamic shapes of sharks and dolphins. In the case of social networks, the environment is a social one, consisting of other actors. One formulation of this concept is the notion of structural equivalence, which states that two nodes are equivalent to the extent that they have the same types of ties to the same others. Thus, two childless siblings are structurally equivalent with respect to the parenting relation, because they have the same parents. The generic hypothesis is that structurally equivalent actors in a network will develop similarities in characteristics and outcomes, due to their similar social environments. Thus, two unconnected actors who are each central in their organizations' advice networks might both develop similarly negative attitudes toward checking email and answering the phone, because for both these are sources of more work and interruption.[6]

At first glance, the adaptation mechanism looks like the transmission mechanism because both involve influence from the environment. The difference is that in transmission the focal node acquires the same characteristic as the environment (e.g., adopts a touch-screen mobile phone). In the adaptation mechanism, the environment shapes the focal node but not by making the node the same as the environment. Instead, the node reacts to the environment, making internal changes (such as in mood or internal structure) that are not the same as the environment (as when a node is surrounded by jerks, and becomes angry but does not become a jerk).

Finally, it is worth noting that virtually all of social network research can be classified as trying to answer one of two types of research questions: the homogeneity question, which is

[6] A detailed discussion of structural equivalence and attitude formation is provided by Erickson (1988)

why some actors have similar characteristics, and the performance question, which is why some actors have better outcomes than others (Borgatti and Foster, 2003). In principle, these are not entirely separate questions: the first focuses on sameness while the second focuses on difference, which are two sides of the same coin. However, the first tends to be phrased in terms of attributes that refer to internal characteristics of a node, while the second tends to be phrased in terms of outcomes of some kind. Furthermore, the outcomes of the second question tend to be value-loaded in the sense of being goods, such as performance, achievement, or reward, whereas the attributes of the first question tend to be more value-neutral, such as having the same kind of accounting system or adopting the same innovation.

CONCEPTS FOR SUPPLY NETWORKS

The objective of this section is to relate social network concepts more specifically to the supply chain context. We begin with a discussion of terminology.

Selecting Nodes and Ties

Most fields have difficulty defining their most central concepts.[7] Supply chain management is no exception. Unfortunately, adding in a social network perspective only adds to the complexity. A naïve social network theorist would probably take the term “supply network” to mean the network in which a tie exists from A to B if A supplies B. Of course, we’d want to define what we mean by supply – does everything count, including office supplies, or just materials used directly to produce firms’ outputs? Although thorny from an SCM perspective, this would not be considered a big problem from the point of view of the social network theorist, who is generally comfortable with the idea that we get to study whatever relations we choose to define. It is not a matter of getting it “right” but of deciding what we are interested in studying. Furthermore, even though the supply tie might be regarded as fundamental, we remain keenly aware of multiplexity (the property of a given pair of actors having ties of many kinds simultaneously) and would expect to measure many other kinds of ties among the same set of actors.

We would also want to define some criteria for what is considered a node. By default, the network theorist would regard the nodes in the network as consisting of all entities (presumably firms) that have supply relations with anyone, although having said that we might choose to partition the network into what are known as weak components – maximal fragments of a network in which every node can reach every other by some direction-ignoring path. In this context, a weak component is essentially an economy, a maximal set of firms that are engaged in economic transactions with each other, directly or indirectly. Of course, even in principle we might want to restrict the network further via additional node-based criteria, such as geography (e.g., Chicago-based firms) or industry (e.g., biotech). In practice, we would most certainly have to bound the network even more drastically.

When we think about applying this full network concept to the SCM context, a thorny question immediately comes up, which is ‘how are going to collect the data?’ To our naïve social network researcher, the obvious approach to collecting supply network data is to survey firms.[8] For example, given a set of focal firms of interest, we ask each firm to reveal its major suppliers. We then survey these suppliers and ask them (a) to verify the outgoing link to the firm(s) that named them, and (b) to reveal their own suppliers. This snowballing process is repeated up to the natural limit, or as constrained by the limits of funding and time.[9]

There are a number of difficulties here, of course. Social network researchers who wish to ask about confidential and sensitive relations have found that a great deal of energy must be expended to secure the trust of respondents. Sometimes there are also legal constraints on information disclosure. A couple of strategies from different fields are worth considering. For example, in public health settings, AIDS researchers need to collect sexual and needle-sharing networks, both of which are highly sensitive and confidential, and indeed involve illegal activities. One technique they use is to ask the informant to contact the people they have confidential ties with to obtain their permission and in effect recruit them into the study. With this permission, the researchers then contact (or are contacted by) these alters, and the snowball rolls on. It is a time-consuming process but it is in fact feasible.

Another strategy used in several fields is aggregation. For example, in ecological food web research (in which the nodes are species and the links are who eats whom), there are often too many species to work with (e.g., insect species alone number in the tens of millions), and so sets of similar species are grouped together into what are called compartments, and these are taken as the units of analysis instead of individual species. Often, it is a mixed strategy, where high-level predators, which are few and easily discerned, are kept at the individual species level while low-level creatures (especially microscopic ones) are aggregated into very general categories. In the supply chain case, this corresponds to aggregating by industry or technology or some other convenient variable. Although under-appreciated in the supply chain literature, input-output tables at varying levels of sector aggregation are readily available. As it happens, several key measures in network analysis are based on Leontief’s (1941) methods for analyzing input-output data.

Another aggregation approach is found in sociology, where the social capital theorist Nan Lin has advocated the use of “position generators” which is a survey technique in which the respondent is asked not for their ties to specific others, but to categories of others, such as “priests” or “managers” or “marketing people” (Lin, Fu and Hsung, 2001). This can be done with firms as well, so that instead of asking for the names of individual suppliers, the firm is asked for inputs

[7] For example, anthropology is famous for its multiplicity of mutually incompatible definitions of culture (Kroeber and Kluckhohn, 1952).

[8] Of course, the term “survey” here is used very generally to refer to a range of data collection activities from asking firm representatives to fill out questionnaires to examining firm records (bill of materials, vendor agreements, etc.)

[9] An example is provided by Carter, Ellram and Tate (2007).

from different kinds of suppliers (whether these are industry codes or some other researcher or firm-provided classification system depends on the research objectives).

Returning to the question of defining our supply network, another possibility for the naïve network theorist would be to interpret "supply network" as a simple ego network. In this case, the supply network would be the ego network defined by the set of all firms with a direct supply relationship (in or out) to a focal firm. And just as before, while the supply tie provides a criterion for inclusion, it is understood that the ego network consists of the full set of all interesting ties among all members.[10] Methodologically, the ego network approach is fairly easy, although in a complex organization it may be necessary to ask the same information from a number of different organizational members (each with a limited view of the organization's activities) in order to construct a complete ego network.

The ego network concept is probably the closest to a supply chain theorist's intuitive understanding of a supply network, but it is not a perfect match. For one thing, the SCM theorist would probably want to add some nodes upstream from the first order suppliers and some nodes downstream from the first order customers. However, in applying network concepts it is necessary to keep the full network and simple ego network definitions in mind, both because network measures are constructed with one of these images in mind, and because they are frankly useful. It is not a question of what the right definition is, but what is useful in a given study.

Let us now turn to some analytical concepts. For the moment, let us consider only one kind of tie, namely supply ties. (We leave for later discussions of other kinds of ties.) We define the supply network as a matrix $\boldsymbol{X}$ in which $x_{ij} = 1$ indicates that firm i supplies firm j, and $x_{ij} = 0$ otherwise. (We also leave for later the possibility of valued ties representing costs or quantities.) The row sums of this matrix give the number of outgoing ties for each node (a property known as outdegree centrality), and we interpret this as the number of different customers for each firm. Similarly, the column sums (indegree centrality) give the number of incoming ties, which indicates the number of different suppliers. Simple as they are, both of these quantities have strong implications for a firm's organizational structure, since dealing with, say, millions of consumers requires different structures than dealing with a few distributors, and implies different levels of dependencies to be managed.[11] At the same time, each supply tie is necessarily embedded to some extent in other social relations among the two parties, such as a given level of trust, varying amounts of communication, and so on. A firm dealing with many alters has many opportunities for non-redundant information flow, but the flow from each interaction may also be miniscule and the message may not penetrate past the boundary personnel (e.g., the telephone order-taker).

[10] An example of this approach in the supply chain literature is provided by Choi, Dooley, and Rungtusanatham (2001)

[11] Although our focus here is on a single type of tie, namely, supply, it is worth noting that smaller indegree implies greater dependency, which in turn creates a greater need for social relationships and countervailing dependencies to maintain control (Jones et al, 1997; Pfeffer & Salancik, 1978; Emerson 1962).

Egonet Composition

Restricting our attention to cases with smaller ego networks in which ego-alter relationships are deeper and more multiplex, we might consider that suppliers and customers are not all equal. Some suppliers are more stable than others, more able to maintain the proper flow of goods even in turbulent times. Similarly some customers have deeper pockets than others and provide a more reliable stream of revenues. To the extent that a firm's strength is derived from the strength of its trading partners, a useful ego-network property is the 'quality' of ego's alters, as defined by an alter attribute such as capacity or capitalization. This measure is simply the average (or sum, or maximum value, as needed) of the attribute values for a given ego's alters. For example, using the averaging operator and focusing on the in-network (i.e., the suppliers), we can define egonet quality as follows:

$$q_i = \sum_j x_{ji} a_j \qquad \textbf{Eq. 1}$$

In the equation, q_i gives the quality of ego i's network, a_j is the score assigned to supplier j on an attribute such as reliability or quality, and x_{ji} indicates whether (or how much) j supplies ego i.[12] Dividing q_i by $\sum x_{ji}$ or the number of suppliers gives the average of the alter scores, as opposed to the sum.

Depending on the choice of attribute, the variance or standard deviation of alter scores may also be of interest. For example, if attribute A refers to organization size, in turbulent times one might hypothesize that having a diversity of different sized suppliers might be advantageous.

Comparable metrics can be constructed for categorical attributes as well. For example, if we categorize suppliers by country of origin, we can compute the percentage of suppliers that come from each country, and also, via a categorical heterogeneity measure, the extent to which a firm's suppliers tend to come from many nations or just a few.

Structural Holes

As noted earlier, the structure of the network around a node can also be studied. In recent years, the relative sparseness of an ego network (i.e., the number of structural holes) has attracted a great deal of attention in the management literature. For certain kinds of ties, the prevailing wisdom is that dense ego-networks provide egos with fewer non-redundant resources than sparse ego-networks (see Figure 4). An obvious application of structural hole theory to the supply chain case is where the ties among the suppliers are information exchanges about their interactions with the focal firm, such as prices paid. In this case, we might hypothesize that more structural holes (greater sparseness) bring benefits to the firm. On the other hand, where the ties are information exchanges about better integrating their outputs, we clearly

[12] For continuity with other equations in this paper, we note that Equation 1 can be rewritten in matrix form as follows: $q = X'a$

expect structural holes to be negatively related to firm performance.

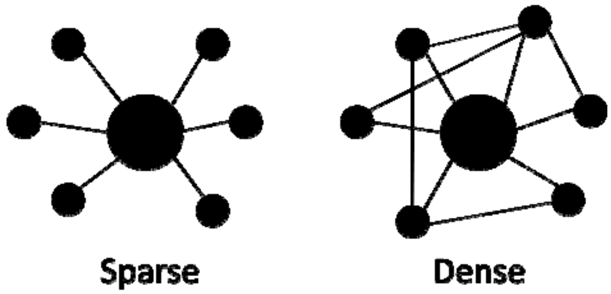


Figure 4. *Sparse ego network (many structural holes) and dense ego networks (few holes).*

It is also interesting to speculate about the effects of structural holes for the case where all ties are supply ties. The most frequently used measure of (the absence of) structural holes is called constraint. It measures the extent to which a firm is both directly and indirectly invested in specific alters. In the case of supply ties, a high constraint score (low structural holes) would mean that even though the firm might have many suppliers, it could still be highly vulnerable to disruptions in one of them if that one were also supplying some of the other suppliers – i.e., a lack of independence in the supply chains, causing all to fail when one did.

Our discussion of structural holes with respect to different kinds of ties illustrates the dangers of borrowing concepts from other fields at very abstract levels. Most recent discussions in the social network literature on structural holes focus on the claim that structural holes increase the amount of non-redundant information available to ego. This works well for information in the sense of interpretations of current events. For example, a manager who needs to react to a competitive move seeks advice from her five confidants and ideally would receive five independent views. But if the confidants have already hashed it out among themselves, they may well furnish ego with just one perspective. In that case, the manager would rather have had independent advisors. But if the information in question is, say scientific or manufacturing knowledge, such as might be provided by high tech suppliers, sharing of this knowledge among the suppliers does not reduce the amount of it available to the firm. In fact, sharing may lead to syntheses that result in a larger pool of knowledge that the firm can tap.

More generally, if we take the ego network around a focal firm to include all kinds of ties, including trust, helping and flows of personnel and information, we are likely to take a different view on the value of structural holes. The case of Toyota and the fire at the Aisin Seiki plant is instructive here (Nishiguchi and Beaudet, 1998). Aisin was Toyota's sole supplier of proportioning valves (known as p-valves, a brake component). On Saturday, Feb 1, 1997, a fire destroyed the facility and, within 72 hours, shut down production of Toyota cars. Toyota's 1st and 2nd -tier suppliers, under Toyota's leadership, had routinely been sharing personnel and intellectual property, establishing common technical languages, and creating a sense of trust and mutual dependence. When the fire broke out, the supply network immediately began working together to create an alternative source of p-valves. This included all kinds of companies from tire-makers to leather sewing specialists. Aisin itself provided blueprints, personnel and as many undamaged tools as it could. Another supplier, Nippon Denso emerged as logistics manager for the effort. Toyota's well-equipped R&D prototyping lab was brought to bear, and on Tuesday night, Koritso Sangyo, a 2nd tier supplier, was the first to deliver a working p-valve. By the next Monday, 9 days after the fire, Toyota production was basically back to normal levels, with suppliers who had never in their lives built a p-valve turning them out at a fast rate. Obviously, in this case, it was the lack of structural holes that made the difference for Toyota.

Hubs and Authorities

Returning to Equation 1, an interesting case emerges if we set the attribute $\boldsymbol{a}$ to be the number of customers that a supplier has. In that case, a firm would receive a high score on Equation 1 to the extent that their suppliers have many alternative customers, which would provide an inverse measure of the firm's bargaining position, which is to say, its ability to reduce costs. Equation 1 is a good first approximation, but in reality the situation is more complicated: the suppliers themselves depend on suppliers who may have many alternative buyers, in which case the level 1 suppliers may have to pay higher prices, either reducing their profit margins or raising prices for their customers (including our focal firm), and also making them more dependent on their customers (because they need them more).

$$u_i = \lambda \sum_j x_{ij}\, v_j \qquad \text{Eq. 2a}$$

$$v_j = \lambda \sum_i x_{ij}\, u_i \qquad \text{Eq. 2b}$$

If we carry this logic out to the limit, we obtain Equations 2a and 2b. In the equations, lambda is a scaling constant known as the singular value. Each firm is described by two measures, u and v. A firm gets a high score on u to the extent that it supplies firms that have many suppliers. A firm gets a high score on v to the extent it is supplied by firms with many customers. In the context of web sites linking to other web sites, nodes with high u scores are referred to as hubs, while nodes with high v scores are called authorities (Kleinberg, 1999). A hub is a node that has pointers to very popular sites (authorities). An authority is a node that receives links from big gateway sites (hubs). The two concepts are defined in terms of each other, but the equations are easily solved via singular value decomposition (Eckart and Young, 1936).

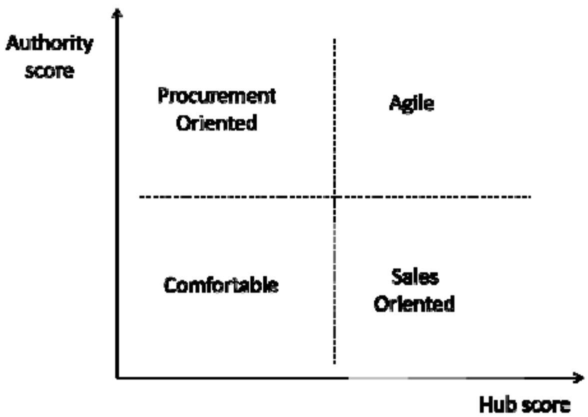


Figure 5. *Typology of firms based on hub and authority scores.*

As summarized in Figure 5, in the supply chain context, firms that are both hubs (sellers to those with many alternative suppliers) and authorities (buyers from those with alternative customers) are in very competitive markets. These are firms that must be highly agile to survive. Firms that are hubs but not authorities are firms that face serious competition in selling their goods, but have a good situation with respect to their suppliers. We have labeled these firms sales-oriented. Firms that are authorities but not hubs have to be nimble procurers, but face relatively simple sales environments. We label these procurement-oriented. Finally, firms that are neither hubs nor authorities are in relatively calm waters on both fronts – an enviable position but also at risk of stagnation.

Node Centrality

A key concept in social network analysis has been the notion of node centrality, which we might define as the importance of a node due to its structural position in the network as a whole. Several centrality concepts have already been discussed, so our objective here is to focus on the application of the concepts to supply networks. An interesting type of centrality is closeness (Freeman, 1979), which is defined as the sum of distances to or from all other nodes, where distance is defined graph-theoretically in terms of the number of links in the shortest path between two nodes. In the case of directional ties, such as who supplies whom, closeness is problematic because it may be impossible for a given node to reach another due to all the "one-way streets", creating, in effect, an infinite distance from one node to another. However, in the case of a network defined by supply ties, the closeness measure remains interesting even when there are unreachable pairs. Let us define in-closeness as the average valid graph-theoretic distance from all firms to the focal firm. If we discard as invalid the supply chains that do not reach the focal firm, what we have left is all chains from the "bottom" of the economy (e.g., natural resource processors) to the firm. The average length of these chains indicates the number of steps that a focal firm's raw materials had to go through to get to the focal firm. All else being equal, we might hypothesize that longer chains provide greater opportunities for disruption and cost increases. An analysis of this kind would probably be most valuable using a modification of closeness centrality which took into account the relative importance of each of a firm's inputs, such as information centrality (Stephenson and Zelen, 1989).

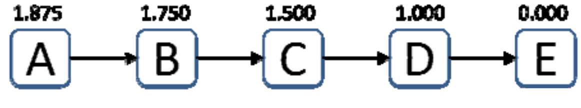
One of the best-known types of centrality, especially in the interlocking directorate literature, is eigenvector centrality (Bonacich, 1972). The idea here is that a node that is connected to nodes that are themselves well connected should be considered more central than a node that is connected to an equal number of less connected nodes. Thus, in a playground setting, being friends with one of the popular kids is worth more than being friends with any number of outcasts. In a supply chain setting, consider two firms, each with ten customers. Suppose firm A's customers have many customers of their own, and those customers have many customers and so on. Firm A's actions potentially affect a great number of other firms downstream. In contrast, if firm B's ten customers do not have many customers of their own, B's actions could have much less effect on the system as a whole. Thus, the eigenvector concept takes into account both direct and indirect influences.

In the case of networks with directed ties (in which a tie from i to j does not necessarily imply a tie of the same kind from j to i), it is convenient to express the eigenvector concept in a form known as alpha centrality (Bonacich and Lloyd, 200x).[13] The equation formalizing alpha centrality (Equation 3a) looks similar to those for hubs and authorities, but is subtly different. In the equation, c_i refers to the alpha centrality or influence of node i, the constant alpha is an attenuation factor that determines how important long chains are, and $\boldsymbol{e}$ is a vector of exogeneous importance scores for each firm (often set to all ones). A solution, in matrix notation is given in Equation 3b, where $\boldsymbol{I}$ is the identity matrix.

$$c_i = \alpha \sum_j x_{ij} c_j + e_i \qquad \text{Eq. 3a}$$

$$c = (I - \alpha X)^{-1} e \qquad \text{Eq. 3b}$$

As shown in Figure 6, if Equation 3b is applied to a simple chain where we take α=0.5, the influences scores for each firm decrease predictably from source to sink. Firm E has a score of 0 because it supplies no one. Firm D has a score of 1 because it influences one firm directly (Firm E, worth α^0 or 1 point). Firm C has a score of 1.5 because it influences one firm directly (worth α^0 or 1 point) and another firm at one step removed (Firm E, worth α^1 or 0.5 points). Firm B has a score of 1.75 because it influences one firm directly (α^0, 1 point), a second firm one step removed (α^1, 0.5 points), and a third firm two steps removed (α^2=0.25). The sum of α^0, α^1, and α^2 is 1.75.



[13] Whereas alpha centrality can always be meaningfully calculated, eigenvector centrality is inappropriate for certain classes of directed networks. In those cases where both can be calculated, alpha centrality is indistinguishable from eigenvector centrality.

Figure 6. *Alpha-centrality scores for each of five firms in a simple chain, where alpha = 0.5.*

It should be noted that if the type of tie is information flow, then it will be nodes at the tops of the chains that will have more information. However, we don't expect every bit of information that exists in the system to be funneled all the way up the chain to the highest firms. The attenuation factor α can be seen as proportional to the generic probability that a bit of information is passed along from one firm to another.[14] By setting α low enough, we can make it highly improbable that any given bit of information travels several links up the trail. Interestingly, this measure of influence comes directly from Leontief's input-output analysis (1941)

Another well-known type of centrality is betweenness (Freeman, 1977). A node has high betweenness to the extent that it lies along many shortest paths between pairs of others. A node gets a high score to the extent that it exclusively controls the short paths between all pairs of others – i.e., there are no other equally short paths that bypass the node. Thus, given a network of supply ties, a firm will have high betweenness to the extent that all of the shortest (and, let us assume, best) chains from first makers to end consumers pass through that firm. Such firms are structurally important to the economy itself, because if they disappear or slow production, they will affect more other firms than if they had lower betweenness. These are "key players" that need to be healthy for the rest of the network to be healthy.[15]

Also of interest is edge betweenness (Anthonisse, 1971). Edge betweenness refers to the betweenness of a tie rather than a node, or, in the context of supply chains, of a supplier-buyer relationship. It measures the importance of a given tie to the general shortness of paths throughout the network. In other words, removing high betweenness ties from a network does more damage, on average, to the network's transmission capabilities than does removing low betweenness ties. This fact has been exploited to construct an algorithm (Girvan and Newman, 2002) for detecting what is known in the social networks world as cohesive subgroups, which we discuss next.

Cohesive Subgroups

Cohesive subgroups (Borgatti, Everett and Shirey, 1990) are identifiable regions of a network that are particularly cohesive. Cohesion can refer to many different things. Perhaps the most basic concept of cohesion is density, which is simply the number of ties among a set of nodes expressed as a function of the number of pairs of nodes. A clique is a maximal[16] subset of nodes in which the density is 100%. In other words, in a clique, everybody has a tie with everybody else. In real data, perfect cliques tend to be rare or very small. However, network analysis has developed a number of techniques for finding imperfect cliques – ones in which some ties are missing. Other concepts of group cohesion are based on geodesic distance – the number of links along the shortest path between two nodes in the group.

If we define our network in terms of cooperative ties among firms in an economy, algorithms for detecting cohesive subgroups can be used to find "network organizations", keiretsus, chaebols, business groups, industrial districts and other knots of interrelated firms. Even within a single firm's supply network, cohesive subgroups can be found representing clusters of suppliers that work more with each other than with other suppliers in the network.

Equivalence

One important concept in social network analysis that does not require knowledge of a full network is structural equivalence (Lorrain and White, 1971). A pair of nodes A and B is structurally equivalent to the extent that A has incoming ties from the same nodes that B has incoming ties from, and A has outgoing ties to the same nodes that B has outgoing ties to (See Figure 7). Applied to supply ties among firms, two firms are structurally equivalent to the extent that they have the same customers, and the same suppliers. Structurally equivalent firms face similar environments; to the extent that environments are influential, structurally equivalent firms should strain toward adopting similar internal processes, at least at a functional level. More generally, structurally equivalent nodes are identical with respect to all network measures, including measures of social capital such as Freeman's betweenness centrality or Burt's constraint. As a result, we might hypothesize that structurally equivalent firms will have similar performance outcomes. Moreover, it is plausible to hypothesize that structurally equivalent firms will take notice of one another, possibly judging each other to be valid benchmarks or referents in adopting innovations, and generally in responding to one another's competitive moves.

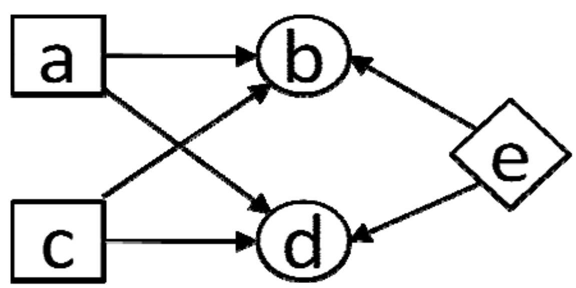


Figure 7. *Nodes a and c are structurally equivalent, as are b and d.*

[14] The matrix of ties X can also be valued to represent strength of tie, so that in spite of the general setting of α, a given node may be highly likely to pass something on to a certain other node.

[15] An analogy is found in ecosystems where the term "keystone species" is used to refer to species whose prevalence (not too much, not too little) has major consequences for many other species, and whose removal or unchecked growth can unravel an entire ecosystem. See also the work on ensembles of key players by Borgatti (2006).

[16] Maximal means that every node that can be included (while retaining 100% density) is included. In other words, no subset of a clique is considered a clique.

A generalization of structural equivalence is the notion of regular equivalence (White and Reitz, 1983; Borgatti and Everett, 1992). Like structural equivalence, the idea is that equivalent nodes will have similar network neighborhoods. However, whereas with structural equivalence pairs of equivalent nodes will share some of the same alters, in regular equivalence this is relaxed to sharing equivalent alters – where equivalent refers to regular equivalence. In other words, the concept is defined recursively so that if nodes A and B are regularly equivalent, then if A has an outgoing tie to node C, B must have an outgoing tie to a node D that is regularly equivalent to C. In addition, if A has an incoming tie from a node E, then B must have an incoming tie from a node F that is equivalent to E. For example, a pair of auto manufacturers that are regularly equivalent might not share any of the same suppliers or customers, but they would have equivalent suppliers and customers (who in turn would have matching suppliers and customers of their own, and so on). The concept is illustrated in Figure 8.

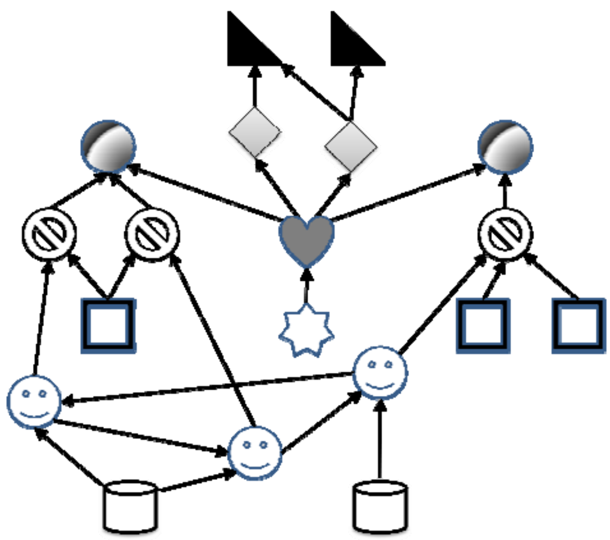


Figure 8. *Regular equivalence. Nodes colored/shaped the same are regularly equivalent. Equivalent nodes have ties to the same kinds of others. E.g., all black nodes have incoming ties from blues and blacks, and have outgoing ties to yellows and blacks.*

An important feature of both structural and regular equivalence is the ability to create a reduced model of the network – called a blockmodel – by constructing a network in which the nodes are equivalence classes and a tie exists between two nodes if there was a tie between the corresponding nodes in the original network. For example, Figure 9 shows a blockmodel based on the structural equivalence shown in Figure 7. Figure 10 shows a blockmodel based on the regular equivalence shown in Figure 8. Blockmodels serve as a data reduction device that enable the researcher to understand the structure of the network.

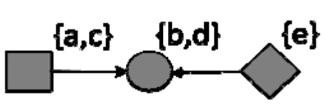


Figure 9. *Blockmodel based on Figure 7.*

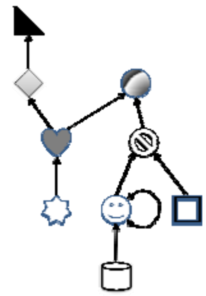


Figure 10. *Blockmodel based on Figure 8. Note the link from smiley faces to other smiley faces.*

In ecology, the concept of regular equivalence has been used as a way to discover sets of species that play similar trophic roles, meaning they are positioned equivalently in the ecosystem, including being at similar positions relative to the top(s) and bottom(s) of the food web (Luczkovich, Borgatti, Johnson, and Everett, 2003). In the supply chain context, regular equivalence would identify firms that have similar dependency chains from consumers to raw material processors, and therefore similar risk positions relative to shocks in the economy.

Whole Network Properties

For many good reasons, supply chain management has focused on the focal firm as the unit of analysis. It has not focused on the properties of the economic network as a whole. As a result, a number of very basic network properties remain unknown. For example, typical length (and standard deviation around it) of supply chains is unknown, as are the implications for nodes of their positions along these chains. Another field that has developed an interest in networks is ecology, where network analysis is used to understand what used to be called food chains and are now called food webs or trophic networks. In food webs, the nodes are species and the links can be conceptualized as either who eats whom, or as energy flows (from prey to predator). The number and total mass of species higher in the food chains are known to be smaller than the quantities lower in the food chains (i.e., a pyramid), presumably because energy transfers are inefficient (about 90% escapes as heat). The question is whether similar constraints exist for supply chains.

In ecology, such network properties as density (the number of ties divided by the number of pairs of nodes) are the subject of considerable theorizing and empirical prediction. It is known, for example, that food webs contract and become less dense and more brittle when there is less energy available (e.g., in winter). Analogous principles may hold for supply networks as well. Another network property of interest in ecology is omnivory (which does not mean eating lots of species but rather eating at multiple levels on the food chain, as when Species A eats Species B and also eats B’s prey C). Omnivory manifests itself as the network property of transitivity (where A→B, B→C, and A→C), and is of considerable interest in social networks as well. Food webs can also exhibit cycles (e.g., A→B, B→C, C→A) and even reciprocity (A→B and B→A), as when species A preys on the young of species B, while the adults of B prey on A. We would venture to guess that these kinds of properties have not been well studied in the supply chain literature, although they are clearly relevant to understanding the robustness of a position in the supply network.

Bipartite Graphs

Up to this point, we have discussed both whole-networks and ego networks. Now we introduce a different way of slicing the relational world – one that could be seen as intermediate between the whole network and the ego network approach. Consider the network in Figure 11, which depicts sexual ties among students at Jefferson High School (Bearman, Moody and Stovel, 2004). Boys and girls are distinguished by different colored nodes. Note that in this population, nearly all the reported ties are between colors – there are no ties within color. Networks with this characteristic are known as bipartite graphs.

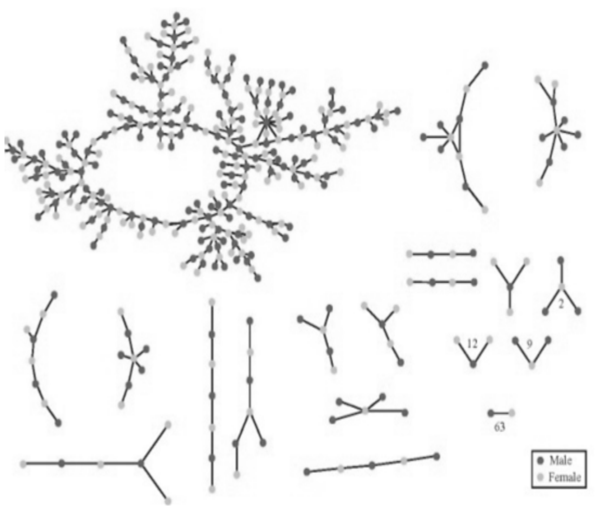


Figure 11. *Sexual ties among high school students. Node colors distinguish genders. From Bearman, Moody and Stovel (2004).*

Now let us translate to the supply chain context. Suppose we consider a focal firm and all of its competitors. Let us refer to these as buyers. Now consider the set of all suppliers for these buyers (for conceptual clarity, let us assume that all of the suppliers are selling the same basic kind of product). For the moment, let us assume the ties in the network are potential sales, so that there is a tie between a seller and a buyer if the former could reasonably sell to the latter (the lack of tie for a given pair could be because of geographic distance, legal restrictions, asset specificity, etc). The resulting network forms a bipartite graph (see Figure 12), which is a network in which the set of nodes can be partitioned into two classes, and there are no ties within classes, only between them.

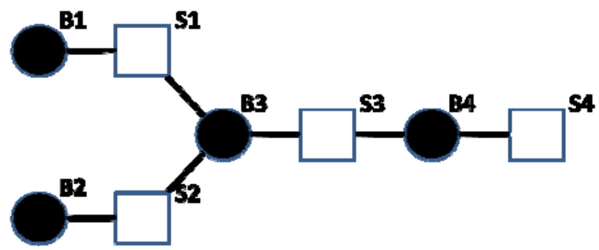


Figure 12. *Bipartite buyer-seller network.*

Such a graph can be profitably analyzed simply by attending to basic principles of benefits and exclusion (Markovsky, Willer and Patton, 1988).[17] For example, consider the case of buyer B3 in the figure. Since it has three potential suppliers, it would seem to be in a better position than any other buyer. However, suppliers S1 and S2 are both sole-suppliers of buyers B1 and B2, which could make those buyers more attractive than B3. As a result, B3 is likely to find them relatively hard bargainers. Indeed, if S1 and S2 have enough preference for B1 and B2 respectively, it is possible that over time S1 and B1 (and, separately, S2 and B2) drift off to become isolated dyads, a commonly observed result in the experimental exchange network literature (Markovsky et al, 1988). If this happens, we might expect S1 and S2 to help their buyers by sharing risks with each other. This would leave B3 to negotiate with S3, who is in a relatively strong position, having two buyers to work with (unless B4 and S4 pair up).

Now consider another hypothetical buyer-seller network (shown in Figure 13). In this graph, the ties indicate actual supplier relationships rather than potential ties. A close look at the graph shows that the market is structured into two segments. One segment, on the left, has a set of suppliers (S10-S14) that only work with buyers from the left segment (B10 through B15). These are specialists that supply just one part of the market. Similarly, the right-hand segment contains another set of specialist suppliers (S1-S5) who work exclusively with the buyers from the right segment (B1-B7). Note also that the middle of the graph shows a set of generalist suppliers (S6-S9) that supply buyers in both market segments. If we were to remove these four nodes from the market, the network would split in two, with no connections between the two halves.[18] In this sense, the generalists are almost single-handedly responsible for keeping the market unitary, enabling practices and information to move from one part of the market to the other.

[17] See also triadic analyses such as found in Choi and Wu (2009)
[18] Technically, the graph would split into 4 components, as B16 and B8 only serve the generalists, so they would become isolates.

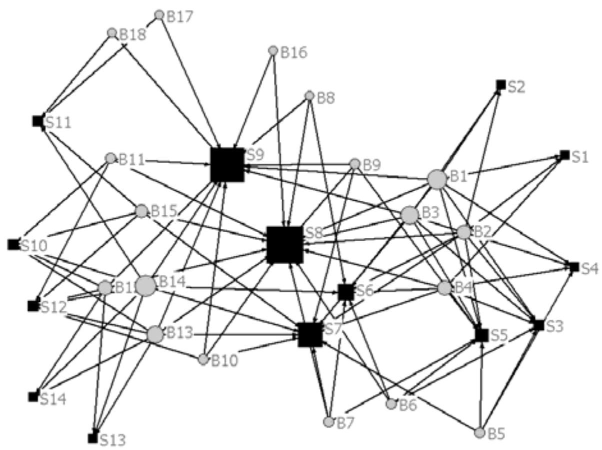


Figure 13. *Hypothetical bipartite buyer-seller graph showing segmentation. Square nodes are sellers, round nodes are buyers. All nodes sized by betweenness centrality.*

CONCLUSIONS

In this paper, we have tried to provide supply chain researchers with a relatively systematic, though necessarily incomplete, overview of social network analysis. Instead of providing (just) a catalog of concepts (such as structural holes or betweenness centrality) we have tried to outline the explanatory mechanisms that network theorists have used to relate network concepts to outcomes of interest. One reason for doing this is in hopes of avoiding a well-known potential pitfall in borrowing ideas from another field, which is to bypass the usual common-sense filters that are routinely applied when developing concepts "in-house". There is little point (beyond personal gain) in blindly applying concepts such as structural holes simply because they are "hot" in other fields. Consider, for example, that one of the conceptual bases of weak-tie theory is the drive to reduce cognitive dissonance, a principle that says that if A likes B, and B likes C, it creates unpleasant dissonance in the mind of A to actively dislike C. To reduce this psychological discomfort, A learns to tolerate C or loses interest in B. If this is essential to the theory of weak ties, we need to think twice about applying weak-tie theory to inter-organizational relationships, as it is not clear that firms are governed by the same psychological laws that govern individuals. Indeed, the division of labor within firms makes it possible for one part of the firm to make decisions that are incongruent ("dissonant") with decisions made in another part of the firm.

Another reason for stressing the theoretical underpinnings of network analysis is that the principal value of any theoretical perspective is not in the specific propositions that have been found true in some particular empirical context but in the kinds of questions that the perspective allows one to ask. For example, we have suggested that one question a network-theoretic perspective on supply chain management would ask is what are the consequences, for the firm and the supply network, of being located at any particular position (say, high or low) along a supply chain? That is, what are the opportunities and constraints that a firm faces as a function of its position in the supply network? Part and parcel of this question is how a firm can be affected by supply relations outside its ego network, such as cascade effects and impacts on bargaining position (as in the example illustrated by Figure 12).

We have also stressed a whole network perspective, which is not without difficulties. For one thing, the supply chain field is managerially oriented (more so than most management fields), and this means a strong focus on a single focal firm. For another, collecting the kind of data needed for a proper full network analysis is certainly a daunting prospect. However, it would be a mistake to give up before we start. As we have discussed, there are a number of methodological tactics to be pursued here, such as the methods used in AIDS research. In addition, there are increasing possibilities for obtaining electronic data sources, such as we already have at the sector level (e.g., input-output tables). The field may also want to adopt the strategy used by ego network researchers who collect data at the actor level (e.g., the firm) but derive their hypotheses and interpret the data from a network perspective.

We have illustrated the network analysis concepts with both "hard" material/money flow types of ties and "soft" alliances and sharing-of-information types of ties. It might have been assumed that the insertion of social network analysis would advocate for and apply only to the softer, more social kinds of ties. However, it is fundamental to the network approach to include both kinds of ties. Both are important to understanding what happens, and it is a fact of social life that transactions of any kind are embedded in other relations between the same parties, along with their relations with third parties.

One thing we have tried to do in this review is to point to areas in other fields that we think are particularly suitable for SCM to draw from. The most obvious example is ecology, whose food webs are closely analogous to supply networks. But we have also noted the parallels with input-output research, the source of key centrality concepts in social network analysis, and the study of heterosexual romantic networks, whose networks bear strong structural similarities to certain kinds of supplier-buyer networks.

At the same time, we have tried to go beyond simply pointing to existing concepts in other fields that can be applied to the SCM context. The SCM context has specific features that cry out for developing new network theory. An example we provided was the modeling of a simple 1-tier market of buyers and sellers in terms of a bipartite graph (Figures 12 and 13).

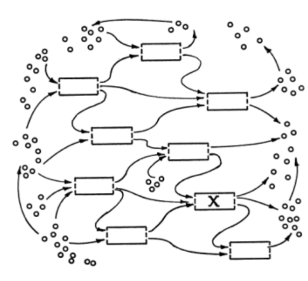


Figure 14. *Terreberry's (1968) depiction of the environment of organization X.*

As a final note, if one examines classic contributions to organization theory, it is evident that supply chains have occupied a central place in organizational theorizing. For example, early work on organizations as open systems, influenced by and adapting to their environments, typically saw those environments primarily in supply chain terms (e.g., Thompson, 1967; see also Figure 14, drawn from Terreberry 1968). Today, there are more supply chain articles in mainstream management journals, and more articles that cite supply chain journals (Carter, Leuschner and Rogers, 2007), but, in the opinion of the present authors, fewer cases where the supply chain is part of general organizational theory, as it was in Thompson's work. For example, institutional theory, perhaps the dominant perspective in organizational theory today and one that clearly cares about interactions among firms, has largely ignored the supply chain. Similarly, stakeholder theory, which faithfully includes suppliers in every definition of stakeholders, rarely focuses on suppliers. Based on the analogy with ecological food chains, it seems incredible that who supplies whom is not at the very backbone of organizational theorizing. On the other hand, the good news is that the network perspective is rapidly becoming a lingua franca across virtually all of the sciences from economics (Jackson, 2008) to physics (Newman, Barabási & Watts, 2006). The network paradigm provides a common language that many different fields can use to conceptualize interactions among actors, and many of the concepts of network analysis, such as centrality or equivalence, are highly portable across fields. We believe that the network perspective has the potential to be a unifying force that can bring together many different streams of management research, including supply chain management, into a coherent management science perspective.

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