Exploring the Multiplex Architecture of Supply Networks

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Abstract— **This paper attempts to provide quantitative and statistically significant evidence on the multiplex nature of a multi-tier supply network, in other words, how the overall architecture of supply network varies depending on different network tie types. All the supply network partners' bidirectional responses stretching from an OEM to its raw materials suppliers are collected and treated as directed-valued in the analysis. As one of the very few studies in this approach, the current research analyzes the unique primary data consisted of component-level supply networks to reveal the interrelationships among their architectural properties based on various network tie types. Our empirical findings offer a draft set of practical guidelines collectively suggesting that SCM practitioners need to consider both the visible interorganizational (i.e., contractual and transactional) and invisible interpersonal (i.e., professional and personal) exchanges encompassing non-immediate partners to better manage their supply networks.**

Keywords— supply network, multiplexity, directed valued network, whole network approach

1. Introduction

Previous supply chain management (SCM) studies have investigated the importance of building and managing supply chain dyads between one buyer and its immediate supplier. Regardless of the means by which supply chain dyads are managed, the literature has identified mostly their positive or negative impacts on firm performance (e.g., [1,2]). More recently, this dyadic approach was extended to the triadic case which consists of one focal firm or OEM and two immediate or tier-one suppliers in a single supply chain (e.g., [3]). While previous dyadic and triadic approaches were useful for investigating interfirm exchanges between a focal firm and its *immediate* supply chain partners, in the era of *network competition* [4], they fall short of grasping the whole picture of a complicated supply network in which a focal firm and its *multiple* tiers of suppliers are nested [5,6]. In practice, Toyota and Nissan have managed their supply networks by establishing Japanese first-tier suppliers' associations (*Kyohokai* and *Nishiokai*, respectively) since mid-90s [7]. When earthquake and tsunami struck Japan's Tohoku region on March 2011, however, their entire assembly lines *outside* the region were completely stopped for over two weeks. Tohoku region has been the biggest parts production base of Japanese automakers; interestingly, most of the affected suppliers were second- or lower-tier suppliers [8]. Indeed, recent evidence indicates that an over-reliance on first-tier suppliers can present dangerous vulnerabilities to OEMs [9,10]. This underscores the importance of the need to study supply *networks*, consisting of a set of *multiple* supply chain partners connected by a set of *interactive* ties, not just dyadic (or triadic) and unidimensional buyer-supplier relationships. Furthermore, in order to overcome the shortcomings with current approaches to studying supply networks, there have been calls for more detailed investigations of the supply network *architecture*. The *architecture* of supply network is formulated from both exogenous and endogenous sources for linking the members in the entire network, whereas its *structure* is related to a firms better functional outcome or regional (i.e. local) collaboration [11]. The architecture of supply network thus can be interpreted as more than a simple collective representation of multiple supply chain dyads or triads. This view enables SCM researchers to better investigate supply networks which consist of multiple independent entities pursuing their own interests.

Notwithstanding the aforementioned calls, many firms do not fully understand, track, or analyze the inherent risks within their supply network even though suppliers are their largest source of supply chain failures. This unaddressed call for research reveals several limitations of the existing studies in providing a comprehensive understanding and analysis of a supply network architecture. First, current SCM literature has predominantly focused on developing conceptual frameworks – taxonomies or typologies – to differentiate supply *networks* from supply *chains* or identifying unique attributes of supply networks without empirical substantiation. These works have broadened the scope of traditional buyer-supplier relationship studies and have garnered more research attention to the area of understudied supply network architecture by introducing theoretical propositions. However, they lack empirical evidence to show

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the practical applicability of the propositions developed in them. Second, a few recent empirical studies of supply network architecture fall within the limited domain of descriptive case studies (e.g., [12,13]). Such exploratory studies have provided some empirical the limited domain of descriptive case studies. Such exploratory studies have provided some empirical support for the theoretical propositions concerning supply network architecture. At the same time, however, those findings were heavily focused upon one single industry (e.g. automotive, banking, etc.) or firm, and thus lack empirical evidence that can be consistently applied across different supply networks. Last but most important, many studies are still using overly simplified, ambiguous, or non-exclusive measures for different types of network ties (e.g., [6,14]). Seminal works on social networks have disclosed that: 1) a network is weaved by both strong and weak ties on the basis of reciprocity, frequency, emotional intensity, and intimacy in the relationship [15,16], and 2) those social ties are not always reciprocal [17,18]. Those findings collectively suggest that both the strength and direction of network ties should be taken into account to better understand network phenomena. In other words, one network consisting of the same entities can demonstrate different architectural properties with regard to different tie attributes (e.g., tie type, strength, direction, etc.), which is commonly referred to as *multiplexity* [19,20]. Prior studies that overlooked such inherent heterogeneity of a supply network can prevent SCM academics and practitioners from fully grasping the multi-faceted supply network phenomena.

To address these theoretical and practical issues in the supply network literature, this study investigates how different *directed valued* network ties across *multiple* tiers of supply chain partners shape different supply network architectures. Drawing upon social network analysis (SNA), the primary survey data from 153 component-level supply networks is analyzed to explore the associations between 12 network-level SNA indices for characterizing different supply network architectures. This research is, to the best of our knowledge, among the first few quantitative and statistically significant evidences on the existence of *supply network multiplexity* and its effects on supply network architecture. This study is organized as follows: the first section sets out theoretical background and testable propositions on supply network and multiplexity of various network ties in a supply chain context; sections two and three outline methodology, measures, data source/analysis used to describe supply network architecture; section four presents quantitative findings and interpretations examining the propositions, followed by the final section on theoretical/managerial contributions, limitations, and directions for future research.

2. Theoretical Background and Proposition

2.1 Multiplexity

Pioneering scholars such as Borgatti and Li [21] have proposed multiplexity in supply networks as a promising area for future research. Multiplexity in social networks is defined as two or more types of exchange (i.e. layering) within the same network ties [15,22]. Social anthropologists and sociologists introduced the term to denote coexistence of different normative elements in an interpersonal tie. In a family-owned business, for instance, a father-son relationship also can be viewed as an employer-employee relationship. Social ties containing only one such role represent ‘uniplex’ or ‘single-stranded’ ties, whereas those that involve two or more roles are ‘multiplex’ or ‘many-stranded’ ties [19,23]. The practical importance of the concept in social network research was immediately recognized in that it helped to uncover ‘hidden’ network properties and clearly manifested the underlying dynamics of personal ties. For instance, researchers found that multiplex ties were more likely to be intimate, supportive and/or durable, especially during times of need, because: 1) they have multiple bases of interaction [24], and 2) there is less chance that one of them will be unavailable [25].

The concept of network multiplexity can also complement the shortcomings of existing buyer-supplier relationship literature. SCM researchers have stressed the importance of creating trust and reciprocity from repeated transactions with the same supply chain partners. According to the tenets of embeddedness theory, an embedded relationship alleviates information asymmetry and opportunistic behavior in relations between organizations and thus leads to improved performance [26,27]. However, growing evidence indicates that repeated interactions do not necessarily result in trust or the expected benefits; they might even have negative consequences [28]; rather, several studies present interdependent contingencies facilitating or restraining the transition from repeated transactions to relational embeddedness in inter-firm networks [29,30]. The existence of multiplexity in supply networks can provide a theoretical rationale for such inconclusive and equivocal findings by showing that a given supply network with the same set of firms can be perceived differently based on different tie types with different directions and strengths.

In spite of its apparent applicability and research gaps in existing SCM literature, there have been surprisingly few attempts to provide a systematic empirical examination of multiplexity in supply networks. One notable exception is Kim et al. [12] who depicted three supply networks of the center console assembly for Honda Accord, Acura CL/TL, and DaimlerChrysler Grand Cherokee by using SNA indices. However, it also suffered from the following limitations: 1) as an exploratory case study, it studied only three supply networks all in the automotive industry, 2) their interpretation of results was not drawn from the comparisons between two different network ties (i.e. contract and material flow), but aforementioned three cases, 3) those comparisons were confined to simple description of SNA index scores (e.g. higher or lower) without further statistical verification, 4) network ties were measured on binary (or dichotomous) scales (i.e. '1' if two supply network entities were linked either by contract or non-directional material exchange, '0' otherwise), and 5) other important but invisible supply network ties at the individual level (e.g. professional and personal exchanges) between network entities were overlooked. Despite these limitations, as a pioneering study investigating more than one network tie type within the same network, it hinted at the existence of multiplexity which remains to be tested. To enrich and generalize this skeletal finding on supply network multiplexity, this study proposes the following:

- **Proposition 1.** A supply network exhibits different architectural properties in terms of different tie types which directly or indirectly link all the members of the network.

2.2 Supply Network Tie Types

The first question that should be considered by a network researcher interested in multiplexity is: what are the different types of network ties that should be considered [31]? Supply network entities are interlinked with various types of network ties having different characteristics in accordance with different intentions to achieve different outcomes [21,32]. This study covers four types of supply network ties: contractual, transactional, professional, and personal ties. Table 1 offers conceptual definitions of four supply network tie types under consideration and their measurement items used based on the literature. The first two types represent *visible* network ties for exchanging tangible goods and services, whereas the other two capture *invisible* exchanges taking place among supply network entities.

Obviously, supply network members are linked through visible ties such as contract or delivery and receipt of goods and services as consistent with previous supply network studies (e.g., [12,33]). A formal written contract serves as the most fundamental element of economic exchanges but can be differently interpreted by supply chain partners. From a buyer's perspective, a strong contractual tie (i.e. more complete contract) including explicit work-related provisions and prescriptions can safeguard against opportunistic behavior of its counterpart [34]. From supplier's perspective, however, an interfirm contract specifying more control and legal rules might reflect distrust between exchange partners because buyers may opportunistically utilize it by imposing terms and conditions that are unreasonably difficult to comply with on the supplier [40]. In this vein, findings of prior research confirm that contractual and transactional exchanges between supply network partners should be treated as separate network ties, in which complete contract terms between firms do not necessarily imply the actual exchange of goods or services and vice versa. For instance, transactional tie (i.e. the actual exchange of goods and services) can be established without a formal written contract when both parties share relational norms such as reciprocity, solidarity and information sharing [41,42].

Prior network research has pointed out that "much of commitment occurs at a personal rather than organizational level" [43] (p.65) and "social capital is at the heart of social network analysis" [44] (p.180). Although personal (or social)-level ties are usually invisible and often informal, they are significantly associated with organizational (or network) outcomes such as trust [45,46], knowledge transfer [47,48], and innovation [49,50]. While visible and organization-level network ties (i.e. contractual and transactional ties) representing economic exchange are widely discussed in the supply network literature, invisible and personal-level network ties (i.e. professional and personal ties) between supply network partners have received considerably less research attention. However, some researchers have incorporated the personal dimension into organization-level exchanges to uncover the invisible dynamics between network partners. Ulaga and Eggert [51], for example, found that the extensive interpersonal interaction is a greater differentiator than lower cost for suppliers in achieving key supplier status. More recently, Ahuja et al. [52] conceptually argued that different types of personal and organizational network ties can be embedded within the same business network. Grossman et al. [53] also found the interpersonal similarity between nascent entrepreneurs plays an amplifying role in forming new ventures and their network structures. Extending these ideas from this emerging research stream to the supply network context, this study additionally considers two invisible network ties bridging supply chain personnel in partnering firms. When it is incorporated with social network analysis, this consideration enables the inter- and intra-comparisons of different tie types and comparable network indices, and consequently can provide invaluable insights concerning the underlying network architecture [21,54]. As will be explained in detail in the following sections, social network analysis offers quantitative indices of network properties. To enrich and extend the findings from the first proposition, therefore, this study investigates the following second proposition.

- **Proposition 2.** The supply network properties in terms of different tie types exhibit significant positive or negative associations with one another.

3. Methodology

3.1 Social Network Analysis

In spite of repeated calls for the use of methodology, most of the present SCM studies confine to case-based research using SNA measures solely defined for binary (i.e. ‘1’ if a tie is exists between two supply network entities, ‘0’ otherwise) and non-directional ties (i.e. if one supply network entity perceives a tie, its counterpart’s perception on the existence of the tie is automatically assumed). An important limitation of this approach, however, is that it

Table 1. Conceptual definitions, item measures, and related literature for supply network tie types

Tie Type	Conceptual Definition	Measurement Items
Contractual [35,36]	The extent to which a supply network entity perceives that it has a 'complete' formal written contract with its immediate counterpart	We have a formal written contract(s) detailing the operational requirements. We have a formal written contract(s) that detail(s) how performance will be monitored. We have a formal written contract(s) detailing warranty policies. We have a formal written contract(s) detailing how to handle complaints and disputes (e.g. penalties for contract violations). We have a formal written contract(s) detailing the level of service expected from this supplier.
Transactional [35,37]	A supply network entity's amount of 'monetary' exchange (in percentage points) with its immediate counterpart(s)	For OEMs (i.e. tier-0 firms): A percentage of total spend for each tier-1 supplier of the selected component For tier-(N) (i.e. intermediate) suppliers where N=1 or 2: Percentages of total sales derived from the tier-(N-1) buyer AND total spend for each tier-(N+1) supplier in dealing with the OEM's selected component For tier-3 (i.e. end-tier) suppliers: A percentage of total sales derived from tier-2 suppliers in dealing with the OEM's selected component
Professional [6,35,36]	A supply network entity's perceived strength of the interactions with its immediate counterpart in performing 'work responsibilities'	We regularly communicate (via face-to-face, conference calls, e-mails, etc.) on work matters. We widely share and welcome each other's ideas or initiatives via open communication (e.g. joint workshops, etc.). The communication between us occurs at different levels of management and cross-functional areas. I (or our executives) receive periodic feedback (via face-to-face, conference calls, e-mail, etc.) on progress, problems, and plans from this supplier's counterparts. I (or our executives) do periodic on-site visits to this supplier's plants.
Personal [38,39]	A supply network entity's perceived strength of the interactions 'not directly related to work' with its immediate counterpart	We always invite each other to participate in various activities to socialize. We do personal favors for each other. We voluntarily exchange something of a personal nature to each other on appropriate occasions (e.g. birthday cards, congratulations, condolences, etc.). We often communicate (via face-to-face, phone calls, e-mails, social network services, etc.) during non-working time. We often communicate (via face-to-face, phone calls, e-mails, social network services, etc.) outside work places.

involves two counterintuitive and unrealistic premises – all ties are completely homogeneous and symmetrical – which contradict previous findings in the literature. For instance, strong social ties strengthen interpersonal obligations, facilitate change in the face of uncertainty, and help to develop relationship-specific heuristics. Therefore, by using the binary network approach, network researchers can inevitably overlook important information about network properties embedded in network ties, and consequently arrive at limited or even misleading implications on network architecture.

3.2 Directed Valued Network Indices

From a methodological standpoint, the present study adopts directed valued network approach represented by an asymmetric adjacency matrix to overcome the aforementioned shortcomings of binary network approach [23,55]. This approach takes into account the direction and strength (or magnitude) of each tie between different network entities. In network terms, a directed valued network consists of a set of actors (or nodes) $\{n_1, n_2, \cdots, n_g\}$, a set of arcs (i.e. directional ties or links) $\{l_1, l_2, \cdots, l_L\}$, and a set of values $\{v_1, v_2, \cdots, v_L\}$ attached to the arcs, subject to $l_k =< n_i, n_j > \neq l_m =< n_j, n_i >$ and v_k is not necessarily equal to v_m. This is a more useful and realistic approach for exploring the multiplex architecture of a supply network consisting of different tie types since it allows for the possibility that a focal firm may perceive much less strong (or no) tie with its suppliers than those perceived by its suppliers. In this sense, there has been a growing need for SNA indices that can be used in the directed valued network setting when it is based on a different adjacency matrix.

SNA indices fall into one of two categories: ego-centric and socio-centric approaches [56]. The ego-centric approach focuses on a particular actor's position within the network and is particularly useful in dealing with a large network whose boundary cannot be easily specified. In contrast, based on specific criterion of network boundaries, socio-centric approach analyzes the overall pattern of multiple actors within a single, bounded network. This approach can provide a better understanding of the directed valued network in that the network architecture from one ego's viewpoint can be markedly different from those of others linked directly or indirectly [57]. It also fits perfectly with the purpose of this study to explore the existence of supply network multiplexity and its effects on network architecture. Thus, from a measurement perspective, this study focuses on four socio-centric SNA indices (i.e. betweenness centralization, in-degree centralization, out-degree centralization, and global clustering coefficient) defined only at the network level.

First, betweenness centralization represents whether most network actors are equally central or there are some (i.e. hubs) that are much more central than others. This index can be calculated by the variation in the betweenness centrality divided by the maximum variation in betweenness centrality scores possible in a network of the same size [58]. Betweenness centrality is an ego-centric index indicating how often an actor lies on the shortest path between all combinations of pairs of other actors. The more a given actor has a higher betweenness centrality; its immediate actors are more dependent on this actor to reach out to the rest of the network. This index focuses on the role of an actor as an intermediary and posits that this dependence of others makes the actor central in the network. Betweenness centralization, a socio-centric version of betweenness centrality, ranges from 0 where all network actors have the same betweenness centrality, to 1, where there exists one single actor connecting all the other actors. This study calculates betweenness centralization of a directed valued supply network by adopting the formula suggested by Opsahl et al. [59] for betweenness centrality ($C_B^{w\alpha}(n_i)$) for network actor n_i, defined as:

$$C_B^{w\alpha}(n_i) = \frac{g_{n_j n_k}^{w\alpha}(n_i)}{g_{n_j n_k}^{w\alpha}} \quad (1)$$

where $g_{n_j n_k}^{w\alpha}$ is the total number of geodesics between two actors (n_j and n_k), $g_{n_j n_k}^{w\alpha}(n_i)$ is the number of geodesics passing through actor n_i, and α is a positive tuning parameter that is set to the benchmark value of 0.5 to equally value both the number of ties and their strengths (w) (where a high degree is taken as desirable). Thus, betweenness centralization can be formally expressed as:

$$C_B = \frac{\sum_{i \in G}\{C_B^{w\alpha}(n^*) - C_B^{w\alpha}(n_i)\}}{max \sum_{i \in G}\{C_B^{w\alpha}(n^*) - C_B^{w\alpha}(n_i)\}} \quad (2)$$

where $C_B^{w\alpha}(n^*)$ is the largest value of the betweenness centrality that occurs across the network G; that is $C_B^{w\alpha}(n^*) = max_i C_B^{w\alpha}(n_i)$.

In the case of directed network, two additional degree indices are defined: in-degree, or the number of links terminating at the actor ($k_{n_i}^{in}$); and out-degree, or the number of ties originating from the actor ($k_{n_i}^{out}$) [23]. In-degree centralization calculates the dispersion of or variation in in-degree centrality, the extent of individual actor's influence on other actors, and thus high in-degree centralization indicates the incoming flows of different network resources are focused on a small group of actors in the overall network. In the same sense, high out-degree centralization indicates that a small number of actors send out most of the network resources for the rest of the network actors. This study derives in-degree and out-degree centralization of a supply network from in-degree centrality ($C_{D-in}^{w\alpha}(n_i)$) and out-degree centrality ($C_{D-out}^{w\alpha}(n_i)$) for actor n_i of directed valued network by the following equations [59]:

$$C_{D-in}^{w\alpha}(n_i) = k_{n_i}^{in} \times \left(\frac{s_{n_i}^{in}}{k_{n_i}^{in}}\right)^{\alpha} \quad (3)$$

$$C_{D-out}^{w\alpha}(n_i) = k_{n_i}^{out} \times \left(\frac{s_{n_i}^{out}}{k_{n_i}^{out}}\right)^{\alpha} \quad (4)$$

where s^{in} and s^{out} are the total strengths attached to the incoming and outgoing ties, respectively. Therefore, the general in-degree and out-degree centralizations ranging from 0 to 1 are respectively defined as:

$$C_{D-in} = \frac{\sum_{i\in G}\{ C_{D-in}^{w\alpha}(n^*) - C_{D-in}^{w\alpha}(n_i)\}}{max \sum_{i\in G}\{ C_{D-in}^{w\alpha}(n^*) - C_{D-in}^{w\alpha}(n_i)\}} \quad (5)$$

$$C_{D-out} = \frac{\sum_{i\in G}\{ C_{D-out}^{w\alpha}(n^*) - C_{D-out}^{w\alpha}(n_i)\}}{max \sum_{i\in G}\{ C_{D-out}^{w\alpha}(n^*) - C_{D-out}^{w\alpha}(n_i)\}} \quad (6)$$

where $C_{D-in}^{w\alpha}(n^*)$ and $C_{D-out}^{w\alpha}(n^*)$ are the largest in-degree and out-degree centrality values in the network G.

Lastly, this study uses global clustering coefficient (GCC) varying from 0 to 1 to measure the overall level of cohesion among network actors [60,61]. In social network terms, this indicates the probability that network actors n_i and n_j are also connected to each other when n_i is connected to both of them, collectively represented as (n_i; n_j, n_k). In a directed valued network setting, this socio-centric index is defined as the total value of *closed triplets* (i.e. triples of network actors where each actor is connected to the other two; τ_Δ) divided by the total value of *triplets* (i.e. triples where at least one actor is connected to the other two; τ). Triplet value (ω) calculation is based on the geometric mean of the tie values for the nodes comprising the triplet in that it: 1) captures differences between tie strengths, and 2) is robust to extreme tie strength [62]. Thus, the general GCC (C_g) can be formally stated as:

$$C_g = \frac{1}{N}\sum_{i,j,k\in G}\left\{\frac{\sum_{(n_i;n_j,n_k)\in\{\tau_\Delta\}}\omega_{\tau_\Delta}^{(n_i;n_j,n_k)}}{\sum_{(n_i;n_j,n_k)\in\{\tau\}}\omega_{\tau}^{(n_i;n_j,n_k)}}\right\} \quad (7)$$

where N is the number of possible triplets in network G. Readers can refer to Opsahl and Panzarasa [62] for more details on this technique.

SNA indices have been developed and used within a sociological context, which cannot be directly applied and interpreted within an interfirm supply network context. Consequently, this study adopts the framework of Kim and Narasimhan [63] on the supply network implications of various socio-centric SNA indices for directed valued networks (see Table 2).

4. Data Collection

This study focuses on the individual component-level supply network as the unit of analysis in that a single product is mostly built up by incorporating a mix of functional and innovative components. Major South Korean automobile and consumer electronics manufacturers were contacted to collect the component-level whole network survey data. To lessen the burden of data collection, a combined sampling approach of fixed list and snowball selections was adopted [21]. First, to keep the whole network perspective in data collection, initial contacts mostly at the executive level were asked to select a strategically important component with manageable network sizes (i.e. no more than 3 tiers and 5 suppliers per tier) and recommend the most knowledgeable sourcing manager in charge of the selected component. This step also contributed to minimize key informant bias [64]. Secondly, sourcing managers were asked to evaluate their perceptions on different types of ties (i.e. contractual, transactional, professional, and personal) with their major immediate suppliers mostly listed as the OEM's preferred supplier. Contractual, professional, and personal ties were evaluated using a five-point scale, anchored by '1' (strongly disagree), '3' (neither disagree not agree), and '5' (strongly agree), and transactional tie was assessed by percentages of total spend (or sales) for each supplier (or buyer) for the selected component. Next, the same questions were given to the OEM's counterparts (i.e. tier one suppliers) based on the contact information provided by the focal firm's sourcing manager. These steps were repeated for the successive tiers of suppliers (i.e. tier two and tier three suppliers) until end-tier suppliers were reached. As a result of these efforts, a total of 153 component-level (89 electronics and 64 mechanical) networks consisting of 1,852 total network members were collected.

5. Results and Interpretations

5.1 Descriptive Statistics

Table 3 contains basic descriptive statistics and one-way analysis of variance (ANOVA) results for the calculated socio-centric SNA indices based on 153 component-level supply networks by four different tie types. ANOVA implemented to compare the means of tie types with respect to each SNA index showed that they differ statistically. Homogeneity of variances was tested using Levene's test, and planned comparisons between the means assessed using Dunnett's T3 statistic. The mean values were also plotted by network tie type on a radar chart in Figure 1 for comparison. A few descriptive observations could be made from the computed indices. First, for all the four SNA indices, transactional network had lower means than contractual network. For instance, the betweenness centralization in transactional network (0.3905) was not as high as that in contractual network (0.5786), which indicates the monetary exchanges are relatively more equally distributed among supply network members. Transactional network with a lower in-degree centralization (0.3246) than contractual network (0.3846) also hinted that more complete contract terms given to a fewer particular focal firms within the supply network were not always associated with more percentage amount of their monetary exchanges. Further, as shown in out-degree values, particular focal firms fell short of generating corresponding percentage amount of monetary exchanges (0.2883) even when they yielded more complete contractual terms for their counterparts (0.4895). These observations collectively suggest the completeness of

Table 2. Socio-centric indices, conceptual definitions, and interpretations by supply network tie

Socio-Centric SNA Index	Conceptual Definition	Tie Type	Implications for Directed Valued Supply Network
Betweenness centralization	The extent to which particular network actors serve as hubs relative to the rest of the network	Contractual	The extent to which there exist particular focal firms with unequally complete (or specific) contract terms than other supply network members - The lower the index, the more firms there are which have more equally complete contract terms with their supply network counterparts - The higher the index, the more firms there are which have more unequally complete contract terms with their supply network counterparts.
		Transactional	The extent to which there exist particular focal firms with unequal percentage of monetary exchanges than other supply network members (i.e. distribution of sales and spending in the network) - The lower the index, the more firms there are which have equal percentage of monetary exchanges with their supply network counterparts. - The higher the index, the more firms there are which have more or less percentage of monetary exchanges with their supply network counterparts.
		Professional	The extent to which there exist particular focal firms with unequal amount of work-related interactions than other supply network members - The lower the index, the more firms there are which have equal amount of work-related interactions with their supply network counterparts. - The higher the index, the more firms there are which have more or less work-related interactions with their supply network counterparts.
		Personal	The extent to which there exist particular focal firms with unequal amount of non-work-related interactions than other supply network members - The lower the index, the more firms there are which have equal amount of non-work-related interactions with their supply network counterparts. - The higher the index, the more firms there are which have more or less non-work-related interactions with their supply network counterparts.

Table 2. (Continued)

Socio-Centric SNA Index	Conceptual Definition	Tie Type	Implications for Directed Valued Supply Network
In-degree centralization	The extent to which network resources are converged on particular network actors	Contractual	The extent to which particular focal firms have more complete (i.e. less favorable) contract terms from the other supply network members. - The lower the index, the more firms there are which have fair contract terms with their supply network counterparts. - The higher the index, the fewer particular focal firms possess less favorable contract terms with their supply network counterparts.
		Transactional	The extent to which particular focal firms take up more percentage of the monetary exchanges occurring inside the supply network than others. - The lower the index, the more firms there are which have equal percentage of monetary exchanges. - The higher the index, the fewer particular focal firms account for more percentage of monetary exchanges than the others.
		Professional	The extent to which particular focal firms have more incoming work-related interactions from the rest of the supply network members - The lower the index, then each of the supply network members has more equal amount of work-related interactions with one another. - The higher the index, the more work-related interactions among supply network members is focused on fewer particular focal firms.
		Personal	The extent to which particular focal firms have more incoming non-work-related interactions from the rest of the supply network members - The lower the index, then each of the supply network members has more equal amount of non-work-related interactions with one another. - The higher the index, the more non-work-related interactions among supply network members is focused on fewer particular focal firms.

Table 2. (Continued)

Socio-Centric SNA Index	Conceptual Definition	Tie Type	Implications for Directed Valued Supply Network
Out-degree centralization	The extent to which particular actors disseminate network resources to others	Contractual	The extent to which particular focal firms provide more complete (i.e. less favorable) contract terms for the rest of the supply network members. - The lower the index, the more firms there are which have fair contract terms with their supply network counterparts. - The higher the index, the fewer particular focal firms yield less favorable contract terms for their supply network counterparts.
		Transactional	The extent to which particular focal firms generate more percentage of the monetary exchanges occurring inside the supply network than others. - The lower the index, the more firms there are which have equal percentage of monetary exchanges. - The higher the index, the fewer particular focal firms send out most of the percentage of monetary exchanges for the rest of the supply network members.
		Professional	The extent to which particular focal firms have more outgoing work-related interactions to the rest of the supply network members - The lower the index, then each of the supply network members has more equal amount of work-related interactions with one another. - The higher the index, the fewer particular focal firms send out most of the work-related interactions to the rest of the supply network members.
		Personal	The extent to which particular focal firms generate more outgoing non-work-related interactions for the rest of the supply network members - The lower the index, then each of the supply network members has more equal amount of non-work-related interactions with one another. - The higher the index, the fewer particular focal firms make more non-work-related interactions for the rest of the supply network members.

Table 2. (Continued)

Socio-Centric SNA Index	Conceptual Definition	Tie Type	Implications for Directed Valued Supply Network
Global clustering coefficient	The extent to which how cliquish (or tightly knit) a network is as a whole (i.e. the degree to which all the network actors tend to cluster together)	Contractual	The extent to which how the entire supply network members are directly connected by contract relations - The lower the index, the less proportion out of all supply network members are directly connected by contract relations (i.e. the supply network has a more 'hierarchical' architecture as a whole). - The higher the index, the more proportion out of all supply network members are directly connected by contract relations (i.e. the supply network has a more 'lateral' architecture as a whole).
		Transactional	The extent to which how the entire supply network members are directly connected by monetary exchanges - The lower the index, the supply network as a whole has a more 'hierarchical' architecture of monetary exchanges among supply network members. - The higher the index, the supply network as a whole has a more 'lateral' architecture of monetary exchanges among supply network members.
		Professional	The extent to which all the supply network members freely communicate work-related subjects across firm boundaries - The lower the index, the supply network as a whole has a more 'hierarchical' architecture of work-related interactions among supply network members. - The higher the index, the supply network as a whole has a more 'lateral' architecture of work-related interactions among supply network members.
		Personal	The extent to which all the supply network members freely communicate non-work-related subjects across firm boundaries - The lower the index, the supply network as a whole has a more 'hierarchical' architecture of non-work-related interactions among supply network members. - The higher the index, the supply network as a whole has a more 'lateral' architecture of non-work-related interactions among supply network members.

Table 3. Descriptive statistics and ANOVA results

Socio-Centric SNA Index	Tie	Mean	Stdev	Min	Max	F-Value[a]	Dunnett T3
Betweenness Centralization	Contractual (A)	.5786	.0167	.5505	.6086	759.735**	A > C, D > B
	Transactional (B)	.3905	.0222	.3501	.4300		
	Professional (C)	.4840	.0438	.4102	.5599		
	Personal (D)	.4922	.0455	.4123	.5698		
In-degree Centralization	Contractual (A)	.3846	.0200	.3512	.4185	355.188**	D > A > C > B
	Transactional (B)	.3246	.0191	.2901	.3599		
	Professional (C)	.3424	.0289	.2907	.3894		
	Personal (D)	.4029	.0259	.3628	.4498		
Out-degree Centralization	Contractual (A)	.4895	.0226	.4504	.5299	1,215.549**	A > C > D > B
	Transactional (B)	.2883	.0468	.2115	.3698		
	Professional (C)	.4041	.0150	.3802	.4299		
	Personal (D)	.3404	.0294	.2912	.3898		
Global Clustering Coefficient	Contractual (A)	.1344	.0212	.1003	.1699	45029.104**	D > C > A > B
	Transactional (B)	.0749	.0146	.0503	.0999		
	Professional (C)	.1709	.0121	.1502	.1895		
	Personal (D)	.7976	.0273	.7504	.8497		

Note: N=153 component-level networks
[a] **: Significant at the 0.01 level (2-tailed)

contract terms is not necessarily associated with more or less monetary exchanges among supply network members. Second, the contractual network showed the highest means for betweenness and out-degree centralizations (0.5786 and 0.4895) compared to those of the other three network types (0.3905 and 0.2883 for transactional network; 0.4840 and 0.4041 for professional network; 0.4922 and 0.3404 for personal network), whereas no such notable difference could be seen in in-degree centralization. This implies that: 1) there exists a relatively smaller group of focal firms mediating other members in contractual networks, and 2) those particular focal firms grant rather more complete (i.e. less favorable) contract terms to their supply network counterparts, which supports the first observation on the lack of relatedness between the completeness of contract terms and the amount of transactions. Another noteworthy point was that the contractual and professional networks exhibited the same pattern in the rank order of indices (i.e. higher out-degree centralization than in-degree centralization), which was contrary to transactional and personal networks following the same pattern (i.e. higher in-degree centralization than out-degree centralization). This suggests that each set (i.e. contractual-professional and transactional-personal) can move in the same general direction with different magnitudes, signifying that the monetary exchanges among supply network members are more associated with their personal ties rather than contractual or professional ties. Perhaps the most interesting observation shown in Table 3 is the apparently high GCC in personal network (0.7976) compared to the low values of the other three networks (0.1344, 0.0749, and 0.1709). This demonstrates the personal network has a very loosely knitted architecture as a whole, while the other three are highly clustered together with respect to contractual, transactional, and professional ties. This also clearly shows that supply network members interact very actively with one another on non-work-related matters – creating a lateral (i.e. more egalitarian) personal network architecture – even when they mostly do not share any other network ties with their non-immediate members.

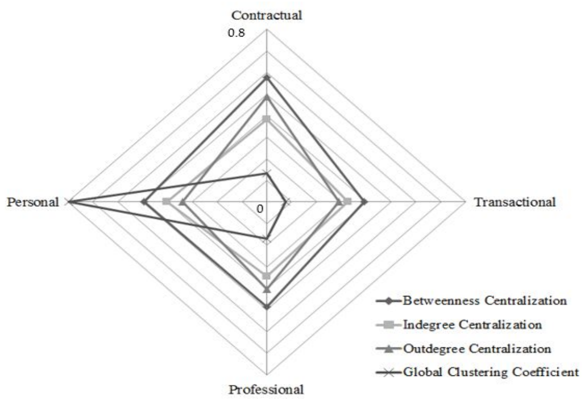

Figure 1. Means of socio-centric SNA indices by network tie type

5.2 Correlations

To find statistical support for the existence of supply network multiplexity, the bivariate correlation matrix among all four different indices in four different relational dimensions is presented in Table 4.

5.3 Tests

Before comparing different SNA indices showing significant correlations in Table 4, the Shapiro-Wilk test was implemented for normality in them. The results rejected the hypothesis that all the indices across different tie types are normally distributed (p-value < 0.01), which indicates nonparametric tests are called for. In this regard, Wilcoxon signed-rank test and sign test were used to statistically assess whether there exists any discernible difference within eight sets of highly correlated socio-centric indices. When the distribution is symmetric, the Wilcoxon signed-rank test is used; in other cases, the less powerful sign test can be used when the distribution is highly skewed [65]. For completeness, both tests were conducted. As shown in the following Table 5, the results indicate that there are statistically significant differences between most pairs (except sets 22, 24, and 29) of different socio-centric indices, which validate the first proposition concerning the *different architectural properties of the same supply network with regard to different types* of network ties (i.e. multiplexity).

5.3 Comparisons

Previous supply network studies using SNA simply compared various SNA indices to interpret the results (e.g. higher or lower). Taking these findings one step further, the present research additionally explores the second proposition on how different socio-centric SNA indices in pairs derived from a directed valued network dataset are related to each other by using scatter plot diagrams with best fit line. The obtained coefficient of determination (R^2) and direction of association of each pairwise set are provided in Table 5. A coefficient of determination (i.e. squared correlation coefficient) greater than or equal to 0.50 was considered to indicate a reasonably predictable relationship and the dependence of the paired SNA indices.

First, as shown in Sets 1-3, all three SNA indices (i.e. contractual betweenness centralization, contractual in-degree centralization, and transactional in-degree centralization) are positively associated with one another. These collectively indicate that there exists a particular few firms with more complete contract terms, and specifically, those firms take more of the outside incoming monetary flows (i.e. sales incurred from other network members) than their supply network partners. This observation corresponds well with previous studies which have investigated the effects of information asymmetry on bargaining power. Specifically, it supports the conventional view that more complete contract terms in favor of fewer focal firms provides them with greater leverage to derive more economic benefits from their partners. The next three sets (7, 8, and 10) extend these findings by additionally considering another SNA index, professional

Table 4. Bivariate correlation matrix

Tie Type	SNA Index[a]	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
Contractual	(a)	1.000															
	(b)	.763**	1.000														
	(c)	.029	.007	1.000													
	(d)	.065	.026	-.201	1.000												
Transactional	(e)	-.127	-.135	.010	-.130	1.000											
	(f)	.759**	.732**	.040	.026	-.100*	1.000										
	(g)	.011	.045	-.080	.026	.056	.023	1.000									
	(h)	.063	.138	.127	-.104	.098	.061	-.068	1.000								
Professional	(i)	.063	-.037	-.068	-.069	.061	.042	.045	-.178	1.000							
	(j)	.177	.139	.036	-.051	-.056	.143*	-.076	-.137	.163	1.000						
	(k)	.781**	.720**	.043	.016	-.050*	.776**	.143	.001	.029	.116	1.000					
	(l)	-.765**	-.716**	.057	.043	.129	-.771**	.022	-.091	.003	-.182	-.751**	1.000				
Personal	(m)	-.759**	-.713**	-.038	-.092	.088	-.717**	-.034	-.079	.013	-.123	-.718**	.683**	1.000			
	(n)	.743**	.764**	.012	.041	-.100*	.737**	.059	.024	.007	.073	.776**	-.730**	-.750**	1.000		
	(o)	-.744**	-.736**	-.078	.039	.114*	-.744**	-.053	-.080	.071	-.122	-.749**	.724**	.671**	-.762**	1.000	
	(p)	.733**	.713**	-.024	.045	-.173*	.763**	.127	.067	-.005	.144	.734**	-.726**	-.717**	.781**	-.712**	1.000

Note: N = 153 component-level networks; **: Significant at the .01 level; *: Significant at the 0.05 level (2-tailed)
[a] (a), (e), (i), (m) = Betweenness centralization; (b), (f), (j), (n) = In-degree centralization; (c), (g), (k), (o) = Out-degree centralization; (d), (h), (l), (p) = Global clustering coefficient

Table 5. Statistical pairwise comparisons between socio-centric indices

Inter-Index Relationship Set[a]	p-value (WSR test)[b]	p-value (sign test)[b]	Direction (+/−)	R-square (R^2)[c]	Inter-Index Relationship Set	p-value (WSR test)	p-value (sign test)	Direction (+/−)	R-square (R^2)
Set 1: (b) – (a)	.000**	.000**	+	.621†	Set 22: (n) – (e)	.000**	.015	−	.026
Set 2: (f) – (a)	.000**	.000**	+	.558†	Set 23: (n) – (f)	.000**	.000**	+	.579†
Set 3: (f) – (b)	.000**	.000**	+	.511†	Set 24: (n) – (k)	.260	.518	+	.645†
Set 4: (f) – (e)	.000**	.000**	−	.029	Set 25: (n) – (l)	.000**	.000**	−	.646†
Set 5: (j) – (d)	.000**	.000**	+	.033	Set 26: (n) – (m)	.000**	.000**	−	.581†
Set 6: (j) – (f)	.000**	.000**	+	.030	Set 27: (o) – (a)	.000**	.000**	−	.529†
Set 7: (k) – (a)	.000**	.000**	+	.565†	Set 28: (o) – (b)	.000**	.000**	−	.569†
Set 8: (k) – (b)	.000**	.000**	+	.567†	Set 29: (o) – (f)	.000**	.332	−	.544†
Set 9: (k) – (e)	.000**	.000**	−	.026	Set 30: (o) – (k)	.000**	.000**	−	.594†
Set 10: (k) – (f)	.000**	.000**	+	.617†	Set 31: (o) – (l)	.000**	.000**	+	.638†
Set 11: (l) – (a)	.000**	.000**	−	.622†	Set 32: (o) – (m)	.000**	.000**	+	.553†
Set 12: (l) – (b)	.000**	.000**	−	.563†	Set 33: (o) – (n)	.000**	.000**	−	.549†
Set 13: (l) – (f)	.000**	.000**	−	.530†	Set 34: (p) – (a)	.000**	.000**	+	.510†
Set 14: (l) – (k)	.000**	.000**	−	.584†	Set 35: (p) – (b)	.000**	.000**	+	.567†
Set 15: (m) – (a)	.000**	.000**	−	.550†	Set 36: (p) – (e)	.000**	.000**	−	.040
Set 16: (m) – (b)	.000**	.000**	−	.561†	Set 37: (p) – (f)	.000**	.000**	+	.591†
Set 17: (m) – (f)	.000**	.000**	−	.579†	Set 38: (p)– (k)	.000**	.000**	+	.575†
Set 18: (m) – (k)	.000**	.000**	−	.560†	Set 39: (p) – (l)	.000**	.000**	−	.520†
Set 19: (m) – (l)	.000**	.000**	+	.632†	Set 40: (p) – (m)	.000**	.000**	−	.595†
Set 20: (n) – (a)	.000**	.000**	+	.543†	Set 41: (p) – (n)	.000**	.000**	+	.527†
Set 21: (n) – (b)	.000**	.000**	+	.517†	Set 42: (p) – (o)	.000**	.000**	−	.592†

[a] (a) Contractual Betweenness Centralization; (b) Contractual In-degree Centralization; (d) Contractual Global Clustering Coefficient; (e) Transactional Betweenness Centralization; (f) Transactional In-degree Centralization; (j) Professional In-degree Centralization; (k) Professional Out-degree Centralization; (l) Professional Global Clustering Coefficient; (m) Personal Betweenness Centralization; (n) Personal In-degree Centralization; (o) Personal Out-degree Centralization; (p) Personal Global Clustering Coefficient

[b] **: Significant at the .01 level; *: Significant at the 0.05 level (2-tailed)

[c] †: Coefficient of determination (R2) ≥ 0.50

out-degree centralization, which measures the extent to which the particular focal firms have more outgoing work-related interactions with other members of the supply network. As commonly observed in all of those three sets, professional out-degree centralization demonstrates positive associations with contractual betweenness, contractual in-degree, and transactional in-degree centralizations. Taken together these show that the particular focal firms with more complete contract terms and more sales sent out more work-related communications to the rest of the supply network members. Second, Sets 11-14 describe the interrelationships between the four SNA indices investigated in first six sets (i.e. contractual betweenness, contractual in-degree, transactional in-degree, and professional out-degree centralizations) and professional GCC which measures how freely supply network members communicate with non-adjacent partners about work-related matters. All of the four sets exhibit that there are negative correlations between professional GCC and those four indices. Linking to the previous findings, this shows that the particular focal firms with the more sales and complete contract terms are present only when the supply network has rather hierarchical (i.e. less egalitarian) architecture of work-related interactions with their supply network partners.

Sets 15-19 further extend previous findings by additionally considering another SNA index, betweenness centralization, for non-work-related interactions within the supply network, demonstrating the extent to which there exist particular focal firms with more of those interactions than others. As shown in first four sets (Sets 15-18), the positive interrelationships among contractual betweenness, contractual in-degree, transactional in-degree, and professional out-degree centralizations decrease as the corresponding personal betweenness centralization decreases. This signifies the particular focal firms with positive interplays among more complete contract terms, sales, and outgoing work-related interactions cannot enjoy those synergies when there are more firms which have similarly equal amount of non-work-related interactions with their supply network counterparts. In addition, Set 19 shows that personal betweenness centralization and professional GCC have a positive correlation. This illustrates there can still exist particular focal firms with more non-work-related interactions even when the supply network as a whole has more lateral (i.e. more egalitarian) architecture of work-related interactions among members. Interestingly, this corroborates the first research proposition by confirming that two invisible network ties (i.e. professional and personal interactions) can be compatibly embedded within the same supply network while holding different network properties.

The next five sets (Sets 20, 21, 23, 25, and 26) show the interrelationships between personal in-degree centralization and the five SNA indices which demonstrated a statistical significance (i.e. contractual betweenness, contractual in-degree, transactional in-degree, personal betweenness centralizations, and contractual GCC). Sets 20, 21, and 23 show the positive relatedness of contractual betweenness, contractual in-degree, transactional in-degree centralizations still holds as personal in-degree centralization increases. This means that the particular focal firms with more complete contract terms and sales also possess more incoming non-work-related interactions than others. However, the more incoming non-work-related interactions those firms have, the less professional GCC and professional betweenness centralization scores they exhibit (See Sets 25 and 26), which collectively implies that: 1) focal firms have more outside incoming non-work-related flows on non-work-related matters when they have more indirect work-related communications with other network members (i.e. under more hierarchical professional network architecture), and 2) focal firms' high control level of work-related interactions may actually discourage their network partners from sending out more non-work-related interactions.

The next six paired sets (Sets 27, 28, 30, 31, 32, and 33) further extend previous findings by considering another index, personal out-degree centralization, which demonstrates the extent to which particular focal firms have more outgoing non-work-related flows. In line with our previous findings, Sets 27, 28, 30, and 33 illustrate negative associations between personal out-degree centralization and four other SNA indices (i.e. contractual betweenness, contractual in-degree, and professional out-degree, and personal in-degree centralizations). These additional findings collectively signify that: 1) the particular focal firms which already have more complete contract terms and more outgoing work-related interactions are less motivated to generate non-work-related interactions for the rest of the supply network members, and 2) this declining motivation for more outgoing non-work-related flows still holds even when focal firms have more incoming non-work-related flows (i.e. no reciprocal exchange). Sets 31 and 32 do rather stretch the second implication by showing that particular focal firms send out more non-work-related flows when the overall supply network has a more lateral communications architecture of work-related interactions.

Lastly, this study investigated the correlations between personal GCC and other network indices with statistically significant predictabilities. The first four sets (Sets 34, 35, 37, and 38) go on to show positive associations with personal GCC that describes the extent to which all the supply network members freely communicate non-work-related matters across firm boundaries. The sum of these findings highlights the double-edged effects of tightly knitted non-work-related interactions within supply networks which result in that particular focal firms acquire more sales as well as less favorable (i.e. more complete) contract terms as they create more work-related communications. It alludes to an interesting aspect that contractual and transactional inter-firm exchanges are more associated with personal ties between supply network partners, rather than professional ties. This hint is further supported by Set 39 illustrating a negative correlation between the personal and professional GCCs. The previous finding on non-reciprocities of non-work-related interactions is also reaffirmed by Sets 41 and 42 which denote that the more incoming non-work-related interactions particular focal firms have, the less of them are returned to the remaining network members even when the overall supply network has a more lateral (i.e. more egalitarian) architecture. This may reflect: 1) the non-work-related exchanges are being regarded as one of the most valuable resources within supply networks, and hence 2) firms are not willing to share them with others despite the network as a whole being characterized by relatively limited variations of non-work-related interactions.

6. Discussion

The findings of the current study make important contributions to theory and practice of supply network. First and foremost, the present work is one of the very few attempts to empirically examine how the overall architecture of supply network varies depending on different network tie types considered (i.e. *multiplex supply network perspective*). Nearly all empirical studies to this point except Kim et al. [12] and Kim and Narasimhan [63] have investigated different network tie types in separate research models or been lumped together under the same research construct (such as buyer-supplier relationship strength or engagement) by assuming supply network as a *uniplex* entity in which a supply network consisting of the same partners would have one single architecture. Opposing to this approach, invisible dimensions (i.e. professional and personal ties) as well as well-known visible interorganizational ties (i.e. contractual and transactional ties) were incorporated into our analyses in efforts to draw a more complete picture of supply network architecture. Our nonparametric tests show that there exist statistically significant differences among different network tie types, which supports the multiplex properties of supply networks. Specifically, we found that more specific or complete contracts between supply chain partners are not necessarily associated with more transactions. The more interesting finding is that interfirm network transactions are more associated with personal network ties than contractual or professional ones exhibiting the same pattern in the rank order of socio-centric SNA indices. These results collectively confirm supply networks are *multiplex* in nature and thus call for a multidimensional (rather than uni- or bi-dimensional) approach in trying to analyze and understand supply dyadic, triadic, and/or network-wide phenomena. In a practical sense, our findings urge the SCM practitioners to view and manage their supply network not as a simple collection of multiple buyer-supplier relationship but a more complex combination of multiplex interfirm and interpersonal ties.

Multiplex networks are stronger and more durable than uniplex ones due to their multiple bases of interaction [24,25]. From a practitioner's standpoint, however, managing those networks is considerably more complex as well because partners involved in the same supply network can view and understand their network architecture differently according to the tie type they pay more or less attention to [66,67]. In a supply network context, those discrepancies can give rise to divergent incentives among supply network partners and consequently hinder the network itself from achieving full cooperative outcomes. We thus offer a draft set of practical guidelines suggesting that SCM practitioners need to consider *both* the visible interorganizational and invisible personal exchanges encompassing *non-immediate* partners to better manage their supply networks. The results of pairwise comparisons generated some interesting observations. For example, particular focal firms can have more incoming flows of professional ties when they give more favorable contract terms to their counterparts; at the same time, they do not have to build stronger professional ties with their supply chain partners if the power across the network is not equally distributed nor concentrated. The empirical findings confirm that no single universal indicator can fully describe the multi-faceted supply network phenomena; rather, different network tie types work interdependently in shaping different architectures. Some notable observations brought to light include: 1) network members interact with one another on non-work-related matters even when they mostly do not share any other network ties, 2) invisible network ties can be compatibly embedded within the same supply network while holding different network properties, 3) focal firms send out more non-work-related flows when the overall supply network has a more lateral communications architecture of work-related interactions, and 4) non-work-related changes are the most valuable network resource in supply network context.

We also attempted to provide more grounded insights about network phenomena by employing a whole network approach, unlike previous case-based and/or local level supply network studies. The difficulties of collecting whole network data have led SCM researchers to restrict their scope of analysis to dyads or triads, rather than to investigate the overall architecture of supply networks. In spite of their usefulness, dyadic and triadic approaches focus on local level exchanges between (or among) two (or three) network actors; and this excessive simplification can inflate measurement errors of SNA indices [68]. It thus falls short of grasping the whole picture of a complicated supply network in which an OEM and its multiple tiers of suppliers are nested [6,69]. Recent studies such as Galaskiewicz [70] have pointed out that SCM theories captured at the local level (e.g. dyad or triad) needs to be reexamined using a whole network approach to avoid those pitfalls. The whole network approach enabled the authors to use socio-centric SNA indices which have been recommended by recent literature on interorganizational network management.

Lastly, this is one of the first supply network studies that adopted a directed valued network approach, which is more realistic and rigorous from the view of social network analysis. While the widely-used binary network approach relies on counterintuitive premises that all ties are completely homogeneous and symmetrical, the selected approach in this study has definite advantages in grasping network phenomena by considering both directions and strengths of network ties. However, the latest developments in directed valued network indices have, to the best of our knowledge, not yet been applied in existing supply network literature. Along with the benefits of whole network approach, we analyzed and compared socio-centric SNA indices defined for directed valued network to draw out the fullest grasp of our unique dataset which have been recommended by latest network literature. Going a step further, the current study explored supply network phenomena in a statistically testable form by using individual supply network as a unit of analysis. Given the exploratory nature of this research, a few limitations should be noted in ways that represent opportunities for future work. First, four different types of network ties examined in this study are not exhaustive. Although this does not curtail the contributions related to the existence of supply network multiplexity, a few additional tie types can be taken into consideration. In addition, the current study does not utilize all available socio-centric SNA indices in describing network architectures. This limitation comes from the setting of this study: an empirically substantive investigation of directed valued supply networks. Hopefully, the findings here provide the basics for verifying whether the current knowledge on supply chain dyads/triads still holds in a supply network setting, which will eventually advance understandings of multi-faceted supply network phenomena.

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