Communities and Centralities in Supplier-Buyer Network of the U.S. Tech Sector

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Abstract

Analysis of the U.S. tech sector's supplier-buyer network shows a strengthening of ecosystems around major firms from 2003 to 2014. Community detection methods reveal four distinct ecosystems, each led by AAPL, DELL, IBM, and MSFT. Supplier-buyer interactions within each ecosystem is far greater than across ecosystems, indicating exclusivity in suppliers and buyers around each of the four firms. Moreover, the substantial growth of AAPL and MSFT's significance, or centrality, in the network and their ecosystems underscore their rising dominance within the U.S. tech sector.

Keywords: networks, centrality

JEL codes: L10, L14, L22

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1 Introduction

Since the pioneering work of Leontief (1951) on input-output linkages across industry sectors, economists have been studying how an economic shock to an industry sector may affect other industry sectors, and more generally, the aggregate economy. Recent research on this topic includes Acemoglu et al. (2012), which studies how microeconomic shocks propagate to macroeconomic fluctuations, and Carvalho et al. (2016), which studies the effect of the Great East Japan Earthquake on the aggregate supply chain in Japan.

This article studies channels of shock propagation for the U.S. tech sector. Using the supplier-buyer network of U.S. tech firms from 2003 to 2014, it identifies four tech firms - AAPL, DELL, IBM, and MSFT[1] - as the most significant firms in the networks and study changes to their significance over time. It uses the community detection method of Leicht and Newman (2008) to identify groups of closely linked firms. For all years, each of the four firms belongs to a distinct community, which is a group of firms that are closely linked to each other. In other words, each firm is associated with a distinct ecosystem of suppliers and buyers. Firms across all ecosystems have similar NAICS[2] codes, indicating that AAPL, DELL, IBM, and MSFT are closely connected with similar industry sectors but with different firms in these sectors. This result suggests that their ecosystems exhibit exclusivity.

In addition, this article computes measures of centrality to evaluate the significance of the four firms in the supplier-buyer network. For five different measures of centrality, it computes *modular* centrality, which separately evaluates their influence on the whole network and on its ecosystem by utilizing the community structure. The result reveals that until 2010, IBM had the largest significance, followed by MSFT. However, the significance of MSFT grew and surpassed IBM in 2014. Furthermore, the growth of AAPL's significance over the years is remarkable.

The rest of this article is organized as the following. Section 2 describes the supplier-buyer networks

[1]These are ticker symbols for Apple Inc., Dell Technologies Inc., International Business Machines Corporation, and Microsoft Corporation, respectively.

[2]The North American Industry Classification System (NAICS) assigns codes to firms based on the industry sector they belong to.

surrounding AAPL, DELL, IBM, and MSFT. Section 3 describes communities of firms in the networks and the associated NAICS codes. Section 4 presents the significance of AAPL, DELL, IBM, and MSFT in the networks by computing measures of centrality. Finally, section 5 concludes.

2 Supplier-Buyer Network

This article uses a directed graph or digraph to describe supplier-buyer relationships among firms. A digraph consists two components: nodes and edges. Each node represents a firm included in the network, and an edge from a node to another indicates that the source node supplies to the destination node. In this article, the terms graph and edge are synonymous to network and link, respectively. Formally, a digraph G is

$$G = (V, E), \tag{1}$$

where

$$V = \{1, 2, \ldots, N\} \tag{2}$$

is the set of nodes included in the graph. Although I've used an enumeration from 1 to N for brevity, one may use any collection of elements, such ticker symbols of firms, to describe the node set. The edge set

$$E \subseteq \{(i, j) | i, j \in V,\ i \neq j\} \tag{3}$$

is such that $(s, t) \in E$ if there exist an edge from source node s to target node t. For node s, (s, t) is an *out-edge,* as it flows from s; for node t, (s, t) is an *in-edge* as it flows into t. Note that unlike an undirected graph, $(s, t) \in E$ does not imply $(t, s) \in E$. Moreover, this specification does not allow self-loops, meaning that a node cannot possess an edge to itself.

A directed graph is commonly represented using an adjacency matrix $A \in \{0, 1\}^{N \times N}$, where the

$(i, j)^{th}$ element

$$A_{ij} = \begin{cases} 1 & \text{if } (i,j) \in E \\ 0 & \text{if otherwise.} \end{cases} \tag{4}$$

One may extend the adjacency matrix such that $A_{ij} \in \mathbb{R}_+$ for $i \neq j$. In this specification, A_{ij} indicates the strength or weight of the edge from i to j. This article employs the binary adjacency matrix; thus it describes whether or not a firm supplies to another, without regards to the amount of the transaction. This limitation is due to the lack of data on the amount of transaction between firms. Note that $A_{ii} = 0$ for all i because self-loops are not allowed. In other words, transactions within a firm are not considered.

The data set[3] contains information on supplier-buyer transactions surrounding large tech companies publicly listed in the U.S. stock market, namely, AAPL, DELL, IBM, and MSFT. Using the data set, this article constructs a supplier-buyer network for each year from 2003 to 2014. The number of included firms, or the size of the node set, ranges from 282 to 400 across the years. An edge indicates that the source node supplies to the target node. For example, an edge from DELL to another firm indicates that DELL sold goods or services to the other firm at least once during the corresponding year. For each year, putting together such transactions among the firms generate the supplier-buyer network.

Table 1 reports summary statistics of the supplier-buyer networks from 2003 to 2014. The first column ("Year") indicates the years. The second column ("#Node") reports the number of firms included in the network, and the third column ("#Edge") reports the total number supplier-buyer transactions among the firms. The fourth column ("Density") reports the *density* of the networks. It is defined as

$$\frac{|E|}{|V| \times (|V| - 1)}, \tag{5}$$

which is the number of edges divided by the number of possible edges. The reported measures indicate that the networks are not dense, meaning that a large fraction of the firms are not directly linked via a supplier-buyer relationship. However, density does not provide information on indirect edges, which

[3] Factset Revere Relationship database. Non-publicly listed firms and non-U.S. firms were removed from the data set. All firms with zero observed transactions (i.e., having zero out- or in-edges) were removed from the data set.

account for relationships such as a supplier of a supplier. The fifth column ("#Avg Path") reports the average number of connected firms per firm. A node is connected to another node is if there exists a path[4], possibly passing through other nodes, from the former to the latter. For each year, the reported measures indicate that on average, a firm is connected to roughly a fourth of the entire set of firms. In other words, after accounting for indirect supplier-buyer relationship, the firms are more strongly linked than what density indicates.

The next three columns report degrees of nodes. The out-degree of a node is equal to the number of out-edges from the node, and in-degree is the number of in-edges into the node. Note that the sum of out-degrees is equal to the sum of in-degrees. The sixth column ("Avg Degree") reports the average degree of a node, which is the sum of degrees divided by the number nodes. The seventh and eighth columns ("Max In" and "Max Out") report the largest out-degree and the largest in-degree, respectively. Together with average degree, they reveal that there are a small number of nodes with large out-degree or in-degree, while a large share of the nodes possess only 1 edge[5]. That is, there are a small number of "significant" firms that supply to or buy from a large number of firms. This feature is observed for all years included in this study.

Finally, the last two columns ("Out [A, D, I, M]" and "In [A, D, I, M]") respectively report the out-degrees and in-degrees of [AAPL, DELL, IBM, and MSFT]. The entries in each bracket correspond to the order of firms given by this bracket. Overall across the years, these four firms have the largest "significance" in the supplier-buyer network. In particular, IBM possessed the largest significance, in out-degree and in-degree combined, until MSFT surpassed it in 2014. It is also notable that the significance of AAPL, both in out-degree and in-degree, has been gradually increasing over the years. We can also observe that AAPL and DELL are net receivers, meaning that their in-degrees are much larger relative to their out-degrees. It indicates that these firms source intermediate goods from a large number of suppliers but sell their products to a relatively small number of buyers. Possibly, such characteristic reveals than

[4] A path is a sequence of edges from a node to another. For example, a path from i to j, exists if $(i,j) \in E$ or $(i,k_1), \dots (k_{L-1},k_L), (k_L,j) \in E$ for some $\{k_l : 1 \le l \le L, L \le |E|-2\} \subset V$. Because edges are directed, paths are not reciprocal.

[5] By construction of the data set, each node possesses at least one in- or out-edge.

the business models of AAPL and DELL are different from IBM and MSFT. Moreover, in the event of an economic shock, AAPL and DELL may be affected differently and also may exert a different effect on the supplier-buyer network than IBM and MSFT.

In the following sections, this article studies the structure of the buyer-supplier network and significance these four firms in the network by dividing the network into communities of firms, characterizing the communities by NAICS codes, and computing measures of centrality. So far, the significance of a firm in the network was characterized only using its out- and in-degree. There are, however, a number of other measures that characterize the significance of a firm. Some of these measures are explained and computed in section 4.

Table 1: Summary Statistics of Supplier-Buyer Networks

Year	**#Node**	**#Edge**	**Density**	**Avg #Path**	**Avg Degree**	**Max Out**	**Max In**	**Out [A, D, I, M]**	**In [A, D, I, M]**
2003	282	453	0.0057	81.1	1.606	86	111	[7, 18, 86, 46]	[19, 57, 111, 54]
2004	290	456	0.0054	78.6	1.572	91	112	[7, 16, 91, 44]	[22, 55, 112, 55]
2005	293	451	0.0053	82.8	1.539	88	123	[5, 18, 88, 49]	[25, 47, 123, 61]
2006	272	415	0.0056	79.6	1.526	77	109	[6, 19, 77, 48]	[26, 40, 109, 53]
2007	267	389	0.0055	66.4	1.457	71	94	[6, 15, 71, 39]	[25, 42, 94, 46]
2008	272	404	0.0055	68.7	1.485	78	89	[5, 23, 78, 43]	[23, 38, 89, 55]
2009	261	388	0.0057	72.8	1.487	73	81	[6, 23, 73, 42]	[22, 37, 81, 54]
2010	286	431	0.0053	72.9	1.507	72	84	[5, 23, 72, 54]	[42, 44, 84, 61]
2011	299	472	0.0053	85.3	1.579	83	84	[6, 21, 83, 67]	[51, 54, 84, 69]
2012	341	504	0.0043	76.7	1.478	79	89	[12, 26, 74, 79]	[66, 63, 89, 68]
2013	370	541	0.0040	88.8	1.462	74	84	[22, 26, 69, 74]	[79, 73, 84, 72]
2014	400	607	0.0038	95.2	1.517	85	90	[32, 26, 69, 85]	[86, 82, 89, 90]

This table reports summary statistics of the supplier-buyer networks from 2003 to 2014. The first column ("Year") lists the years. The second column and third column ("#Node' and "#Edge") report the number of firms and edges between firms, resepctively. The fourth column ("Density") reports network density, which is the number of edges divided by the possible number of edges. The fifth column ("Avg Path") reports the average number of connected firms per firm. A firm is connected to another firm if there exists a sequence of edges from the former to the latter. The sixth column ("#Avg Degree") reports the average number of edges per firm. The next two columns ("Max Out" and "Max In") report the largest outdegree and indegree of a firm, respectively. The last two columns ("Out [A, D, I, M]" and "In [A, D, I, M]") report the out-degrees and in-degrees of [AAPL, DELL, IBM, MSFT], respectively. The entries in each bracket correspond to the order of firms given by this bracket.

3 Community of Firms

Recent research in statistical physics and computer science studies how one may detect communities within a network. A community is generally defined as nodes that are strong linked among themselves than to the rest of the network. Thus, the goal of community detection is to split the node set V into subsets[6], such that nodes belonging to the same subset possess strong linkage among them, while there is relatively weak linkage among the subsets. In this article, an *intra-edge* denotes an edge from a node to another within the same community, and an *inter-edge* denotes an edge from a node to another node belonging to a different community.

Communities are considered as important building blocks of a network. For the supplier-buyer network, a community of firms may be interpreted as a group of closed related firms that are likely to be most significantly affected in the event of an economic shock to a community member. However, if the community member is a bridge between communities, a node that is also strongly linked to another community, the shock may also have a significant impact to another community.

3.1 Community Detection

This article uses the community detection method of Leicht and Newman (2008), which is an extension of Newman (2006) for digraphs. The fundamental idea is to detect groups of nodes, such that nodes within each group are more densely linked to each other than what is expected under a random network configuration preserving the out-degree and in-degree sequence. Arenas et al. (2007) suggest that for a digraph, the strength of the linkage from node i to node j, for $i \neq j$, under a random network configuration is

$$\frac{O_i \times I_j}{M}, \tag{6}$$

[6]The community detection method used in this article partitions V into subsets, meaning that each node belongs to exactly one community. See, for example, Lancichinetti and Fortunato (2009) for community detection methods with overlapping communities.

where O_i and I_j are the out-degree of node i and the in-degree of node j, respectively. $M = |E|$ is the number of edges in the network. Because self-loops are not allowed, the value of equation (6) is set to zero whenever $i = j$.

The *modularity* of a network (Girvan and Newman, 2002) is[7]

$$Q = \frac{1}{4M} s' \left(B + B' \right) s. \tag{7}$$

B is called the *modularity matrix*, with the $(i, j)^{\text{th}}$ element

$$B_{ij} = A_{ij} - \frac{O_i \times I_j}{M}, \tag{8}$$

and $s \in \{-1, 1\}^N$ is the choice variable that partitions the node set into two communities. Essentially, B_{ij} is the difference between the observed strength (as given by the element of the adjacency matrix A_{ij}) and the expected strength of the linkage from i to j. Thus, the larger the value of Q, the greater the strength of linkages within each community is relative to what is expected under a random network with identical out-degree and in-degree sequence. In other words, a larger value of Q indicates that each community contains a larger fraction of edges than what would be expected if edges were placed at random, while preserving the out-degree and in-degree for each node. The optimal choice of s maximizes Q. Because of the binary restriction, it is approximated by choosing a vector in $\{-1, 1\}^N$ that matches the signs of a leading eigenvector[8] of $B + B'$. The result is further fine-tuned using a greedy algorithm, which terminates when Q cannot be improved by altering the community assignment of a node.

The method described above divides the node set of the network into two communities. The node set is divided into more than two communities by iteratively subdividing communities. For a community

[7] This expression uses a symmetrization of $Q = \frac{1}{2M} s' B s$. Since $Q \in \mathbb{R}$, we have $Q = \left(Q + Q' \right)/2$.

[8] A leading eigenvector corresponds to the largest positive eigenvalue.

$C \subset V$, a subdivision, given by $s^{(C)} \in \{-1, 1\}^{\dim(C)}$, occurs only when

$$\Delta Q = \frac{1}{4M} s^{(C)\prime} \left(\tilde{B}^{(C)} + \tilde{B}^{(C)\prime} \right) s^{(C)} \tag{9}$$

is positive. $\tilde{B}^{(C)} \in \mathbb{R}^{\dim(C) \times \dim(C)}$ is defined such that the $(i, j)^{\text{th}}$ element

$$\tilde{B}^{(C)}_{ij} = B^{(C)}_{ij} - \frac{1}{2} \delta_{ij} \sum_{k \in C} \left(B^{(C)}_{ik} + B^{(C)}_{ki} \right), \tag{10}$$

where $B^{(C)}$ is the submatrix of the modularity matrix B obtained by eliminating the rows and columns corresponding to the nodes that do not belong to C. δ_{ij} takes value 1 if $i = j$ and zero if otherwise.

3.2 Communities in Supplier-Buyer Network

Table 2 shows a summary of communities in the supplier-buyer networks, from 2003 to 2014. The second column ("#C") reports the number communities; these communities partition the set of firms included in the network for each year. The remaining columns report additional information about the four largest communities. The entries in each bracket correspond to the $\left[4^{\text{th}}, 3^{\text{rd}}, 2^{\text{nd}}, 1^{\text{st}}\right]$ largest communities.

The third column ("Community Size") reports the sizes of the four larges communities, where the size of a community is equal to the number of firms belonging to the community. It reveals that the largest community is significantly larger than other communities. Until 2009, the largest community contained more than 40 percent of the firms in the network; however, its share diminished since 2010 as other communities gained in size. For all years, the size of the smallest community is two.

The fourth column ("#Intra-Edges) reports the number of intra-edges within each of the four communities, and the next two columns ("#Inter-Edges (Out)" and "#Inter-Edges (In)") report the number of inter-edges to other communities and the number of inter-edges from other communities, respectively. Comparing the number intra-edges to the number of inter-edges reveals that there remains considerable inter-community edges after the community division. However, as a fraction of possible edges, the linkage within a community is far stronger than the linkage across communities (Table 7 in the appendix reports the densities associated with the intra- and inter-edges, where each density measure is obtained using equation (5) with the appropriate number of possible edges as the denominator.). Nevertheless, the existence of considerable inter-edges indicate that if an economic shock occurs to a community member, the shock is likely to affect other communities. Such feature is further confirmed by the seventh column of the table ("#NC"), which gives the number of firms that are not linked to or linked from other communities. Except for one community, a large fraction of firms are linked to or linked from other communities, for every year.

Table 2: Community Structure (Largest Four Communities)

Year	**#C**	**Community Size**	**#Intra-Edges**	**#Inter-Edges (Out)**	**#Inter-Edges (In)**	**#NC**	**Firm**
2003	13	[17, 21, 43, 146]	[18, 21, 49, 158]	[25, 9, 41, 52]	[17, 48, 26, 40]	[3, 18, 29, 93]	[A, D, M, I]
2004	14	[19, 32, 36, 151]	[19, 32, 40, 164]	[28, 18, 28, 53]	[12, 41, 36, 45]	[3, 18, 32, 96]	[A, D, M, I]
2005	13	[26, 30, 53, 142]	[25, 30, 60, 158]	[38, 7, 20, 58]	[15, 44, 43, 26]	[4, 17, 40, 111]	[A, D, M, I]
2006	13	[25, 28, 42, 138]	[25, 27, 48, 152]	[10, 32, 29, 37]	[34, 14, 30, 40]	[18, 4, 37, 96]	[D, A, M, I]
2007	13	[24, 30, 37, 127]	[23, 30, 40, 138]	[20, 22, 23, 33]	[15, 27, 25, 34]	[8, 17, 34, 87]	[A, D, M, I]
2008	14	[23, 31, 44, 124]	[22, 31, 51, 135]	[20, 22, 18, 38]	[10, 31, 34, 38]	[10, 19, 38, 80]	[A, D, M, I]
2009	13	[22, 26, 46, 114]	[21, 26, 51, 125]	[18, 20, 20, 38]	[13, 32, 30, 33]	[9, 15, 41, 73]	[A, D, M, I]
2010	13	[28, 41, 58, 113]	[28, 40, 63, 125]	[15, 32, 23, 39]	[38, 19, 34, 34]	[17, 17, 53, 71]	[D, A, M, I]
2011	13	[37, 44, 61, 123]	[37, 48, 70, 140]	[18, 47, 30, 42]	[29, 28, 40, 45]	[20, 19, 56, 69]	[A, D, M, I]
2012	14	[52, 55, 72, 125]	[54, 55, 81, 129]	[33, 27, 38, 47]	[44, 30, 36, 36]	[24, 34, 66, 76]	[D, A, M, I]
2013	15	[61, 69, 72, 117]	[63, 77, 73, 122]	[27, 37, 39, 55]	[57, 40, 33, 27]	[31, 63, 45, 67]	[D, M, A, I]
2014	18	[61, 66, 77, 137]	[62, 72, 79, 146]	[51, 39, 59, 42]	[45, 55, 27, 66]	[27, 59, 50, 71]	[D, I, A, M]

This table describes the community division results. The first column ("Year") lists the years. The second column ("#C") reports the number communities; these communities partition the set of firms included in the supplier-buyer network. The remaining columns report additional information about the four largest communities. The entries in each bracket correspond to the $\left[4^{\text{th}}, 3^{\text{rd}}, 2^{\text{nd}}, 1^{\text{st}}\right]$ largest communities. The third column ("Community Size") reports the size of the community, which is equal to the number of firms belonging to the community. The fourth column ("#Intra-Edges") reports the number of intra-edges within the community. The next two columns ("#Inter-Edges (Out)" and "#Inter-Edges (In)") report the number of inter-edges to other communities and the number of inter-edges from other communities, respectively. The seventh column ("#NC") reports the number of firms that are not linked to or linked from other communities. The last columnm ("Firm") reports the community membership of AAPL, DELL, IBM, and MSFT. For example, [D, A, M, I] indicates that DELL, AAPL, MSFT, and IBM belong to the fouth, third, second, and first largest communities, respectively.

The last column ("Firm") reports the community membership of AAPL, DELL, IBM, and MSFT. For all years, none of these firms belong to the same community, indicating that each possesses a strong supplier-buyer relationship with a distinct sets of firms. Note that the result does not say that each firm possesses distinct set of suppliers or buyers; each firm may have suppliers or buyers belonging to a different community. It also reveals that IBM belonged to the largest community, until the community MSFT belongs to became the largest in 2014. We can also observe that the size of the community surrounding AAPL grew over the years, from 17 in 2003 to 77 in 2014. It indicates that over the years, AAPL formed strong supplier-buyer relationships with a larger set firms. Belonging to a larger community, however, does not necessarily indicate that the significance of AAPL in the network grew over the years.

Figure 1 graphically illustrate the community divisions. For each year, firms (nodes) are placed on an ellipse, and firms belonging to the same community are placed adjacently. For each of AAPL, DELL, IBM, and MSFT, its community (the community it belongs to) is color-coded to distinguish the communities; all other communities are marked in black. Moreover, each of these four firms are placed at the very first, in clockwise orientation, in its community. For example, in sub-figure (a), the magenta-colored nodes covering the left side of the ellipse is the community of IBM, and IBM is placed as the first in clockwise orientation. Each directed line indicates a link from a firm to another. Red-colored lines indicate intra-edges within a community, and blue-colored lines indicate inter-edges between communities.

The figure confirms the trend of communities explained earlier. By looking at the share of the ellipse each of the four communities occupies, we can observe that the community of IBM possessed the largest share until 2013. Its began to shrink in 2010, and the community of MSFT surpassed it in 2014. Moreover, the the growth of AAPL's community is remarkable, especially from 2010.

Figure 1: Community Division and Out-Edges

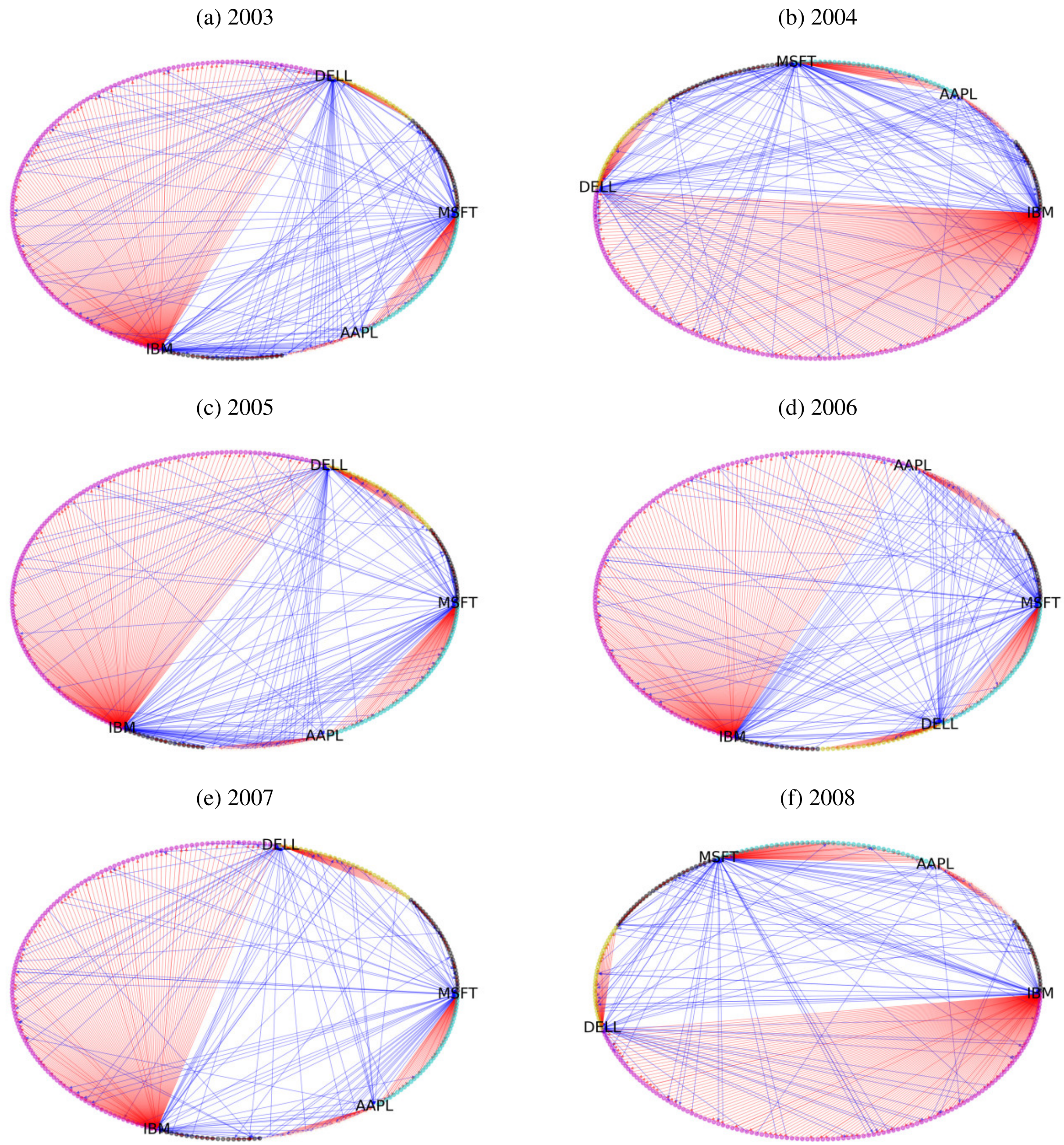
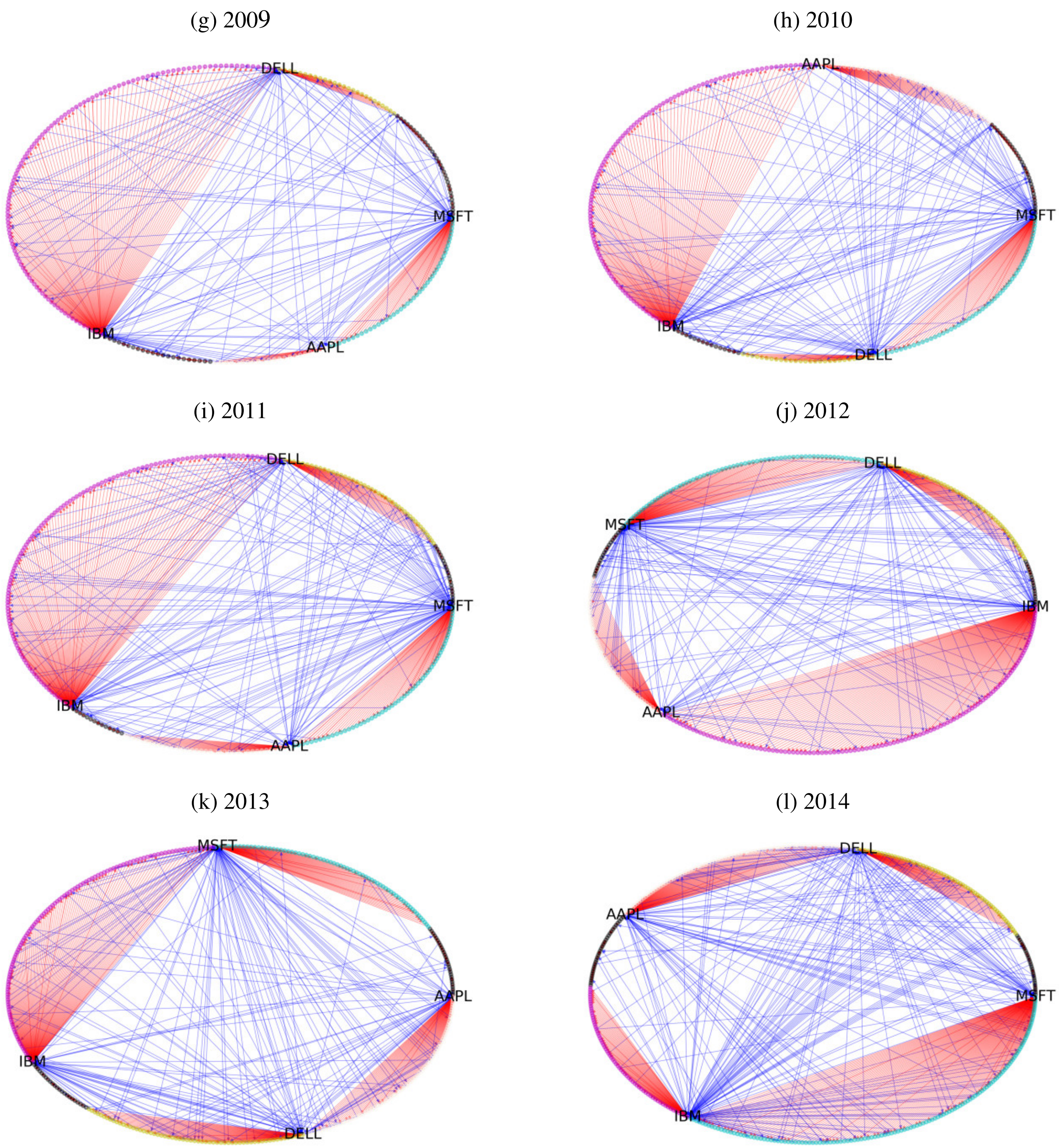


Figure 1: Community Division and Out-Edges (Continued)



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The denseness of red and blue lines at AAPL, DELL, IBM, and MSFT indicates the strength of intra-edges (red lines) and inter-edges (blue lines) of the four firms. First, the denseness of intra-edges at each of AAPL, DELL, IBM, and MSFT is far greater than other firms in the same community, which reveals that each firm is the center of its community. Moreover, until 2013, the denseness of intra-edges is far greater than the denseness of inter-edges at IBM, indicating that IBM had far stronger linkages with its community members than with firms in other communities until 2013. For the same period, the denseness of intra-edges and of inter-edges appear to be similar or the former appears to be slightly denser at AAPL, DELL, and MSFT. In other words, the supplier-buyer relationship of IBM was more strongly restricted to its own community than the other three firms until 2013. In 2014, however, the denseness of intra-edges and of inter-edges at IBM became similar, and the former became much more dense at MSFT. A likely cause for such shift is that the community of MSFT became the largest in 2014. That is, a number of firms that were strongly associated with IBM in previous years became strongly associated with the other three firms, and the community surrounding IBM became smaller. It indicates that IBM became less significant in the supplier-buyer network.

Table 3 shows details on the number of intra- and inter-edges of AAPL, DELL, IBM, and MSFT. The numbers in each bracket follow the order of firms. The numbers reported in the second and third columns describe the role of the firm as a supplier. The second column ("#Intra-Edges (Out)") reports the number of intra-edges from the firm to other firms in the same community, which is equal to the number of firms in the same community the firm supplies to. The third column ("#Inter-Edges (Out)") reports the number of inter-edges from the firm to firms in other communities, which is equal to the number of firms in other communities the firm supplies to. The numbers reported in the next two columns describe the role of the firm as a buyer. The fourth column ("#Inter-Edges (Out)") reports the number of inter-edges to the firm from other firms in the same community, which is equal to the number of firms in the same community the firm buys from. The last column ("#Inter-Edges (In)") reports the number of inter-edges to the firm from firms in other communities, which is equal to the number of firms in other communities the firm buys from.

The last two columns of table 1 indicate that AAPL and DELL are net buyers, meaning that they buy from a much larger number firms relative to the number of firms they supply to. In table 7, comparing the second ("#Intra-Edges (Out)") and the fourth ("#Intra-Edges (In)") columns, and also the third ("#Inter-Edges (Out)") and fifth ("#Inter-Edges (In)") columns, we also can their roles in their own communities and also with other communities. AAPL buys more from its own community than from other communities. In contrast, DELL buys more from other communities than from its own community. Such information tells us that for AAPL, a demand shock may have a stronger effect on its community than on other communities. For DELL, a demand shock may have a stronger effect on other communities than on its community.

Table 3: Edges of [AAPL, DELL, IBM, MSFT]

Year	**#Intra-Edges (Out)**	**#Inter-Edges (Out)**	**#Intra-Edges (In)**	**#Inter-Edges (In)**
2003	[5, 9, 69, 18]	[2, 9, 17, 28]	[13, 12, 89, 31]	[6, 45, 22, 23]
2004	[4, 10, 75, 18]	[3, 6, 16, 26]	[15, 22, 89, 22]	[7, 33, 23, 33]
2005	[5, 16, 57, 31]	[0, 2, 31, 18]	[20, 14, 101, 29]	[5, 33, 22, 32]
2006	[5, 12, 65, 23]	[1, 7, 12, 25]	[22, 13, 87, 25]	[4, 27, 22, 28]
2007	[5, 8, 60, 18]	[1, 7, 11, 21]	[18, 22, 78, 22]	[7, 20, 16, 24]
2008	[4, 14, 65, 26]	[1, 9, 13, 17]	[18, 17, 70, 25]	[5, 21, 19, 30]
2009	[5, 12, 60, 24]	[1, 11, 13, 18]	[16, 14, 65, 27]	[6, 23, 16, 27]
2010	[5, 14, 59, 33]	[0, 9, 13, 21]	[35, 14, 66, 30]	[7, 30, 18, 31]
2011	[6, 10, 75, 39]	[0, 11, 8, 28]	[31, 34, 65, 31]	[20, 20, 19, 38]
2012	[10, 18, 60, 47]	[2, 8, 14, 32]	[45, 36, 69, 34]	[21, 27, 20, 34]
2013	[17, 22, 55, 43]	[5, 4, 14, 31]	[56, 41, 67, 34]	[23, 32, 17, 38]
2014	[16, 14, 38, 79]	[16, 12, 31, 14]	[63, 48, 34, 67]	[22, 23, 53, 21]

This table reports the number of edges associated with AAPL, DELL, IBM, and MSFT. The numbers in each bracket follow the order of firms. The first column ("Year") lists the years. The second column ("#Intra-Edges (Out)") reports the number of intra-edges from the firm to other firms in the same community, and the third column ("#Inter-Edges (Out)") reports the number of inter-edges from the firm to firms in other communities. The fourth column ("#Inter-Edges (Out)") reports the number of inter-edges to the firm from other firms in the same community, and the last column ("#Inter-Edges (In)") reports the number of inter-edges to the firm from firms in other communities.

3.3 NAICS Codes of Communities

The North American Industry Classification System (NAICS) assigns codes to firms based on the industry sector they belong to. For example, AAPL, DELL, IBM, and MSFT, respectively, are assigned 33422 ("Radio and Television Broadcasting and Wireless Communications Equipment"), 33411 ("Computer and Peripheral Equipment Manufacturing"), 51913 ("Internet Publishing and Broadcasting and Web Search Portals"), and 51121 ("Software Publishers"). Table 8 in the appendix provides a dictionary for the NAICS codes that appear in this subsection.

Table 4 describes the NAICS codes associated with the communities of AAPL, DELL, IBM, and MSFT. The numbers in each bracket follow the order of firms. The second column ("NAICS (1^{st})") reports the most frequently observed NAICS code in the community. The third ("NAICS (2^{nd})") and the fourth ("NAICS (3^{rd})") columns report the second-most and the third-most frequently observed NAICS codes in the community, respectively. We can observe that the observed NAICS codes are similar for the four communities. In particular, NAICS codes 33441 ("Computer and Peripheral Equipment Manufacturing"), 51121 ("Software Publishers"), 51913 (Internet Publishing and Broadcasting and Web Search Portals), and 42343 ("Computer and Computer Peripheral Equipment and Software Merchant Wholesalers") are most outstanding. It reveals that an economic shock to this supplier-buyer network will strongly affect these industry sectors. In addition, the fact that AAPL, DELL, IBM, and MSFT belong to different communities indicate that there exists a certain degree of exclusivity in the relationship with their suppliers and buyers[9] . Finally, the last column ("#NAICS") reports the number of unique NAICS codes observed in the community, which can be interpreted as the diverseness of industries in each community. Over the years, the growth in the diverseness of AAPL's community is remarkable.

[9] Recall that AAPL, DELL, IBM, and MSFT are the centers of their own community.

Table 4: NAICS Codes by Community of [AAPL, DELL, IBM, MSFT]

Year	**NAICS (1st)**	**NAICS (2nd)**	**NAICS (3rd)**	**#NAICS**
2003	[33441, 33441, 33441, 51121]	[51121, 54151, 51121, 51913]	[42343, 32521, 33411, 54151]	[8, 16, 45, 27]
2004	[33441, 33441, 33441, 51121]	[51121, 51913, 51121, 54151]	[42343, 54151, 54151, 56149]	[9, 21, 54, 24]
2005	[33441, 54151, 33441, 51121]	[42343, 51121, 51121, 42343]	[51913, 33441, 33411, 51913]	[11, 20, 53, 32]
2006	[33441, 33441, 33441, 51121]	[42343, 51913, 51121, 33441]	[33411, 51121, 54151, 56149]	[13, 16, 49, 27]
2007	[33441, 33441, 33441, 51121]	[42343, 33411, 51121, 33441]	[53112, 51121, 54151, 33411]	[12, 14, 43, 22]
2008	[33441, 33441, 33441, 51121]	[53112, 33411, 51121, 33411]	[51913, 51913, 54151, 51913]	[10, 18, 46, 28]
2009	[33441, 33441, 33441, 51121]	[42343, 51913, 54151, 51913]	[53112, 51121, 51121, 33411]	[11, 15, 43, 24]
2010	[33441, 51121, 51121, 51121]	[51913, 51913, 33441, 51913]	[42343, 33441, 54151, 54151]	[14, 17, 41, 30]
2011	[33441, 33441, 33441, 51121]	[51913, 33411, 51121, 54151]	[33431, 51913, 54151, 53112]	[18, 14, 43, 34]
2012	[33441, 51121, 33441, 51121]	[51913, 33441, 51121, 51913]	[51121, 54151, 54151, 53112]	[24, 22, 48, 34]
2013	[33441, 33441, 33441, 51913]	[51913, 51121, 51121, 51121]	[51121, 54151, 54151, 54151]	[30, 23, 48, 32]
2014	[33441, 33441, 51121, 51913]	[51913, 51121, 33441, 51121]	[51121, 33411, 54151, 54151]	[34, 21, 34, 44]

This table describes the 5-digit NAICS codes associated with the communities of AAPL, DELL, IBM, and MSFT. The numbers in each bracket follow the order of firms. The first column ("Year") lists the years. The second column ("NAICS (1st)") reports the most frequently observed NAICS code in the community. The third column ("NAICS (2nd)") and the fourth column ("NAICS (3rd)") report the second-most and the third-most frequently observed NAICS codes in the community, respectively. The last column ("#NAICS") reports the number of unique NAICS codes observed in the community.

4 Centrality of Firms

This section studies the significance of a firm on the supplier-buyer network. If an economic shock occurs to firm i, the shock will first affect the direct buyers and suppliers of i. Subsequently, the shock will spread out to the buyers and suppliers of these buyers and suppliers, and so on. The centrality of a firm evaluates its influence using the linkages in the supplier-buyer network. A firm with a large centrality is significant, meaning that it is highly influential on the supplier-buyer network. This article studies the influence of a firm using standard centrality measures and also using modular centrality measures. Modular centrality, a concept proposed by Ghalmane et al. (2019), distinguishes the influence of a node on the community it belongs to and on the rest of the network.

The direction of edges matters in interpreting the centrality of a firm. By construction of the adjacency matrix, $A_{ij} = 1$ if firm i supplies to firm j (j is a buyer of i). Thus, centrality measures computed using the adjacency matrix A are interpreted as the influence of a firm on it buyers, the buyers of these buyers, and so on. This is called the *downstream* channel (stream of goods and services from the firm). Centrality measures using the transpose A' are interpreted as the influence of a firm on its suppliers, the suppliers of these suppliers, and so on. This is called the *upstream* channel (stream of goods and services into the firm).

4.1 Measures of Centrality

Researchers of social networks, epidemiology, physics, and more generally, graph theory have utilized measures of centrality to evaluate the influence of a node on the network. This article employs the following measures of centrality [See, for example, Newman (2010) for details.]. Note that a centrality always takes a nonnegative value, and one should focus on the rankings among nodes each measure of centrality assigns, instead of the magnitude. Moreover, comparing magnitudes across different measures of centrality is generally inadequate because they capture different aspects of connectivity in the network. The notations introduced in section 2 are used in the following.

4.1.1 (Out-) Degree Centrality

The degree centrality of node i is the fraction of nodes it links to. For a digraph, it is standard to follow the direction of flow when evaluating the influence of a node. Thus, the out-degree of i, denoted by O_i, is used for computation, and the degree centrality of i is equal to

$$\mathcal{C}_{\mathrm{D}}(i) = \frac{O_i}{N-1}. \tag{11}$$

For the supplier-buyer network, degree centrality evaluates the influence of firm i as a supplier. Note that the transpose of the adjacency matrix can be used to evaluate the influence of i as a buyer, which is called the indegree centrality of i. A limitation is that degree centrality only captures the direct influence of a firm.

4.1.2 Eigenvector Centrality

Let α denote the largest positive eigenvalue of the adjacency matrix A, with the corresponding normalized eigenvector $\mathcal{C}_{\mathrm{E}} = (\mathcal{C}_{\mathrm{E}}(1), \mathcal{C}_{\mathrm{E}}(2), \ldots, \mathcal{C}_{\mathrm{E}}(N))'$, such that

$$A\mathcal{C}_{\mathrm{E}} = \alpha\mathcal{C}_{\mathrm{E}}. \tag{12}$$

The eigenvector centrality of node i is equal to $\mathcal{C}_E(i)$, and it can be also written as

$$\mathcal{C}_{\mathrm{E}}(i) = \alpha^{-1}\sum_j A_{ij}\mathcal{C}_{\mathrm{E}}(j). \tag{13}$$

Recall that A_{ij} take value 1 if there exists an edge from i to j and zero if otherwise. Thus, equation (13) indicates that the eigenvector centrality of node i is large if it is linked to nodes with large eigenvector centrality. In other words, more significance is given to nodes that are linked to significant nodes. Note that this specification evaluates the influence of a firm as a supplier in the downstream channel. The transpose of A is used to compute the influence of a firm as a buyer in the upstream channel. This article uses the following two variations of eigenvector centrality.

Katz Centrality

A potential problem of eigenvector centrality is that in order to possess a positive centrality, a node needs to be linked to a node that possesses a positive centrality. In the extreme case with an acyclic[10] digraph, all nodes possess zero eigenvector centrality regardless of the number of links. Thus, eigenvector centrality underestimates the influence of a node that links to a large number of insignificant nodes (i.e., with zero centrality). Katz centrality alleviates this problem by assigning a minimum positive centrality to each

[10] A digraph is acyclic if it contains no path from a node to itself.

node. The Katz centrality of node i is defined as

$$\mathcal{C}_{\mathrm{K}}(i) = a_{\mathrm{K}} \sum_{j} A_{ij} \mathcal{C}_{\mathrm{K}}(j) + b_{\mathrm{K}}, \tag{14}$$

which adds a minimum positive centrality b_{K} to the eigenvector component in equation (13). a_{K} assigns a weight to the eigenvector component, and it should be bounded away from zero so that we do not have $\mathcal{C}_{\mathrm{K}}(i) = b_{\mathrm{K}}$ for all i. Moreover, it can be shown that $a_{\mathrm{K}} < \alpha^{-1}$ is necessary for convergence of equation (14). This article uses $a_{\mathrm{K}} = 0.9\alpha^{-1}$ and $b_{\mathrm{K}} = 1$. The magnitude of b_{K} is unimportant because we are only interested in ranking the nodes, instead of the magnitude of the centrality.

PageRank Centrality

A possible weakness of Katz centrality is that it assigns large values of centrality to all nodes that are linked to a node with large centrality. This can be problematic because for example, the significance of a firm that is the sole supplier to a highly significant firm (i.e., with large centrality) should be greater than a firm that is one of many suppliers to a highly significant firm. PageRank centrality alleviates this problem by weighting the eigenvector centrality component of a node by its in-degree. The PageRank centrality of node i is defined as

$$\mathcal{C}_{\mathrm{P}}(i) = a_{\mathrm{P}} \sum_{j=1}^{N} A_{ij} \frac{\mathcal{C}_{\mathrm{P}}(j)}{I_j} + b_{\mathrm{P}}, \tag{15}$$

where I_j is the in-degree of node j. For the supplier-buyer network, I_j is large if firm j buys from a large number of suppliers. The suppliers of j gains in centrality by supplying to j, especially if j is a significant firm. The weighting factor $1/I_j$ equally distributes the significance of j to its suppliers. For $I_j = 0$, it is replaced with a constant; the value of the constant is irrelevant because in this case, $A_{ij} = 0$ for all i. With the modification, convergence of equation (15) requires $a_{\mathrm{P}} < \tilde{\alpha}^{-1}$, where $\tilde{\alpha}$ is the largest positive eigenvalue of AD^{-1}, and $D = \mathrm{diag}\left(I_1, I_2, \ldots, I_N\right)$. This article uses $a_{\mathrm{P}} = \min\left(0.85, 0.9\tilde{\alpha}^{-1}\right)$

and as before, $b_{\text{P}} = 1$.

4.1.3 Closeness Centrality (Harmonic)

The closeness centrality of node i measures the average distance from i to other nodes in the network. For $i \neq j$, a path from i to j exists (equivalently, i is connected to j) if there exists a sequence of directed edges, possibly passing through other nodes, from i to j. The length of a path is equal to the number of edges in the path. Alternatively, a path from i to j exists if $[A^p]_{ij} > 0$ for some $p \in \mathbb{N}$. If such power p exists, then the distance from i to j is equal to the minimum power that attains $[A^p]_{ij} > 0$. Formally, the distance from i to j is[11]

$$d(i,j) = \begin{cases} \text{Length of shortest path from } i \text{ to } j & \text{if path from } i \text{ to } j \text{ exists} \\ \infty & \text{if no path from } i \text{ to } j \text{ exist} \\ 0 & \text{if } i = j. \end{cases} \tag{16}$$

Then the closeness centrality of i is defined as

$$\mathcal{C}_C(i) = \frac{1}{N-1} \sum_{j \neq i} \frac{1}{d(i,j)}, \tag{17}$$

which is the inverse harmonic mean of the distances from i to other nodes in the network. It essentially counts the number of nodes i is connected to, discounted by the inverse distance. Thus the closeness centrality of i is large if it is connected to a large number of nodes via short paths.

Closeness centrality assigns high significance to all firms that supply to a highly significant firm (i.e. large closeness centrality), as they can connect to other firms via that firm. Similar to Katz centrality, it can be problematic as it may not distinguish the significance between the sole supplier and one of many suppliers to a significant firm. Moreover, it may not account for the existence of multiple shortest paths. For example, consider a case when i is connected to j via a single path $\{(i,k_1),(k_1,j)\}$. Also consider

[11] Note that for a digraph, $d(\cdot,\cdot)$ is not a metric because it does not satisfy the symmetry property.

another case when there exists an additional path from i to j, $\{(i,k_2),(k_2,j)\}$, for $k_1 \neq k_2$. In both cases, the distance from i to j is equal to 2, and closeness centrality may not capture the difference in multiplicity.

4.1.4 Betweenness Centrality (Shortest Path)

Unlike the previous measures centrality, betweenness centrality captures the significance of a node in maintaining the connectivity within the network. Consider a path $\{(i,k),(k,j)\}$, which connects i to j via k. Node k plays an important role because without it, the flow from i to j may be disrupted. This article uses a version of betweenness centrality based on shortest paths. Let $\pi(s,t)$ and $\pi(s,t,;i)$ denote the number of shortest paths from node s to node t and the number of such paths passing through i, respectively. The betweenness centrality of i is defined as

$$\mathcal{C}_B(i) = \sum_{s} \sum_{t \neq s} \frac{\pi(s,t;i)}{\pi(s,t)}, \tag{18}$$

where $\pi(s,t;i)/\pi(s,t)$ is set to zero if $\pi(s,t)$ and $\pi(s,t;i)$ are both zero. For the supplier-buyer network, a firm with large betweenness centrality plays a significant role in maintaining the flow of goods and services in the supply chain. An economic shock to such a firm may disrupt the supply chain.

4.2 Modular Centrality

Modular centrality (Ghalmane et al., 2019) utilizes a community division in computing measures of centrality. Because this article distinguishes significance of a firm in the downstream channel (out-edges) and the upstream channel (in-edges), it is necessary to first establish that the community division discussed in subsection 3.1 does not depend on whether we use out-edges or in-edges. Recall that computing centrality using the adjacency matrix A corresponds to the downstream channel and using the transpose A' corresponds to the upstream channel. Let O_i' and I_j' denote the out-degree of node i and the in-degree of node j obtained from A'. Using the notation in subsection 3.1,

$$O'_i = I_i,\ I'_j = O_j. \tag{19}$$

Thus, the $(i, j)^{\text{th}}$ element of the modularity matrix corresponding to A' is

$$[A']_{ij} - \frac{O'_i \times I'_j}{M} = A_{ji} - \frac{I_i \times O_j}{M} \tag{20}$$

$$= [B']_{ij}\,. \tag{21}$$

Because the modularity in equation (7) uses $B + B'$, the community division method in subsection 3.1 accounts for both the downstream and the upstream channels.

A measure of modular centrality exists for every measure of centrality, and it is defined as a weighted sum of the *local component* and the *global component.* For each measure of centrality, the corresponding local component is computed only using intra-edges. The corresponding global component is computed only using inter-edges; for a node with zero inter-edges, the global component is set to zero. Thus, the local component of a node is its significance in its own community, and the global component is its significance in other communities except for its own. A different weight is assigned to each community. For community C, the weight of the local component is

$$\mu_C = \frac{\sum_{k\in C} O_k^{\text{intra}}}{\sum_{k\in C} O_k}, \tag{22}$$

where O_k^{intra} is the number of out-edges (or simply edges) of node k to the members of its community. Thus, μ_C is the fraction of intra-edges of community C. The modular centrality of node i in community C is

$$\mathcal{C}^{\text{M}}(i) = \mu_C \mathcal{C}^{\text{L}}(i) + (1 - \mu_C)\, \mathcal{C}^{\text{G}}(i), \tag{23}$$

where $\mathcal{C}^L(i)$ and $\mathcal{C}^G(i)$ denote the local component and global component of node i, respectively. Note that the default specification follows the direction of edges, which corresponds to the downstream channel. To compute the modular centrality corresponding to the upstream channel, all components are computed using A'.

The weight μ_C assigns a larger importance to the local component for a community with a larger fraction of intra-edges, contained within the community. Equivalently, the weight assigns a larger importance to the global component for a community with a larger fraction of inter-edges, to other communities. Consider a community of firms C in the supplier-buyer network. If μ_C is large, then an economic shock to a member of the community is likely to have stronger effect on the community than the rest of the network, and modular centrality assigns a larger weight to the local significance of firms belonging to the community. If μ_C is small, then an economic shock to a member of the community is likely to have a stronger effect on other communities, and modular centrality assigns a larger weight to the global significance of firms belonging to the community.

4.3 Centrality in the Supplier-Buyer Network

Table 5 reports a summary of centrality rankings, and table 6 reports a summary of modular centrality rankings for AAPL, DELL, IBM, and MSFT. Five measures of centrality - degree, Katz, PageRank, closeness, and betweenness - and the corresponding measures of modular centrality were computed. For each year, firms were ranked based on each measure of centrality. The numbers in each bracket indicate the number of times the firm took the $\left[1^{\text{st}}, 2^{\text{nd}}, 3^{\text{rd}}, 4^{\text{th}}\right]$ rank among the five measures of centrality. For example, $[0, 4, 1, 0]$ indicate that the firm took the second rank four times and the third rank once. Note that each number in the bracket is at most five. For both tables, a column with "(D)" indicates centrality in the downstream channel (significance of the firm as a supplier), and "(U)" indicates centrality in the upstream channel (significance of the firm as a buyer). Tables 9, 10, 11, and 12 in the appendix show ticker symbols of the four firms with the largest centrality, for each of the five measures of centrality.

Table 5 confirms the overwhelming significance of IBM until 2010, in both the downstream and the upstream channels. Until 2010, IBM held the highest rank for each of the five measures of centrality.[12] MSFT, on the other hand, generally held the second highest rank until 2010. Such result coincides with the fact that IBM possessed the largest number of edges and that MSFT possessed the second largest number of edges (see table 3). From 2011, however, MSFT began to catch up with IBM, and the significance of MSFT in the supplier-buyer network finally surpassed IBM in 2014, in both the downstream and upstream channels.

Table 5: Frequency of Ranking (Centrality)

Year	**AAPL (D)**	**DELL (D)**	**IBM (D)**	**MSFT (D)**	**AAPL (U)**	**DELL (U)**	**IBM (U)**	**MSFT (U)**
2003	[0, 0, 0, 0]	[0, 1, 3, 0]	[5, 0, 0, 0]	[0, 4, 1, 0]	[0, 0, 0, 2]	[0, 1, 3, 0]	[5, 0, 0, 0]	[0, 4, 1, 0]
2004	[0, 0, 0, 1]	[0, 1, 3, 0]	[5, 0, 0, 0]	[0, 4, 1, 0]	[0, 0, 0, 2]	[0, 0, 4, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]
2005	[0, 0, 0, 1]	[0, 1, 4, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]	[0, 0, 0, 2]	[0, 0, 4, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]
2006	[0, 0, 0, 1]	[0, 0, 4, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]	[0, 0, 0, 2]	[0, 0, 4, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]
2007	[0, 0, 0, 1]	[0, 0, 2, 0]	[5, 0, 0, 0]	[0, 4, 0, 1]	[0, 0, 0, 2]	[0, 0, 3, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]
2008	[0, 0, 0, 1]	[0, 0, 4, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]	[0, 0, 0, 3]	[0, 0, 4, 0]	[4, 1, 0, 0]	[1, 4, 0, 0]
2009	[0, 0, 0, 0]	[0, 0, 4, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]	[0, 0, 0, 2]	[0, 0, 4, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]
2010	[0, 0, 0, 1]	[0, 0, 4, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]	[0, 0, 1, 1]	[0, 0, 3, 1]	[5, 0, 0, 0]	[0, 5, 0, 0]
2011	[0, 0, 0, 2]	[0, 0, 4, 0]	[3, 2, 0, 0]	[2, 3, 0, 0]	[0, 0, 1, 2]	[0, 0, 3, 1]	[3, 2, 0, 0]	[2, 3, 0, 0]
2012	[0, 0, 1, 2]	[0, 0, 3, 1]	[2, 3, 0, 0]	[3, 2, 0, 0]	[0, 0, 2, 0]	[0, 1, 1, 2]	[4, 0, 0, 1]	[1, 4, 0, 0]
2013	[0, 0, 1, 3]	[0, 1, 2, 1]	[3, 1, 1, 0]	[2, 3, 0, 0]	[1, 1, 2, 0]	[0, 1, 2, 1]	[3, 1, 0, 0]	[1, 2, 0, 2]
2014	[0, 1, 3, 0]	[0, 0, 1, 3]	[1, 3, 0, 1]	[4, 1, 0, 0]	[1, 1, 2, 0]	[0, 0, 1, 3]	[1, 2, 1, 0]	[3, 2, 0, 0]

This table reports centrality rankings of AAPL, DELL, IBM, and MSFT, for five measures of centrality: degree, Katz, PageRank, closeness, and betweenness. The numbers in each bracket indicate the number of times the firm took the $\left[1^{\text{st}}, 2^{\text{nd}}, 3^{\text{rd}}, 4^{\text{th}}\right]$ rank among the five measures of centrality. A column with "(D)" indicates centrality in the downstream channel (significance of the firm as a supplier), and "(U)" indicates centrality in the upstream channel (significance of the firm as a buyer).

Generally speaking, there is a strong correlation between centrality ranking and the number of edges possessed by the firm, as one would expect from degree centrality. In other words, a firm with a larger number of edges tends to possess a larger significance in the supplier-buyer network. However, in 2013, MSFT possessed more out-edges than IBM (see table 3, 2^{nd} and 3^{rd} columns); yet, IBM held the highest

[12] A single exception is the upstream channel in 2008. For this year, IBM held the highest rank among 4 measures of centrality.

rank among three out of the five measures of centrality in the downstream channel. It confirms that different measures of centrality capture different influence of a firm, and careful interpretation is necessary in evaluating the significance of a firm in the supplier-buyer network.

Table 6: Frequency of Rankings (Modular Centrality)

Year	**AAPL (D)**	**DELL (D)**	**IBM (D)**	**MSFT (D)**	**AAPL (U)**	**DELL (U)**	**IBM (U)**	**MSFT (U)**
2003	[0, 0, 0, 0]	[0, 0, 2, 1]	[5, 0, 0, 0]	[0, 5, 0, 0]	[0, 0, 0, 2]	[2, 2, 1, 0]	[3, 2, 0, 0]	[0, 1, 4, 0]
2004	[0, 0, 0, 0]	[0, 0, 4, 0]	[5, 0, 0, 0]	[0, 4, 0, 0]	[0, 0, 0, 2]	[0, 2, 2, 0]	[4, 1, 0, 0]	[1, 2, 2, 0]
2005	[0, 0, 0, 0]	[0, 0, 2, 1]	[5, 0, 0, 0]	[0, 3, 0, 0]	[0, 0, 0, 2]	[0, 2, 2, 0]	[4, 1, 0, 0]	[1, 2, 2, 0]
2006	[0, 0, 0, 0]	[0, 0, 3, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]	[0, 0, 0, 2]	[0, 2, 2, 0]	[5, 0, 0, 0]	[0, 3, 2, 0]
2007	[0, 0, 0, 1]	[0, 1, 3, 0]	[5, 0, 0, 0]	[0, 3, 1, 0]	[0, 0, 0, 2]	[0, 0, 4, 0]	[5, 0, 0, 0]	[0, 4, 0, 0]
2008	[0, 0, 0, 0]	[0, 1, 3, 0]	[5, 0, 0, 0]	[0, 3, 1, 0]	[0, 0, 0, 2]	[0, 0, 4, 0]	[5, 0, 0, 0]	[0, 5, 0, 0]
2009	[0, 0, 0, 0]	[1, 1, 2, 0]	[4, 1, 0, 0]	[0, 2, 2, 0]	[0, 0, 0, 2]	[1, 0, 4, 0]	[4, 0, 1, 0]	[0, 5, 0, 0]
2010	[0, 0, 0, 0]	[0, 0, 4, 0]	[4, 1, 0, 0]	[1, 3, 0, 0]	[0, 0, 0, 2]	[1, 1, 3, 0]	[4, 0, 1, 0]	[0, 4, 1, 0]
2011	[0, 0, 0, 0]	[1, 0, 3, 0]	[3, 2, 0, 0]	[1, 3, 1, 0]	[0, 0, 0, 2]	[0, 0, 3, 0]	[4, 1, 0, 0]	[1, 4, 0, 0]
2012	[0, 0, 1, 2]	[0, 1, 3, 0]	[1, 4, 0, 0]	[4, 0, 0, 1]	[0, 0, 1, 1]	[0, 1, 1, 1]	[2, 3, 0, 1]	[3, 1, 1, 0]
2013	[1, 0, 0, 3]	[0, 0, 4, 0]	[0, 5, 0, 0]	[4, 3, 0, 1]	[0, 1, 0, 0]	[1, 0, 2, 0]	[1, 4, 0, 0]	[3, 0, 1, 1]
2014	[1, 0, 2, 1]	[0, 1, 1, 2]	[1, 2, 2, 1]	[3, 1, 0, 1]	[0, 2, 0, 2]	[0, 1, 1, 1]	[3, 1, 0, 0]	[2, 1, 2, 0]

This table reports modular centrality rankings of AAPL, DELL, IBM, and MSFT, corresponding to five measures of centrality: degree, Katz, PageRank, closeness, and betweenness. The numbers in each bracket indicate the number of times the firm took the $\left[1^{\text{st}}, 2^{\text{nd}}, 3^{\text{rd}}, 4^{\text{th}}\right]$ rank among the five measures of centrality. A column with "(D)" indicates centrality in the downstream channel (significance of the firm as a supplier), and "(U)" indicates centrality in the upstream channel (significance of the firm as a buyer).

The results using modular centrality, as reported in table 6, are similar, but not the same. Recall that modular centrality distinguishes the significance of a firm in its own community (local component) and in other communities (global component). Moreover, it assigns weights to the local and global components depending on the overall intra- and inter-community linkages of the community a firm belongs to. The difference between standard centrality and modular centrality is most apparent if we compare the rankings of IBM and MSFT in the upstream channel in 2012 and 2013. Standard centrality (see table 5, 8^{th} and 9^{th} columns) suggests that IBM possessed a larger significance than MSFT in these years; however, modular centrality (see table 6, 8^{th} and 9^{th} columns) suggests otherwise. A possible explanation for such difference is that the community of IBM possessed a large fraction of intra-community edges (see table 2, 4^{th}, 6^{th}, and 8^{th} columns) and that IBM possessed a stronger significance in other communities than on its own. In other words, in 2012 and 2013, an economic shock to the community of IBM was likely to have a stronger effect on the community members than on others. Because IBM possessed a larger significance on other communities than on its own, the overall significance of IBM under the economic shock was smaller than what standard centrality indicates.

5 Concluding Remarks

Using supplier-buyer networks of U.S. tech firms from 2003 to 2014, this article identifies four distinct ecosystems, each led by AAPL, DELL, IBM, and MSFT. Each ecosystem exhibits exclusivity, as the supplier-buyer transactions within an ecosystem is far greater than across ecosystems. Moreover, there has been remarkable growth in AAPL and MSFT's ecosystem and their significance in the supplier-buyer network. These results were obtained by utilizing community detection method and various centrality measures.

These results can be used to evaluate how an economic shock to a large tech firm can propagate to its ecosystem and also to the entire supplier-buyer network of tech firms. However, a shock not only affects other firms via its ecosystem but also can alter the ecosystem. To better understand the propagation of shocks via the supplier-buyer network, it is necessary to develop an econometric model that describes the formation of ecosystems. I leave it for future research.

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Appendix

Table 7: Community-Based Density (Largest Four Communities)

Year	**Intra-Density**	**Inter-Density (Out)**	**Inter-Density (In)**
2003	[0.066, 0.077, 0.181, 0.581]	[0.006, 0.002, 0.004, 0.003]	[0.004, 0.009, 0.003, 0.002]
2004	[0.069, 0.118, 0.147, 0.603]	[0.005, 0.002, 0.003, 0.003]	[0.002, 0.005, 0.004, 0.002]
2005	[0.092, 0.110, 0.221, 0.581]	[0.005, 0.001, 0.002, 0.003]	[0.002, 0.006, 0.003, 0.001]
2006	[0.092, 0.099, 0.176, 0.559]	[0.002, 0.005, 0.003, 0.002]	[0.006, 0.002, 0.003, 0.002]
2007	[0.085, 0.110, 0.147, 0.507]	[0.003, 0.003, 0.003, 0.002]	[0.003, 0.004, 0.003, 0.002]
2008	[0.081, 0.114, 0.188, 0.496]	[0.003, 0.003, 0.002, 0.002]	[0.002, 0.004, 0.003, 0.002]
2009	[0.077, 0.096, 0.188, 0.460]	[0.003, 0.003, 0.002, 0.002]	[0.002, 0.005, 0.003, 0.002]
2010	[0.103, 0.147, 0.232, 0.460]	[0.002, 0.003, 0.002, 0.002]	[0.005, 0.002, 0.003, 0.002]
2011	[0.136, 0.176, 0.257, 0.515]	[0.002, 0.004, 0.002, 0.002]	[0.003, 0.002, 0.003, 0.002]
2012	[0.199, 0.202, 0.298, 0.474]	[0.002, 0.002, 0.002, 0.002]	[0.003, 0.002, 0.002, 0.001]
2013	[0.232, 0.283, 0.268, 0.449]	[0.001, 0.002, 0.002, 0.002]	[0.003, 0.002, 0.002, 0.001]
2014	[0.228, 0.265, 0.290, 0.537]	[0.002, 0.002, 0.002, 0.001]	[0.002, 0.002, 0.001, 0.002]

This table reports density measures accompanying table 2. The numbers in each bracket correspond to the $\left[4^{\text{th}}, 3^{\text{rd}}, 2^{\text{nd}}, 1^{\text{st}}\right]$ largest communities. The second column reports the density measure accompanying the fourth column of table 2 ("#Intra-Edges"). The third and fourth columns report the density measures accompanying the fifth and sixth columns of table 2 ("#Inter-Edges (Out)" and "#Inter-Edges (In)"), respectively. Each density mesure is obtained by dividing the number of edges by the appropriate number of possible edges. The density measures confirm that linkage within each community is far stronger than linkage across communities.

Table 8: NAICS Codes Definition

NAICS Code	Definition	Examples (from Network)
32521	Resin and Synthetic Rubber Manufacturing	DuPont, Eastman Chemical
33411	Computer and Peripheral Equipment Manufacturing	Broadcom, Sandisk, Western Digital
33441	Semiconductor and Other Electronic Component Manufacturing	AMD, Micron, Nvidia
42343	Computer and Computer Peripheral Equipment and Software Merchant Wholesalers	CDW, Ingram Micro, Tech Data
51121	Software Publishers	Electronic Arts, Red Hat, Salesforce,
51913	Internet Publishing and Broadcasting and Web Search Portals	AOL, Chegg, Twitter
53112	Lessors of Nonresidential Buildings	Digital Realty, Lexington Realty, Rexford Realty
54151	Computer Systems Design and Related Services	FalconStor, Teradata, Unisys
56149	Other Business Support Services	Startek, Convergys, West Corp

This table is a dictionary for the NAICS codes that appear in table 4. The first column lists the NAICS codes, and the second column contains the definitions. The third column provides exmaples of firms in the supplier-buyer network that correspond to the NAICS code.

Table 9: Top 4 Ranking by Centrality (Downstream)

Year	Degree	Katz	PageRank	Closeness	Betweenness
2003	[IBM, MSFT, DELL, INVE]	[IBM, MSFT, NVDA, AKAM]	[IBM, MSFT, DELL, SOFO]	[IBM, DELL, MSFT, PLUS]	[IBM, MSFT, DELL, XLNX]
2004	[IBM, MSFT, DELL, SOFO]	[IBM, MSFT, ON, NVDA]	[IBM, MSFT, DELL, SOFO]	[IBM, DELL, MSFT, AAPL]	[IBM, MSFT, DELL, XLNX]
2005	[IBM, MSFT, DELL, ZIGO]	[IBM, MSFT, ELX, ON]	[IBM, MSFT, DELL, ZIGO]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, XLNX]
2006	[IBM, MSFT, DELL, VRSN]	[IBM, MSFT, INTC, ON]	[IBM, MSFT, DELL, AMKR]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, ORCL]
2007	[IBM, MSFT, DELL, SOFO]	[IBM, TTGT, SMTC, MSFT]	[IBM, MSFT, SOFO, PLCM]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, PLCM, SOFO]
2008	[IBM, MSFT, DELL, SOFO]	[IBM, MSFT, ATML, TTGT]	[IBM, MSFT, DELL, SOFO]	[IBM, MSFT, DELL, TECD]	[IBM, MSFT, DELL, AAPL]
2009	[IBM, MSFT, DELL, SOFO]	[IBM, MSFT, ATML, IRF]	[IBM, MSFT, DELL, SOFO]	[IBM, MSFT, DELL, TECD]	[IBM, MSFT, DELL, SOFO]
2010	[IBM, MSFT, DELL, SOFO]	[IBM, MSFT, ATML, TTGT]	[IBM, MSFT, DELL, SOFO]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, SOFO]
2011	[IBM, MSFT, DELL, ZIGO]	[IBM, MSFT, ATML, STX]	[IBM, MSFT, DELL, ZIGO]	[MSFT, IBM, DELL, AAPL]	[MSFT, IBM, DELL, AAPL]
2012	[MSFT, IBM, DELL, AAPL]	[MSFT, IBM, NXPI, AMD]	[MSFT, IBM, DELL, AAPL]	[IBM, MSFT, AAPL, DELL]	[IBM, MSFT, DELL, RCMT]
2013	[MSFT, IBM, DELL, AAPL]	[IBM, MSFT, NVDA, AMD]	[IBM, MSFT, DELL, AAPL]	[MSFT, DELL, IBM, AAPL]	[IBM, MSFT, AAPL, DELL]
2014	[MSFT, IBM, AAPL, DELL]	[IBM, MSFT, MU, CHKP]	[MSFT, IBM, AAPL, DELL]	[MSFT, AAPL, DELL, IBM]	[MSFT, IBM, AAPL, DELL]

This table reports ticker symbols of the four firms with the largest degree, Katz, PageRank, closeness, and betweenness centrality in the downstream channel (significance as a supplier). The first column lists the years. The entries in each bracket indicate the ticker symbol of the firm with the $\left[1^{\text{st}}, 2^{\text{nd}}, 3^{\text{rd}}, 4^{\text{th}}\right]$ largest centrality.

Table 10: Top 4 Ranking by Centrality (Upstream)

Year	Degree	Katz	PageRank	Closeness	Between.
2003	[IBM, DELL, MSFT, AAPL]	[IBM, MSFT, DELL, PLUS]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, MECK, DNB]	[IBM, MSFT, DELL, XLNX]
2004	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, UIS]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, XLNX]
2005	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, PLUS]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, ATML, STX]	[IBM, MSFT, DELL, XLNX]
2006	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, PLUS]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, ATML, ON]	[IBM, MSFT, DELL, ORCL]
2007	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, MCRS]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, TTFT, ATML]	[IBM, MSFT, PLCM, SOFO]
2008	[IBM, MSFT, DELL, AAPL]	[MSFT, IBM, DELL, MSCR]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, TTGT, ATML]	[IBM, MSFT, DELL, AAPL]
2009	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, MCRS]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, ATML, TTGT]	[IBM, MSFT, DELL, SOFO]
2010	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, PLUS]	[IBM, MSFT, AAPL, DELL]	[IBM, MSFT, ATML, TTGT]	[IBM, MSFT, DELL, SOFO]
2011	[IBM, MSFT, DELL, AAPL]	[MSFT, IBM, DELL, PLUS]	[IBM, MSFT, AAPL, DELL]	[IBM, MSFT, ATML, STX]	[MSFT, IBM, DELL, AAPL]
2012	[IBM, MSFT, AAPL, DELL]	[MSFT, DELL, TECD, IBM]	[IBM, MSFT, AAPL, DELL]	[IBM, MSFT, NXPI, NVDA]	[IBM, MSFT, DELL, RCMT]
2013	[IBM, AAPL, DELL, MSFT]	[MSFT, DELL, AAPL, PLUS]	[AAPL, IBM, DELL, MSFT]	[IBM, MSFT, NVDA, AMD]	[IBM, MSFT, AAPL, DELL]
2014	[MSFT, IBM, AAPL, DELL]	[MSFT, AAPL, DELL, PLUS]	[AAPL, MSFT, IBM, DELL]	[IBM, MSFT, MRVL, GUID]	[MSFT, IBM, AAPL, DELL]

This table reports ticker symbols of the four firms with the largest degree, Katz, PageRank, closeness, and betweenness centrality in the upstream channel (significance as a buyer). The first column lists the years. The entries in each bracket indicate the ticker symbol of the firm with the $\left[1^{\text{st}}, 2^{\text{nd}}, 3^{\text{rd}}, 4^{\text{th}}\right]$ largest centrality.

Table 11: Top 4 Ranking by Modular Centrality (Downstream)

Year	Degree	Katz	PageRank	Closeness	Between.
2003	[IBM, MSFT, DELL, SOFO]	[IBM, MSFT, NVDA, SIGM]	[IBM, MSFT, DELL, SOFO]	[IBM, MSFT, PLUS, ANSS]	[IBM, MSFT, XLNX, DELL]
2004	[IBM, MSFT, DELL, ZIGO]	[IBM, NVDA, ON, EQIX]	[IBM, MSFT, DELL, ZIGO]	[IBM, MSFT, DELL, ANSS]	[IBM, MSFT, DELL, XLNX]
2005	[IBM, MSFT, DELL, NVDA]	[IBM, SMTC, NVDA, ELX]	[IBM, MSFT, DELL, ATML]	[IBM, XLNX, PLXT, SPRT]	[IBM, MSFT, XLNX, DELL]
2006	[IBM, MSFT, DELL, INTC]	[IBM, MSFT, INTC, SMTC]	[IBM, MSFT, DELL, VRSN]	[IBM, MSFT, JKHY, ANSS]	[IBM, MSFT, DELL, VRSN]
2007	[IBM, MSFT, DELL, SOFO]	[IBM, ATML, SMTC, AKAM]	[IBM, MSFT, DELL, SOFO]	[IBM, DELL, MSFT, CTCT]	[IBM, MSFT, DELL, AAPL]
2008	[IBM, MSFT, DELL, SOFO]	[MSFT, ATML, IRF, SMTC]	[IBM, MSFT, DELL, SOFO]	[IBM, DELL, MSFT, SNX]	[IBM, MSFT, DELL, AVT]
2009	[IBM, MSFT, DELL, SOFO]	[IBM, ATML, IRF, TTGT]	[IBM, MFST, DELL, SOFO]	[IBM, DELL, MSFT, PFSW]	[DELL, IBM, MSFT, SOFO]
2010	[IBM, MSFT, DELL, SOFO]	[IBM, ATML, TTGT, IRF]	[IBM, MSFT, DELL, SOFO]	[IBM, MSFT, DELL, NSIT]	[MSFT, IBM, DELL, SOFO]
2011	[IBM, MSFT, DELL, ZIGO]	[IBM, MSFT, AMD, DAEG]	[IBM, MSFT, DELL, ZIGO]	[DELL, IBM, MSFT, CSPI]	[MSFT, IBM, DELL, CTXS]
2012	[MSFT, IBM, DELL, AAPL]	[MSFT, IBM, NXPI, RCMT]	[MSFT, IBM, DELL, AAPL]	[IBM, DELL, AAPL, MSFT]	[MSFT, IBM, DELL, RCMT]
2013	[MSFT, IBM, DELL, AAPL]	[MSFT, IBM, RCMT, STX]	[MSFT, IBM, DELL, AAPL]	[AAPL, IBM, DELL, MSFT]	[MSFT, IBM, DELL, AAPL]
2014	[MSFT, IBM, AAPL, DELL]	[MSFT, NVDA, IBM, SCOR]	[MSFT, IBM, AAPL, DELL]	[AAPL, DELL, IBM, MSFT]	[IBM, MSFT, DELL, AAPL]

This table reports ticker symbols of the four firms with the largest modular centrality corresponding to degree, Katz, PageRank, closeness, and betweenness centrality in the downstream channel (significance as a supplier). The first column lists the years. The entries in each bracket indicate the ticker symbol of the firm with the $[1^{\text{st}}, 2^{\text{nd}}, 3^{\text{rd}}, 4^{\text{th}}]$ largest modular centrality.

Table 12: Top 4 Ranking by Modular Centrality (Upstream)

Year	Degree	Katz	PageRank	Closeness	Betweenness
2003	[DELL, IBM, MSFT, AAPL]	[IBM, DELL, MSFT, PLUS]	[IBM, DELL, MSFT, AAPL]	[IBM, MSFT, DELL, WDC]	[DELL, IBM, MSFT, XLNX]
2004	[IBM, DELL, MSFT, AAPL]	[IBM, DELL, MSFT, IM]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, WDC, INTC]	[MSFT, IBM, DELL, IM]
2005	[IBM, DELL, DMSFT, AAPL]	[IBM, DELL, MSFT, MCRS]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, FFIV, ORCL]	[MSFT, IBM, DELL, XLNX]
2006	[IBM, DELL, MSFT, AAPL]	[IBM, DELL, MSFT, MANH]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, ELX, FLWS]	[IBM, MSFT, DELL, ORCL]
2007	[IBM, MSFT, DELL, AAPL]	[IBM, BA, DELL, JKHY]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, FLWS, LIOX]	[IBM, MSFT, DELL, INTC]
2008	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, SNX]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, ATTU, LIOX]	[IBM, MSFT, DELL, SPRT]
2009	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, MCRS]	[IBM, MSFT, DELL, MCRS]	[IBM, MSFT, DELL, APPL]	[DELL, MSFT, IBM, AVT]
2010	[IBM, DELL, MSFT, AAPL]	[IBM, MSFT, DELL, PLUS]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, DELL, ACTG]	[DELL, MSFT, IBM, SOFO]
2011	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, SNX, PLUS]	[IBM, MSFT, DELL, AAPL]	[IBM, MSFT, AMD, EDGW]	[MSFT, IBM, DELL, CTXS]
2012	[IBM, DELL, MSFT, AAPL]	[MSFT, IBM, SNX, TECD]	[IBM, MSFT, AAPL, DELL]	[MSFT, IBM, ACTG, MG]	[MSFT, IBM, DELL, RCMT]
2013	[DELL, IBM, MSFT, AAPL]	[MSFT, IBM, TECD, PLUS]	[IBM, AAPL, DELL, MSFT]	[MSFT, IBM, ORCL, RPXC]	[MSFT, IBM, DELL, AAPL]
2014	[IBM, DELL, MSFT, AAPL]	[MSFT, AAPL, PLUS, TECD]	[IBM, AAPL, MSFT, DELL]	[MSFT, IBM, NVDA, PLCM]	[IBM, MSFT, DELL, AAPL]

This table reports ticker symbols of the four firms with the largest modular centrality corresponding to degree, Katz, PageRank, closeness, and betweenness centrality in the upstream channel (significance as a buyer). The first column lists the years. The entries in each bracket indicate the ticker symbol of the firm with the $\left[1^{\text{st}}, 2^{\text{nd}}, 3^{\text{rd}}, 4^{\text{th}}\right]$ largest modular centrality.