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Using a Systems Lens and Transaction Data to Visualize the Architecture of the Economy

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Abstract

We provide visualizations of the architecture of the economy that are informed by theory, empirically based, and meaningful at multiple levels of analysis. The systems-based view of industry architecture disaggregates the economy into demand-based vertical sectors in which firms collaborate and compete to collectively satisfy a set of similar demands. Within vertical sectors, inter-industry relations are hierarchically structured with firms in customer service industries depending on firms in upstream industries that perform a range of wholesale, manufacturing, supplier, and complementary roles. Our visualizations incorporate data on over 53,000 of the largest inter-firm transactions in the US economy between 1976 and 2010. They show the value of transactions within and between vertical sectors and sector roles and thereby enable an accessible, yet richly informed understanding of the nature of inter-industry relations that comprise the architecture of the economy.

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Over recent decades, social, economic, and technological forces have combined to produce a global economy that is highly interdependent. Global value chains now account for some 80 percent of global trade, about 60 percent of which consists of trade in intermediate goods and services (UNCTAD, 2013). Other characterizations of the higher order aggregates in which firms innovate and compete include industry architectures (Baldwin & Clark, 2000; Jacobides, Knudsen & Augier, 2006), sectoral systems of innovation and production (Malerba, 2002), alliance networks (Schilling & Phelps, 2007), and ecosystems (Iansiti & Levien, 2007). Researchers examining the antecedents of industry architectures have found that they are shaped by technological exigencies (Luo, Baldwin, Whitney & McGee, 2012), institutional factors (Cacciatori & Jacobides, 2005), and the strategic behaviours of firms (Ferraro & Gurses, 2009; Fixson & Park, 2008; Jacobides, 2005; Jacobides & MacDuffie, 2013).

The impacts of interdependence are significant. At the jurisdictional level, global value chains have significant impacts on development, trade, the environment, and innovation (UNCTAD, 2013). At the firm level, researchers have found that survival and performance are affected by the behaviours of firms that perform complementary upstream or downstream roles. For example, upstream carburetor and clutch suppliers can increase their chances of survival by selling to multiple downstream system integrators or by aligning themselves with prestigious system integrators (Hoetker, Swaminathan & Mitchell, 2007), the survival rates of downstream laser printer manufacturers is influenced by the population density of upstream laser printer engine manufacturers (de Figueiredo & Silverman, 2011), and the profitability of computer manufacturers depends on the configuration of the value chain (Dedrick, Kraemer & Linden, 2010).

Complementarity is fundamental to interdependence. But information on the inter-firm complementarities that lead to upstream-downstream relationships and global value chains is absent from government economic data. Policy makers concerned about the impact of global value chains lament the data limitations (Boileau & Sydor, 2011; UNCTAD, 2013) and researchers, including the authors of all of the above-cited studies use proprietary datasets, rather than government data, to examine the impact of firms in neighbouring industries. We believe the problem is conceptual. Government economic data classifies industries in a manner that does not reflect industry structure (Census Bureau, 1991), despite this being a guiding principle of their design (SIC, 1957). Input-output tables, designed in part to depict industry structure, do not solve the problem because they employ similar industry classification schemes, exacerbated by the use of broad classes (Drejer, 2002; Hirschman, 1958).

We describe the systems-based view of industry architecture and use the systems lens to provide simple, high-level visualizations of the architecture of the economy. The systems-based approach employs the principle of similarity to divide the economy into demand-based vertical sectors, and the principle of complementarity to divide vertical sectors into a common, hierarchically structured set of sector roles (Dalziel, 2007; Hicks, 2011). Simon wrote that "it is a familiar proposition that the task of science is to make use of the world's redundancy to describe that world simply" (1962: 479). Researchers have thus far been unable to describe the economy simply, because there has not been a theoretical basis for eliminating the redundancy. The common set of sector roles is the redundant feature that allows us to describe the economy simply.

For 80 years or more economists have used transaction data in their investigations of the structure of the economy (Leontief, 1936). Our visualizations are supported by a novel dataset of over 53,000 of the most important interfirm transactions in the US economy between 1976 and 2010. We use matrix diagrams to visualize transactions within and between sectors and roles, and chord diagrams to visualize transaction flows within and between roles within vertical sectors. The data relies on the fact that the US Securities and Exchange Commission (SEC) requires firms (including foreign firms) that are publicly traded in the US to report the percentage of their revenues that is attributable to sales to a specific customer, in cases where those sales exceed 10% of total revenues. Similar data has been used to support research in finance (Cohen & Frazzini, 2008; Hertzel, Li, Officer & Rodgers, 2008), and to describe business ecosystems (Basole, 2009) and industry structure (Kamehama et al., 2010). But because the systems-based approach carves the economy 'at the joints' our depictions of industry structure are more easily interpreted than those based on conventional industry classification systems (Kamehama et al., 2010).

In the next section we introduce the systems approach to understanding inter-industry relations and contrast it with other approaches to understanding the economy. We then illustrate the systems-based approach by showing how the 20 2-digit NAICS (North American Industry Classification) sectors map to their systems-based counterparts. The section that follows describes our transactions data and its coverage of the US economy. We then provide visualizations of the structure of the US economy, first at the level of sectors, then at the level of roles, and finally at the level of within-sector relationships between roles for the four sectors best represented in our dataset: Transportation, Information and Communications Technologies (ICT), Health, and Energy. We conclude with a discussion of the contributions and limitations of our work.

THE SYSTEMS LENS

The systems-based approach to understanding the architecture of the economy (Dalziel, 2007) follows from Simon's analysis of complex systems. Simon (1962) observed that complex systems are partially decomposable and hierarchically structured, and that these properties allow us to abstract from the complexity of systems that is observable at the micro level, to create macro level descriptions of their structure (Ethiraj & Levinthal, 2004; Schilling, 2003). According to the systems-based approach, the economy is partially decomposable into vertical sectors, where the relations between industries within the same vertical sector are more prevalent and stronger than the relations between industries in different vertical sectors. Vertical sectors are comprised of firms that engage in a range of extraction, manufacturing, and service provision activities to collectively address a set of similar individual and organizational needs (e.g. needs for food, energy, transportation, health care) (Malerba, 2002).

On the basis of firm activities and their complementarities, a set of sector roles is identified. These sector roles recur across vertical sectors and are hierarchically structured, with firms in industries that provide services (including retailing services) to final user customers depending on firms in multiple upstream industries that perform a complementary set of wholesale, manufacturing, and supplier roles. The systems-based approach is essentially a two-dimensional approach to classifying industries both by the demand to which they respond, and their role, or, equivalently, the nature of the activity performed.

As is common in economics, we consider inter-industry, rather than inter-firm, relations. As industries are groups of similar firms, in principle this results in no loss of generality. The high-level patterns in inter-industry relations that we describe have arisen organically as a consequence of material constraints and the way firms self-organize to produce goods and services efficiently. We believe these emergent patterns will persist despite changes in technology, the strategic behaviours of firms, the appearance and disappearance of specific organizations, and differences in business environments across regions and nations. In the following we describe how the systems-based approach compares to other well-established approaches for understanding inter-industry relations.

Comparisons of Descriptions of the Economy

Contrasting the material and demand-based views. The simplest approach to understanding and measuring economic activities is based on the division of the economy into primary, secondary, and tertiary sectors. This division of the economy into broad, activity-based sectors exemplifies the material-based view of the economy, which remains integral to all standard industry classification systems used today. According to the material view, the key to understanding the structure of the economy is to trace the flow of materials through extraction, manufacturing, distribution, and sales activities. While this perspective was highly effective in describing the economy in earlier times, and was useful in understanding the transformation of economies from agrarian to manufacturing-based, and from manufacturing-based to service-based (Kenessey, 1987), it is not helpful for understanding the now significant portion of the economy that responds to demands for intangible goods such as knowledge, entertainment, and education.

In contrast, by identifying vertical sectors that address related sets of demands, the systems-based approach uses demand as the primary segmentation criterion. As fundamental demands persist across changes in technology, understood broadly as the means by which work is done, the systems view is less sensitive to technological change than the material view. Also, a top-level demand-based segmentation will better accommodate firms that are vertically integrated than will a top-level activity-based segmentation. So it is unfortunate that the first version of a standard industry classification system began by distinguishing between manufacturing and non-manufacturing activities (Pearce, 1957), a distinction that persists despite research that has shown it to be of diminishing utility (Christensen, 2013; Leiponen & Drejer, 2007).

Similarity versus complementarity in industry classification. In describing the effect of firm capabilities on the organization of industry, Richardson (1972) observed that similarity is the criterion for determining the set of activities that firms perform internally, while complementarity is the criterion for identifying the external partners with which a firm engages. A century ago, when firms performed most activities internally and inter-firm relationships were few, similarity was a useful criterion for understanding inter-industry relationships. Industries were grouped together into sectors such as manufacturing, wholesale and retail trade, and services on the basis of similarities in activities. Only in later years, as services came to account for a greater proportion of the economy, was the service sector disaggregated into the health care, education, professional services, and the arts, entertainment and recreation sectors. This resulted in industry classification systems where, in principle, sectors were identified on the basis of similarity in activities, but where in practice some sectors were identified on the basis of similarity in activities performed, while other sectors were identified on the basis of similarity in the nature of the set of demands being fulfilled.

As a consequence of dissatisfaction with standard industry classification systems (Bryce & Winter, 2009; Burt, 1998; Christensen, 2013; Griliches, 1994; Graham, 2007; McGahan & Porter, 1997), several researchers have devised alternative approaches to provide more meaningful classifications of the firms in the economy. Burt (1998) uses social network analysis to identify empirically valid industries, while other researchers have constructed inter-industry relatedness indices based on the frequency with which pairs of industries appear jointly in firm portfolios (Teece, Rumelt, Dosi, Winter, 1994), technological relatedness as measured by the t relatedness of products produced by different plants in Sweden (Neffke & Henning, 2013), or the joint industry participation decisions of US manufacturing firms (Bryce & Winter, 2009).

But Burt is silent on how the industries he identifies relate to one another, and his partitioning is not hierarchical and so is meaningful only at the level of industries, not at higher-level aggregates such as sectors. Furthermore, all of the studies that consider inter-industry relatedness employ similarity in firm activities as their relatedness criterion. As a result, they capture the *similarities* between, for example, food and pharmaceutical manufacturers, but miss important *complementarities* between agricultural firms and food manufacturers, and between pharmaceutical manufacturers and pharmacies.

Input-output tables. Input-output (I-O) tables are large, two-dimensional matrices that show, for each industry in an economy, the value of its inputs and outputs by source and destination. Excluding taxes and subsidies, possible input sources include domestic firms that produce intermediate products and services, and imports. Possible output destinations include domestic firms that purchase intermediate products and services, private households and governments that consume final products and services, investment, and exports. For the last several decades, economists have used I-O tables to gauge the strength of inter-industry relations and to estimate the effect of changes in demand, supply, or investment in one industry on other industries in the regional, national, or international economy under consideration (Leontief, 1966; Bureau of Economic Analysis, 2009).

Both I-O tables and the systems-based view of industry architecture employ knowledge of inter-industry transactions to depict the structure of the economy. The difference is that I-O tables are constructed empirically, whereas the systems-based approach is theoretically based. At the lowest level of analysis, the level of industries, there is no conceptual difference between the two approaches. The difference is in the choice of aggregations that are necessary to create higher level tables. I-O tables follow the material-based conventions of standard industry classification systems that group industries together into higher order aggregates on the basis of similarity in activities performed. For example, the most recent US Bureau of Economic Analysis I-O tables group all wholesalers together, even in relatively large tables with 389 industries (Bureau of Economic Analysis, 2007). Such groupings obscure industry structure because aggregates will contain entities that are unlikely to transact, and so transactions between aggregates are likely to exceed transactions within aggregates (Hirschman, 1958; Jones, 1976). The result is that I-O linkage measures no longer provide meaningful indications of inter-sectoral relations (Drejer, 2002). Also, input-output tables are now created infrequently; the OECD last published input-output tables in 2005 (OECD, 2012). The systems-based approach, in contrast, groups industries into sectors and roles according to theorized inter-industry relationships. If industry classification systems were designed using the systems-based approach, they would inherently reflect industry structure.

We now state formally the two propositions, stated informally at the beginning of this section, that are fundamental to the ability of the systems approach to describe the economy simply.

Proposition 1: The architecture of the economy, as manifested by inter-industry transactions, is best revealed by disaggregating it, insofar as possible, into demand-based vertical sectors. Each vertical sector will be less complex than the economy as whole because transactions between vertical sectors will be fewer than transactions within sectors.

Proposition 2: Within vertical sectors, industries can be classified into a recurring set of hierarchically structured roles where firms in industries that perform downstream roles depend on firms in industries that perform upstream roles for input products and services.

MAPPING NAICS INDUSTRIES TO VERTICAL SECTORS AND SECTOR ROLES

In the following we provide specifics on how the systems-based approach segments the economy, and map NAICS industries to systems-based sectors and sector roles. We begin by identifying 11 systems-based vertical sectors associated with fundamental human and organizational needs (Food; Clothing; Durable Goods; Energy; Buildings and Infrastructure; Transportation; and Information and Communications Technology (ICT), Health; Entertainment; Finance; and Education) and two residual sectors, the Horizontal Industries sector, which is comprised of industries that serve general needs and so could not be assigned to specific vertical sectors, and the Public Administration sector, which comprises primarily non-profit and government organizations.

Each of the 13 vertical sectors is then divided into the same five subsectors defined on the basis of sector role. The customer service provider role includes retailers and other firms that provide services to the sector's final user customers. The manufacturer role, more fully manufacturers and system integrators, includes firms that are responsible for the production of final products, either physical or intangible, that are used by final user customers. The parts and materials supplier role, more fully parts, materials, and component suppliers, includes firms that produce physical or intangible outputs that are used in the creation of final products, and the complementary supplier role includes firms that offer tools, equipment, or services that are used in the production of the goods and services produced by the sector, but that are not consumed by the sector's final user customer. The wholesaler role, like the complementary supplier role, is a complementary role, while firms that perform the customer service provider, manufacturer, and parts and materials supplier roles provide goods or services that are used by the sector's final user customers, and so these are considered central roles (Dalziel, 2007). The manufacturer and parts and materials supplier roles are more meaningful in sectors that include manufacturing (Health) or content production (Entertainment) subsectors, and less meaningful in sectors that do not (e.g. Finance, Education).

NAICS organizes industries into 20 2-digit sectors, 91 3-digit subsectors, and 313 4-digit industry groups (NAICS, 2012). Table 1, below, provides a high-level mapping of the 20 2-digit NAICS sectors to systems-based sectors and roles. Appendix A provides a complete mapping of 4-digit NAICS industries to systems-based sectors and roles. By classifying the 313 4-digit NAICS industries, rather than the approximately 10,000 firms in our dataset, we increase the efficiency and transparency of our classification and provide a concordance table that other researchers may wish to use.

The first row of Table 1 shows the six NAICS sectors that are activity based. The first three sectors (Retail Trade, Wholesale Trade, and Manufacturing) map to their respective systems-based roles, and the other three sectors (Agriculture, Forestry, Fishing and Hunting; Mining, Quarrying, and Oil and Gas Extraction; and Utilities) provide commodities and map to the systems-based parts and material suppliers role.

The first column of Table 1 shows the four NAICS sectors that are demand-based (Health; Arts, Entertainment, and Recreation; Finance; Education), and the two residual NAICS sectors (Other Services (except Public Administration); and Public Administration). These map to their respective systems-based sectors. Another five NAICS sectors (Construction; Information; Real Estate and Rental and Leasing; Transportation and Warehousing; and Accommodation and Food Services) map to roles within specific demand-based sectors based both on the nature the demands to which the sector's firms respond, and the activities they perform. Finally, there are three NAICS sectors that provide general services across the economy (Professional, Scientific, and Technical Services; Management of Companies and Enterprises; Administrative and Support and Waste Management and Remediation Services) and that map to the customer service provider role within the Horizontal Industries sector.

We encountered the following issues in classifying the 313 NAICS 4-digit industries into vertical sectors and sector roles. In cases where the industry spanned multiple sectors, we classified it into the Horizontal Industries sector. In cases where it spanned multiple roles, as does the Electric Power Generation, Transmission and Distribution industry, we classified it according to the dominant role on the basis of contributions to GDP (materials supplier). There were also cases where in theory the demand is general (rubber), but in practice it is specific (tires). As our approach is theory-based, we favored the theoretical classification (materials supplier in the Horizontal Sector, rather than the Transportation sector). For consistency and simplicity of exposition, we have identified vertical sectors on the basis of general sets of demands (e.g. transportation, energy), an alternative approach would have been to identify more specific demands (e.g. road, rail, air, and water transportation). We have similarly constrained ourselves to a limited set of roles, although there are cases where more specific roles would be helpful. Finally, sometimes the classification works well but yields unconventional results. For example, artists are classified as component suppliers and broadcasters as system integrators.

TRANSACTIONS DATA

We have assembled a unique dataset of over 53,000 major inter-firm transactions that took place between 1976 and 2010, and that have a total value of over $6 trillion. The data relies on the fact that the US Securities and Exchange Commission (SEC) requires firms (including foreign firms) that are publicly traded in the US to report the percentage of their revenues that is attributable to sales to a specific customer, in cases where those sales exceed 10% of total revenues. For example, Cardinal Health reported that in 2009 CVS Caremark and Walgreens accounted for 21% and 23% of revenues, respectively. As Cardinal Health’s 2009 revenues were $99.6 billion, its sales to its major customers are amongst the most significant transactions in the economy. We prepared the raw data for analysis by: 1) removing observations where the customer was a geographic region, a product market, or a government; 2) iteratively applying a string-matching algorithm to firm names to ensure, for example, that Ford International, Ford

Motors, and FMC were identified as the same firm throughout the dataset; and 3) identifying missing NAICS codes.

Transactions Data by Sector

Figure 1 shows the total value of transactions in the dataset, over the 35 year time period, by the sector of the selling and buyer firms***(color). Only 12 vertical sectors are shown because transactions involving non-firm organizations (government and non-profit organizations) were eliminated from the dataset and so the Public Administration sector is not represented. By the value of sales, 90 percent of the transactions in the dataset are in the Transportation (26%), ICT (26%), Health (16%), Energy (13%), and Horizontal Industries sectors (10%). The same five sectors are strongly represented by buying firm. These five sectors are strongly represented in part because they are large. When 2012 US Value-Added GDP is segmented by systems-based vertical sector, these five sectors account for approximately 55 percent of GDP. Another reason for the prominence of these five sectors is that, in the case of the Transportation, ICT, and Horizontal Industries sectors, they produce complex products that are comprised of intermediate products, making the number of within sector transactions high, relative to GDP. A third possible explanation for the prominence of these five sectors is the degree of industry concentration. Sectors with a small number of large firms will be disproportionally represented in this dataset relative to industries with a large number of small firms.

Insert Figure 1 about here

Figure 2 shows the total value of transactions in the dataset as a proportion of total value-added GDP by sector. The variability across sectors in Figure 2 is high because the numerator is a subset of transactions (only those that account for more than 10 percent of the revenues of publicly-traded firms), while the denominator is the total value added by all organizations (between 2003 and 2012, inclusive). For example, the clothing sector is disproportionately strongly represented because the value of transactions relative to value-added GDP is high. This is likely because with the offshoring of garment and textile manufacturing, value-added GDP is low, but with high levels of sector concentration, transactions between firms responsible for clothing manufacturing and retail firms is high. Figure 2 shows that as a proportion of GDP, the sectors that are most strongly represented in the dataset are the Clothing (749%), Transportation (203%), ICT (141%), Energy (123%), and Health (100%) sectors.

Insert Figure 2 about here

Transactions Data by Role

Figure 3 shows the total value of transactions by sector role. By seller, the manufacturer and parts and materials supplier roles are most strongly represented, while by buyer the manufacturer and customer service provider roles are most strongly represented. This asymmetry between the most prominent seller and buyer roles is consistent the proposition that sector roles are hierarchically structured with firms in upstream roles selling to firms in downstream roles.

Insert Figure 3 about here

Figure 4 shows total transaction value divided by total value-added GDP (2003-2012), by role. As a proportion of value-added GDP, Figure 5 shows that the seller roles most strongly represented in the dataset are the parts and material supplier and the complementor roles, while the buyer roles most strongly represented are the manufacturer and complementor roles. Again, the asymmetry between the most prominent seller and buyer roles is consistent with the proposition that sector roles are hierarchically structured with firms in upstream roles selling to firms in downstream roles.

Insert Figure 4 about here

The foregoing has shown that our dataset best represents the Transportation, ICT, Health, and Energy Sectors. While the Horizontal Industries sector is well represented in absolute terms, relative to GDP it is poorly represented. And while the clothing sector is poorly represented in absolute terms, relative to GDP is well represented. In terms of sector roles, there is an asymmetry between seller and buyer roles. In both absolute and relative terms sellers are best represented as parts and material suppliers, while buyers are best represented as manufacturers.

VISUALIZATIONS

Visualizations of the economy and economic relations have included the "Tableaux Economique" (Quesnay, 1758), the Atlas of Economic Complexity (Hausmann & Hidalgo, 2014), the dotlink360 visualizations (Basole, Clear, Hu, Mehrotra & Stasko, 2009), and alliance network graphs (Rosenkopf & Schilling, 2003). Our visualizations, created using the D3 drawing library developed by the Stanford Visualization Group (Bostock, Ogievetsky & Heer, 2011), show inter-industry transactions at multiple levels of analysis. In this paper we present the most salient visualizations, additional views will be made available online in the near future.

We present both matrix and chord diagrams. Matrix views of transactions can be understood as economy-wide dependency structure matrices (more frequently referred to as design structure matrices, Baldwin & Clark, 2000; Eppinger, Whitney, Smith & Gebala, 1994) or as visualizations of the inter-industry portion of input-output tables. Each cell in the matrix diagrams shows the sales from the row entity to the column entity, where rows and columns are sectors (Figure 5) or roles (Figure 6). Chord diagrams (Figures 7-10) show net sales between sector-role pairs as a proportion of total net sales between all sector-role pairs. We use matrix diagrams to show total transactions within and between and sectors and roles, and chord diagrams to show transactions that originate or terminate within the vertical sectors that are best represented in our dataset.

Figure 5 shows the total value of transactions within and between sectors. Cell values greater than $711 billion (half the maximum cell value) are shown in maximum color saturation. The total value of the diagonal cells that indicate within sector transactions is $4,263 billion, while the total value of the off-diagonal cells that indicate between transactions is $1,756 billion. Firms in the Transportation sector, for example, sell $1,421 billion worth of goods and services to other firms in the sector, but very little to firms outside the sector (approximately $124 billion).

Similarly, they buy $1,421 billion from other firms in the sector, but only $489 billion worth of goods and services from firms outside the sector. The greater value of the diagonal cells provides support for our proposition that the economy can be partially decomposed into demand-based vertical sectors.

Insert Figure 5 about here.

There are eight cells in Figure 5 whose values exceed $100 billion. The four cells whose values exceed $500 billion represent within-sector transactions in the Transportation, ICT, Health, and Energy sectors. Within-sector transactions in the Clothing sector exceed $100 billion. The remaining three cells whose values exceed $100 billion are off the diagonal. The Transportation sector buys over $200 billion of the Horizontal Industries sector's output (primarily rubber, machinery, and primary metals sold to automotive manufacturers), and it buys approximately $180 billion of the ICT sector's output (primarily instruments and communications equipment sold to aircraft manufacturers). The Horizontal Industries sector buys over $100 billion of the Energy sector's output, primarily the output of utilities.

There are another eight cells in Figure 5 whose values are between $50 and $100 billion, all of which are below $70 billion. These cells represent within-sector transactions in the Food and Horizontal Industries sectors, and sales from the Health sector to the Finance sector (primarily sales from health maintenance organizations to insurance companies). The remaining five cells involve the Horizontal Industries sector. These include sales from the Clothing and ICT sectors to the Horizontal Industries sector (primarily sales from clothing and computer manufacturers to general retailers such as Walmart and Kmart) and sales from the Horizontal

Industries sector to the Food (primarily sales of equipment to food retailers and manufacturers), Buildings and Infrastructure (primarily sales of materials to building retailers such as Home Depot), and ICT sectors (primarily sales of machinery to computer and communications equipment manufacturers).

Figure 6 shows the total value of transactions within and between sector roles. Cell values greater than $905 billion (half the maximum cell value) are shown in maximum color saturation. The total value of the diagonal cells that indicate within role transactions is $1,450 billion, while the total value of the off-diagonal cells that indicate between role transactions is $4,568 billion. The fact that firms are more likely to engage in transactions with firms that perform different roles, than they are to engage in transactions with firms that perform the same role, means that dividing the economy into parts on the basis of the roles or activities performed by firms does not partially decompose it such that the parts are less complex than the whole.

Insert Figure 6 about here.

Figure 6 shows that, consistent with our second proposition, downstream firms that perform customer service roles depend on upstream firms, which perform complementary roles, for input products and services. The total value of cells below the diagonal that represent sales from upstream to downstream firms is approximately $3,895 billion, while the total value of cells above the diagonal that represent sales from downstream to upstream firms is $673 billion. For example, sales from upstream parts and materials suppliers to downstream manufacturers total $1,809 billion, the highest value cell in the matrix, but sales in the reverse direction, from manufacturers to parts and materials suppliers total only $138 billion. The greater total value of the cells below the diagonal shows that roles are hierarchically structured with downstream firms depending on upstream firms for input products and services. But as our second proposition addressed the structure of roles within vertical sectors, the chord diagrams shown below must also be taken into consideration.

There are six cells in Figure 6 whose values exceed $400 billion. Four of these cells are below the diagonal, indicating sales from upstream firms to downstream firms (totaling $3,379 billion), and two of these cells lie on the diagonal indicating sales within the customer service provider role ($440 billion), and sales within the manufacturer role ($740 billion). Four of these high value cells involve manufacturers and three involve customer service providers (one cell is sales from manufacturers to customer service providers). As mentioned, sales from parts and materials suppliers to manufacturers total $1,809 billion. Sales from manufacturers to customer service providers, wholesalers, and other manufacturers are approximately $580, $500, and $740 billion, respectively. Customer service providers buy large amounts of output from other customer service providers ($440 billion), wholesalers ($490 billion), and manufacturers ($580 billion).

The chord diagrams in Figures 7-10 depict the transactions that originate or terminate in the four sectors that are best represented in our dataset: Transportation, ICT, Health, and Energy. A chord diagram arranges the nodes radially, drawing thick chords between nodes. To best show within-sector relationships between roles, sector roles are shown on the outer ring and sectors on the inner ring, occupying areas that are proportional to their representation as sellers in the dataset. Consistent with the data presented in Figure 3, Figures 7-10 show that parts and materials supplier is the predominant seller role, followed by manufacturer. Nodes are role-sector pairs and the thickness of the chords between nodes indicates the net value of transactions as a proportion of all transactions. Where a chord is tapered, there are more sales than purchases by the node at the thick end of the chord (Krzywinski et al., 2009). By showing net transactions between nodes, rather than all transactions, chord diagrams make the patterns in the data visible.

As shown in Figure 7, most transactions in the Transportation sector are from parts and materials suppliers to manufacturers. The largest transactions include sales from automotive parts suppliers such as Delphi, Visteon, Magna, and Lear to vehicle manufacturers such as General Motors, Ford, and DaimlerChrysler, and from aircraft parts suppliers such as United Technologies to aircraft manufacturers such as Boeing. Transactions involving wholesalers and customer service providers are few, likely because automotive manufacturers sell directly to numerous dealers and so no customer accounts for more than 10% of their revenues. Still, there are significant sales from aircraft manufacturers such as Boeing, to air transportation service providers.

Insert Figure 7 about here.

Figure 8 shows transactions within the ICT sector. Again, sales from parts and materials suppliers to manufacturers dominate, but in the ICT sector there are also a significant number of transactions amongst manufacturers and amongst customer service providers, likely as a consequence of the greater degree of vertical disintegration in the ICT sector relative to the transportation sector (Jacobides & MacDuffie, 2013). The largest transactions in the ICT sector include sales from component suppliers such as Intel, Seagate, and STMicrolectronics to computer manufacturers such as HP and Dell, and to communications equipment manufacturers such as Lucent (merged with Alcatel in 2006), Nokia (acquired by Microsoft in 2014), Cisco, and Nortel (which went bankrupt in 2009). Also significant are sales from electronic manufacturing service providers such as Solectron (acquired by Flextronics in 2007) and Jabil Circuit to communications equipment manufacturers such as Cisco. Sales from communications equipment manufacturers such as Motorola, Lucent, and NEC to communications service providers such as Verizon, AT&T, and Nippon Telegraph and Telephone are also important, as are sales amongst communications service providers. Finally, sales from wholesaler Tech Data to HP are also significant.

Insert Figure 8 about here.

The Health Care sector is a different story (Figure 9). Here the major players are the wholesalers (Cardinal Health, McKesson, and AmerisourceBergen) who buy the output of pharmaceutical manufacturers (Pfizer, Amgen, and Genentech) and sell it to customer service providers, including pharmacies such as CVS Caremark, Walgreens, and Rite Aid, and to Medco Health Solutions, a pharmacy benefits company acquired by Express Scripts in 2012. The three pharmaceutical wholesalers mentioned above are involved in a significant proportion of the largest transactions in our dataset. When the 53,309 transactions in our dataset are sorted by size, the health care wholesalers account for 43 of the top 100 transactions, worth a total of approximately $466 billion.

Insert Figure 9 about here.

Given the high degree of vertical integration within the Energy sector (Figure 10) it may be surprising that inter-firm transactions within this sector are so prominent in our dataset. Many of the significant within-sector transactions in the Energy sector involve foreign and US firms that are vertically specialized. These include sales from upstream oil and gas companies such as Petro China (the listed arm of state-owned China National Petroleum Corporation) and CNOOC (Chain National Offshore Oil Corporation) to refiners such as China Petroleum and Chemical (better known as Sinopec), and sales from pipeline transport companies such as Enterprise GP Holdings, a transport company sold to Enterprise Products in 2010, Teppco Partners, a transport company sold to Enterprise GP Holdings in 2007, and El Paso, a transport company sold to Kinder Morgan in 2014, to refiners such as Valero and distributers of natural gas such as Southern California Gas. Transactions that involve vertically integrated firms include sales from refiners such as Frontier Oil (which merged with Holly in 2011) to vertically integrated firms such as BP and Shell.

Insert Figure 10 about here.

DISCUSSION

The classic example of a simple visualization of complexity is the periodic table of chemical elements. By identifying the atomic number and other properties of chemical elements as important and recurring, and by using these properties to structure the two dimensional arrangement of elements in rows and columns, the creators of the periodic table produced a simplifying abstraction and a useful framework for understanding chemical behaviour.

Some may believe that inter-firm relationships are too idiosyncratic, too specific to the industry or institutional environment, or too dynamic for it to be possible to devise a description of the architecture of the economy that is as simple and informative as the periodic table of elements. They may be right. But the pursuit of a simple description of the architecture of the economy is, nevertheless, a worthy objective. It asks us to consider the degree to which there are patterns in the way firms self-organize to create the structure of inter-industry relationships, just as there are patterns in the systems created by biological organisms. If the patterns are there, it behoves us to observe, describe, and communicate them.

Contributions

Employing a dataset of over 53,000 inter-firm transactions with a total value of over $6 trillion, we have provided simple, high-level depictions of the structure of inter-industry relationships in the US economy. Our visualizations show the distribution of transactions within and between sectors and sector roles, and within vertical sectors show dependency relationships between firms in upstream and downstream industries. While our visualizations are high-level and omit a great deal, they capture succinctly the major pathways through which value is exchanged.

Our visualizations provide graphical evidence in support of our two propositions regarding the structure of the economy. Consistent with Simon's characterization of the architecture of complexity, which identifies decomposability and hierarchical structure as essential to understanding of complex systems, our visualizations show that the US economy is partially decomposable into vertical sectors, and hierarchically structured. The total value of within sector transactions is more than twice the value of between sector transactions. Overall, transactions are hierarchically structured with the value of transactions from upstream to downstream roles greater than the value of transactions from downstream to upstream or within role transactions. And the four sectors best represented by our data (Transportation, ICT, Health, and Energy) exhibit hierarchically structured relationships between upstream and downstream industries.

The designers of the world's most influential industry classification systems, the US Standard Industry Classification (SIC) system, aimed to create a system that reflected industry structure (Pearce, 1957). The material view of the economy led them to prioritize the similarity in extraction, manufacturing, and service activities as the conceptual basis for the system. We have shown that the primary disaggregation of the economy into parts is demand-based, not activity-based. When we segment the economy by demand-based sectors, we find that the value of within-sector transactions is greater than the value of between-sector transactions. In contrast, when we segment the economy by role, a segmentation that is consistent with activity, we find that the value of between-role transactions exceeds the value of within-role transactions. Segmenting the economy on the basis of activities, as current industry classification systems do, does not "carve at the joints", and so the resulting parts are no less complex than the whole, and cannot be related to one another in a way that is consistent with the structure of inter-industry relationships.

Our final contributions are the creation of a NAICS to Systems-Based industry classification concordance table (Appendix A) and the evaluation and depiction of a high potential dataset that has not yet been used in strategy research.

Limitations

Our dataset has characteristics that limit the generality of our findings. First, it does not include all transactions, but only the largest transactions (those that account for more than 10% of revenues) of publicly traded firms. Furthermore, we excluded from the dataset transactions involving non-firm organizations such as governments and non-profit organizations. As our presentation of the data showed, not all sectors and roles are equally well represented in the data. In absolute terms, we have large samples of transactions from five of twelve sectors. Relative to GDP, six sectors are well represented. We focused on the four sectors (Transportation, ICT, Health, and Energy) for which we have large, representative samples.

We limited ourselves to a basic version of the systems-based approach to industry classification. A more elaborate approach would consider more specific sectors, for example it might split the ICT sector into computing and communications, or into traditional and internet-based communications. Roles could also be more specific, for example manufacturers might be split into material processors and system integrators.

Future Research

Our systems-based theory of industry classification, novel dataset, and visualization platform all provide avenues for future research. The industry classification system can be tested against alternative systems, as Bhojraj, Lee and Oler (2003) did for the alternative Global Industry Classification Standard. The dataset can be augmented to enable an investigation of the antecedents and outcomes of inter-firm transactional relations. And the visualization platform can be expanded to provide additional visualizations and firm information.

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APPENDIX A: CONCORDANCE TABLE

Mapping from 4-Digits NAICS Codes to Systems-Based Sectors and Roles

System-Based Sectors and Roles	Associated 4-Digit NAICS Codes
Sector : Food	
Customer Service Providers	4451, 4452, 4453, 4542, 7223, 7224, 7225
Wholesalers	4244, 4245, 4248
Manufacturers	3111, 3112, 3113, 3114, 3115, 3116, 3117, 3118, 3119, 3121
Parts and Materials Suppliers	1111, 1112, 1113, 1114, 1121, 1122, 1123, 1124, 1125, 1141, 1142
Complementary Suppliers	1151, 1152, 3253
Sector: Clothing	
Customer Service Providers	4481, 4482, 4483, 4521
Wholesalers	4243
Manufacturers	3141, 3149, 3151, 3152, 3159, 3162, 3169, 3399
Parts and Materials Suppliers	3131, 3132, 3133, 3161
Complementary Suppliers	
Sector: Durable Goods	
Customer Service Providers	4421, 4422, 4431, 8114
Wholesalers	4232, 4236
Manufacturers	3351, 3352, 3371, 3372, 3379
Parts and Materials Suppliers	3212, 3255, 3322, 3325
Complementary Suppliers	
Sector: Energy	
Customer Service Providers	2212, 4471, 4543
Wholesalers	4247, 4862, 4869
Manufacturers	3241
Parts and Materials Suppliers	2111, 2121, 2211
Complementary Suppliers	2131, 4861
Sector: Buildings and Infrastructure	
Customer Service Providers	4441, 4442, 5311, 5414, 5617, 7211, 7212, 7213
Wholesalers	5312, 5313
Manufacturers	2213, 2361, 2362, 2371, 2373, 2379
Parts and Materials Suppliers	2381, 2382, 2383, 2389, 3219, 3272, 3273, 3274, 3279, 3323, 3334
Complementary Suppliers	2372, 4233, 4237, 5413
Sector: Transportation	
Customer Service Providers	4411, 4412, 4413, 4811, 4812, 4821, 4831, 4832, 4841, 4842, 4851, 4852, 4853, 4854, 4855, 4859, 4871, 4872, 4879, 5321, 5615
Wholesalers	4231, 4881, 4882, 4883, 4884, 4885, 4889, 4931, 5324, 8111
Manufacturers	3361, 3362, 3364, 3365, 3366, 3369
Parts and Materials Suppliers	3363
Complementary Suppliers	
Sector: Information and Communications Technologies	
Customer Service Providers	4512, 4532, 4911, 4921, 4922, 5171, 5172, 5179, 5182, 5191, 5331
Wholesalers	4234, 4241, 4251
Manufacturers	3231, 3341, 3342, 3343, 3345, 5111, 5112, 5174
Parts and Materials Suppliers	3221, 3344, 3346, 3359
Complementary Suppliers	5415

Sector: Health	
Customer Service Providers	4461, 6211, 6212, 6213, 6214, 6215, 6216, 6219, 6221, 6222, 6223, 6231, 6232, 6233, 6239, 6241, 6242, 6243, 6244, 8121, 8122, 8123, 8129
Wholesalers	4242
Manufacturers	3254, 3256, 3391
Parts and Materials Suppliers	
Complementary Suppliers	
Sector: Arts, Entertainment, and Recreation	
Customer Service Providers	4511, 4539, 5151, 5322, 7111, 7112, 7121, 7131, 7132, 7139
Wholesalers	4239, 7113, 7114
Manufacturers	5121, 5122, 5152
Parts and Materials Suppliers	7115
Complementary Suppliers	
Sector: Finance	
Customer Service Providers	5221, 5222, 5239, 5241, 5251, 5259
Wholesalers	5223, 5231, 5242
Manufacturers	
Parts and Materials Suppliers	
Complementary Suppliers	
Sector: Education	
Customer Service Providers	6111, 6112, 6113, 6114, 6115, 6116
Wholesalers	6117
Manufacturers	
Parts and Materials Suppliers	
Complementary Suppliers	
Sector: Horizontal Industries	
Customer Service Providers	4529, 4531, 4533, 4541, 5323, 5411, 5412, 5416, 5417, 5418, 5419, 5611, 5612, 5613, 5614, 5619, 5621, 5622, 5629, 8112, 8113
Wholesalers	4238, 4249
Manufacturers	3122, 3324, 3332, 3333, 3335, 3336, 3339, 3353
Parts and Materials Suppliers	1119, 1129, 1131, 1132, 1133, 2122, 2123, 3211, 3222, 3251, 3252, 3259, 3261, 3262, 3271, 3311, 3312, 3313, 3314, 3315, 3321, 3326, 3327, 3328, 3329
Complementary Suppliers	1153, 3331, 4235, 4246
Sector: Public Administration	
Customer Service Providers	5211, 5232, 5511, 5616, 8131, 8132, 8133, 8134, 8139, 8141, 9211, 9221, 9231, 9241, 9251, 9261, 9271, 9281
Wholesalers	
Manufacturers	
Parts and Materials Suppliers	
Complementary Suppliers	

Figure 1: Total Value of Transactions (1976-2010), by Sector ($ millions)

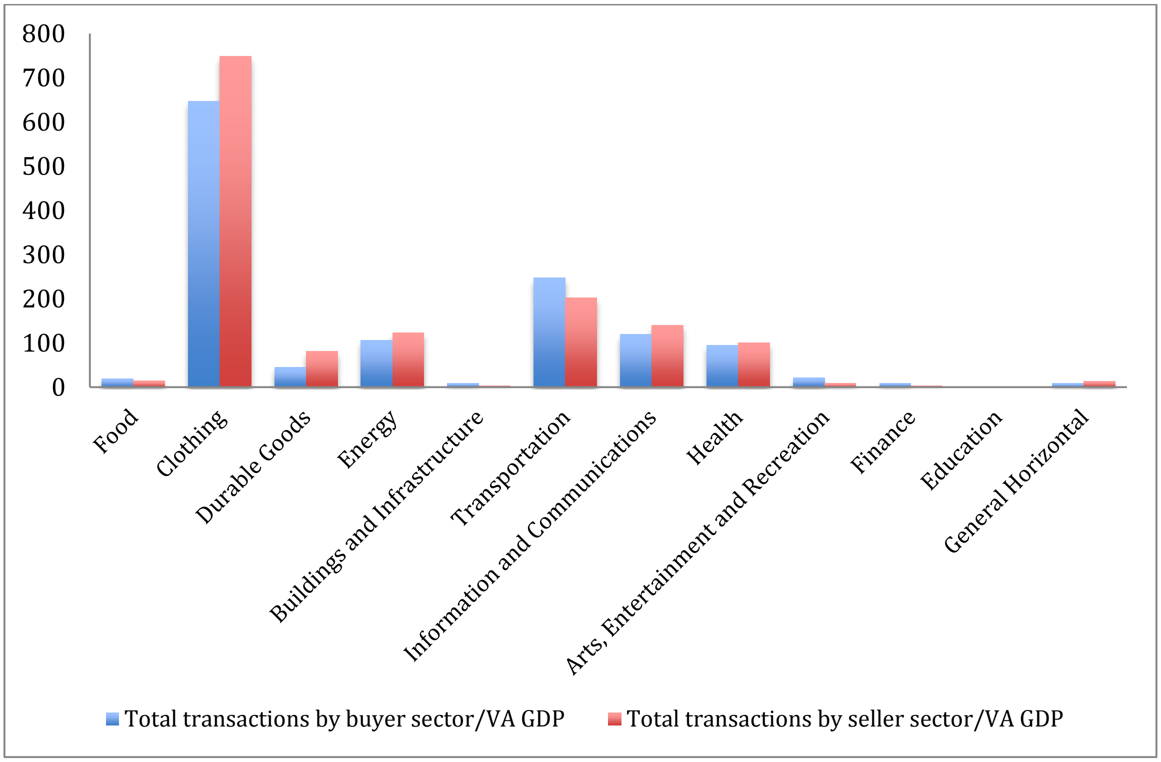


Figure 2: Total Transaction Value / Value-Added GDP, by Sector (%)

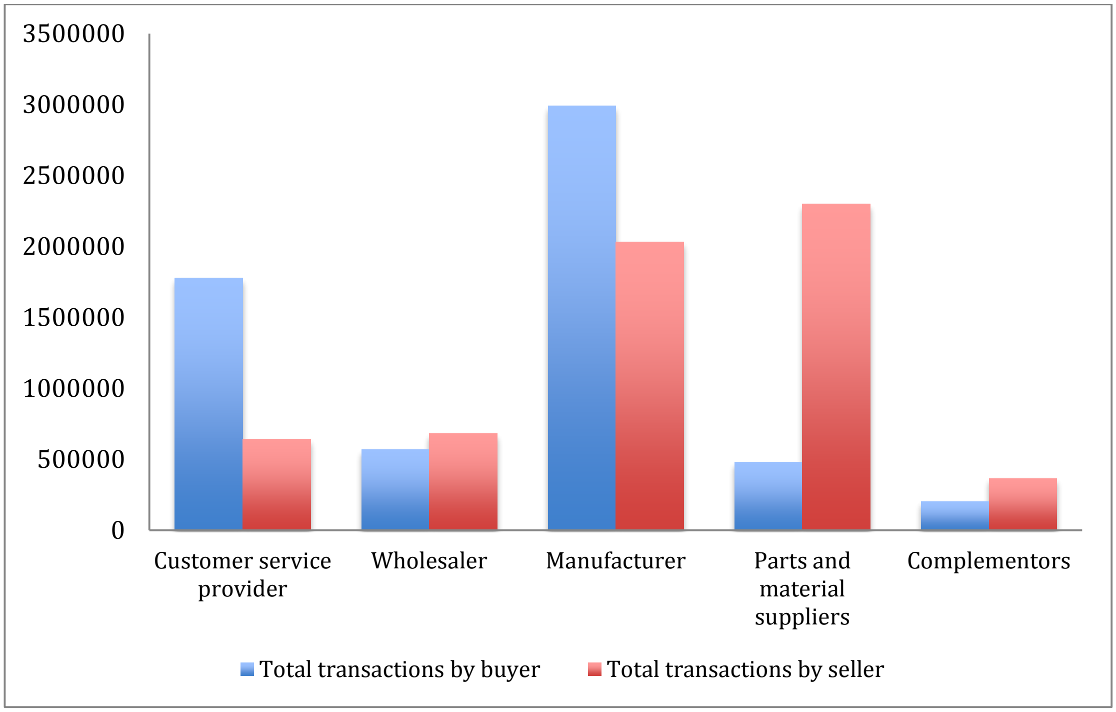


Figure 3: Total Value of Transactions (1976-2010), by Role ($ millions)

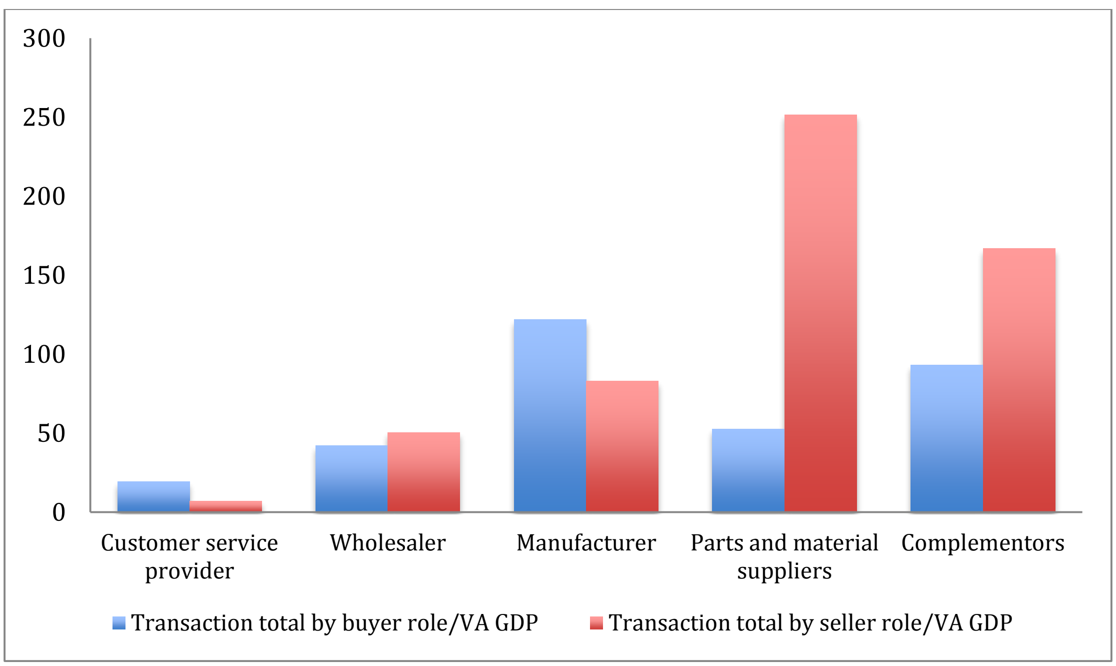
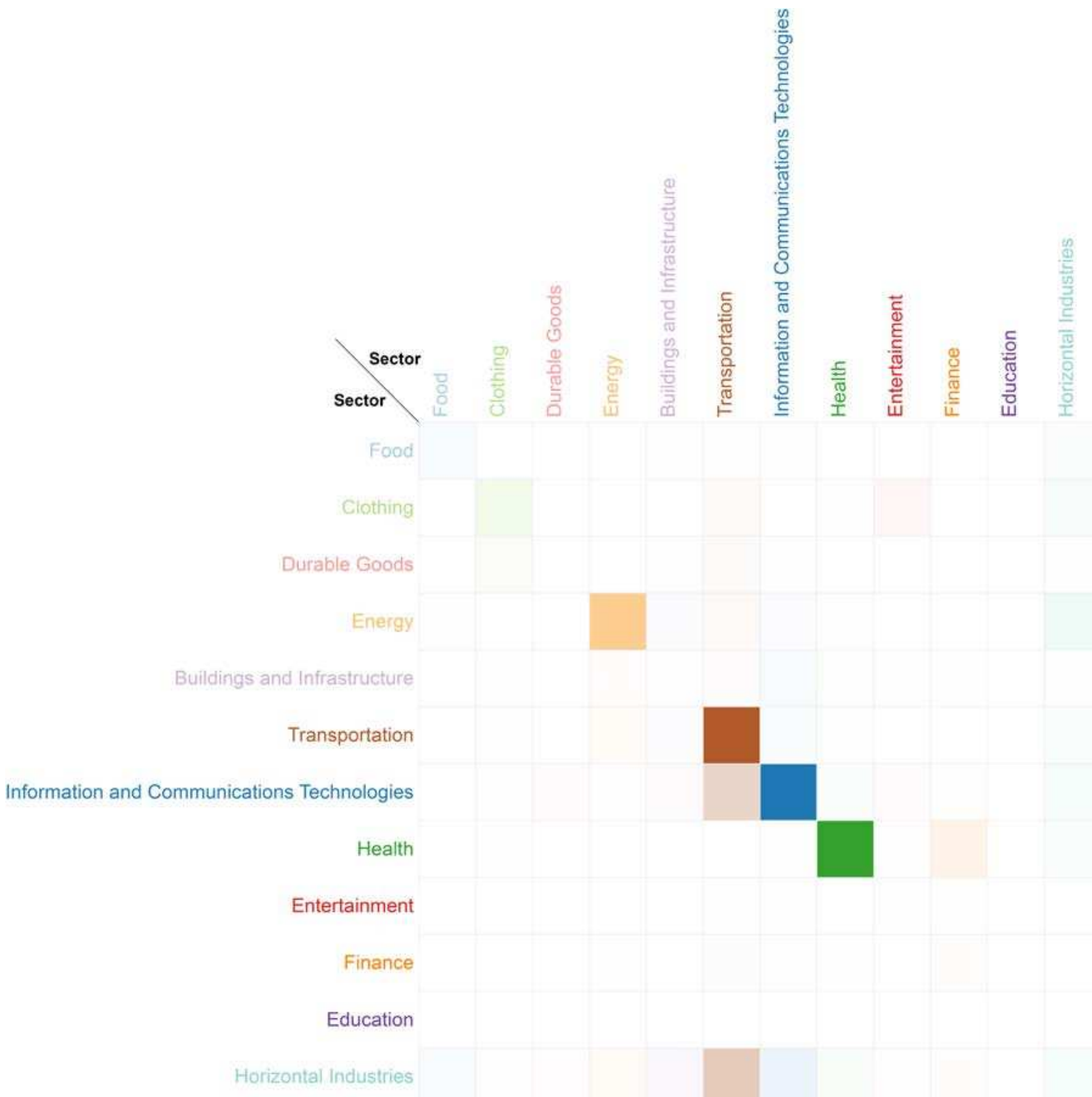


Figure 4: Total Transaction Value / Value-Added GDP, by Role (%)



Dear Reviewer: This chart shows up much better on my computer screen than it does in the DRUID created pdf. And it's probably better online than printed. We hope you can see it and will use more suitable colors in future versions of the paper. Thanks for your understanding.

Figure 5: Total value of transactions within and between sectors.
Cell values greater than $711 billion (half the maximum cell value) are shown in maximum color saturation.

Figure 6: Total value of transactions within and between sector roles.
Cell values greater than $905 billion (half the maximum cell value) are shown in maximum color saturation.

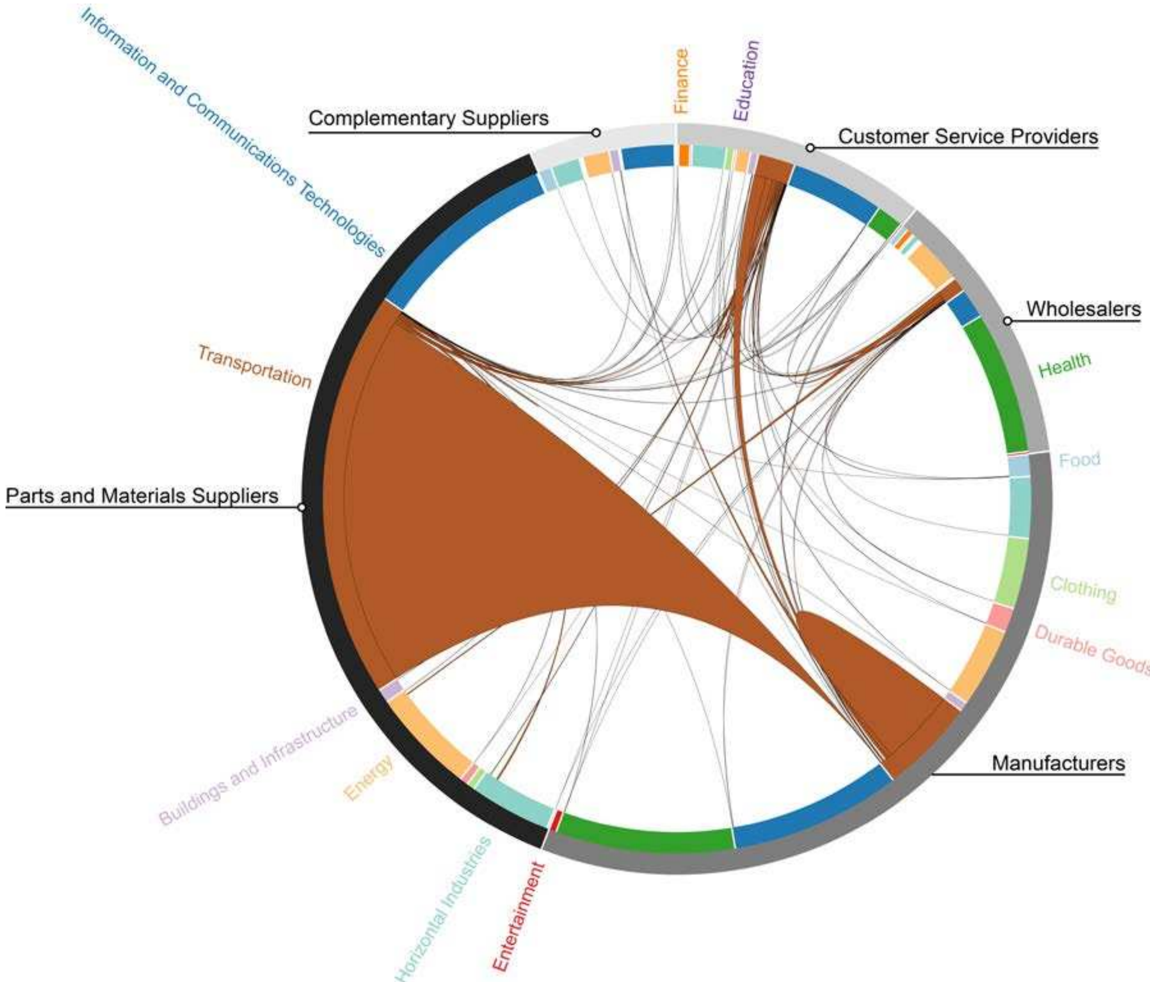


Figure 7: Net transactions within the Transportation sector

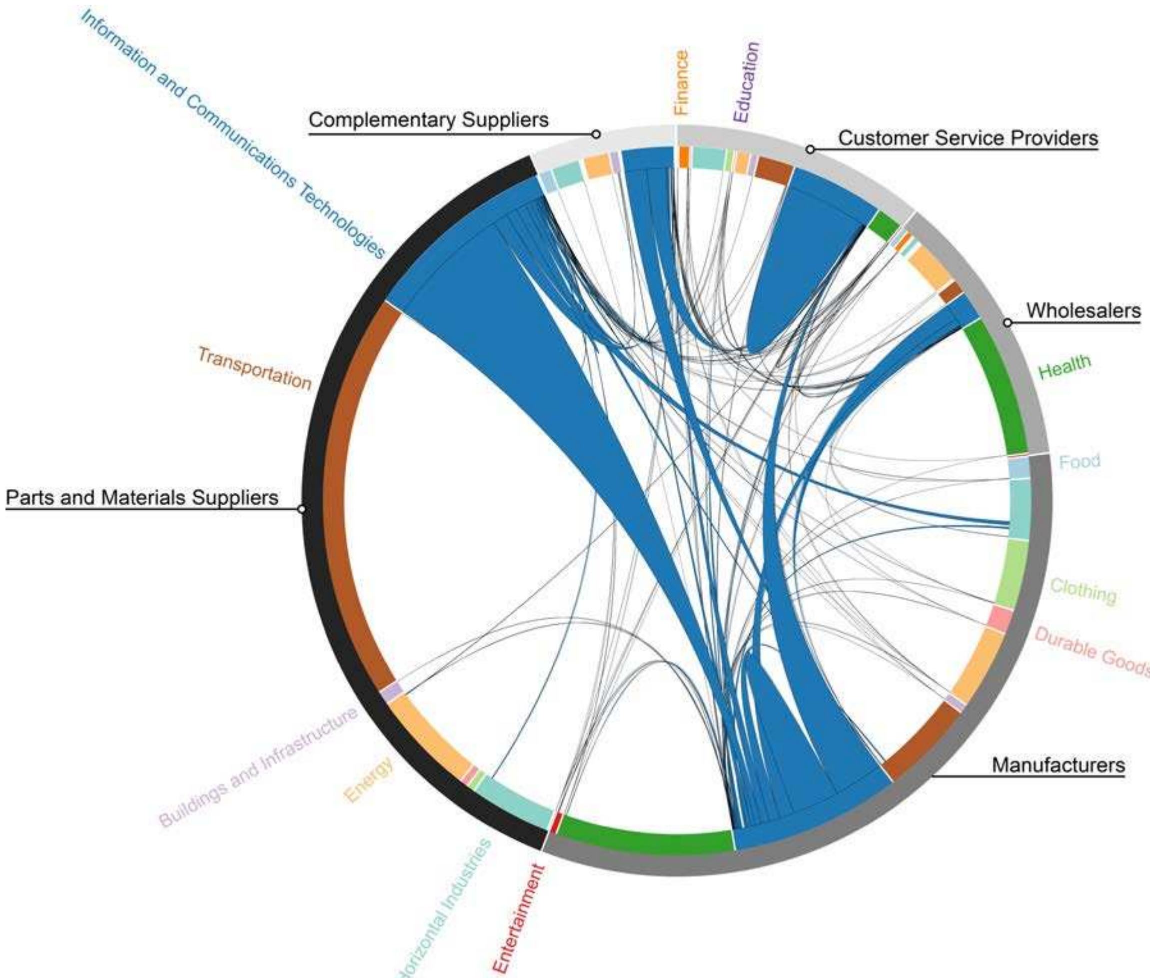


Figure 8: Net transactions within the ICT sector

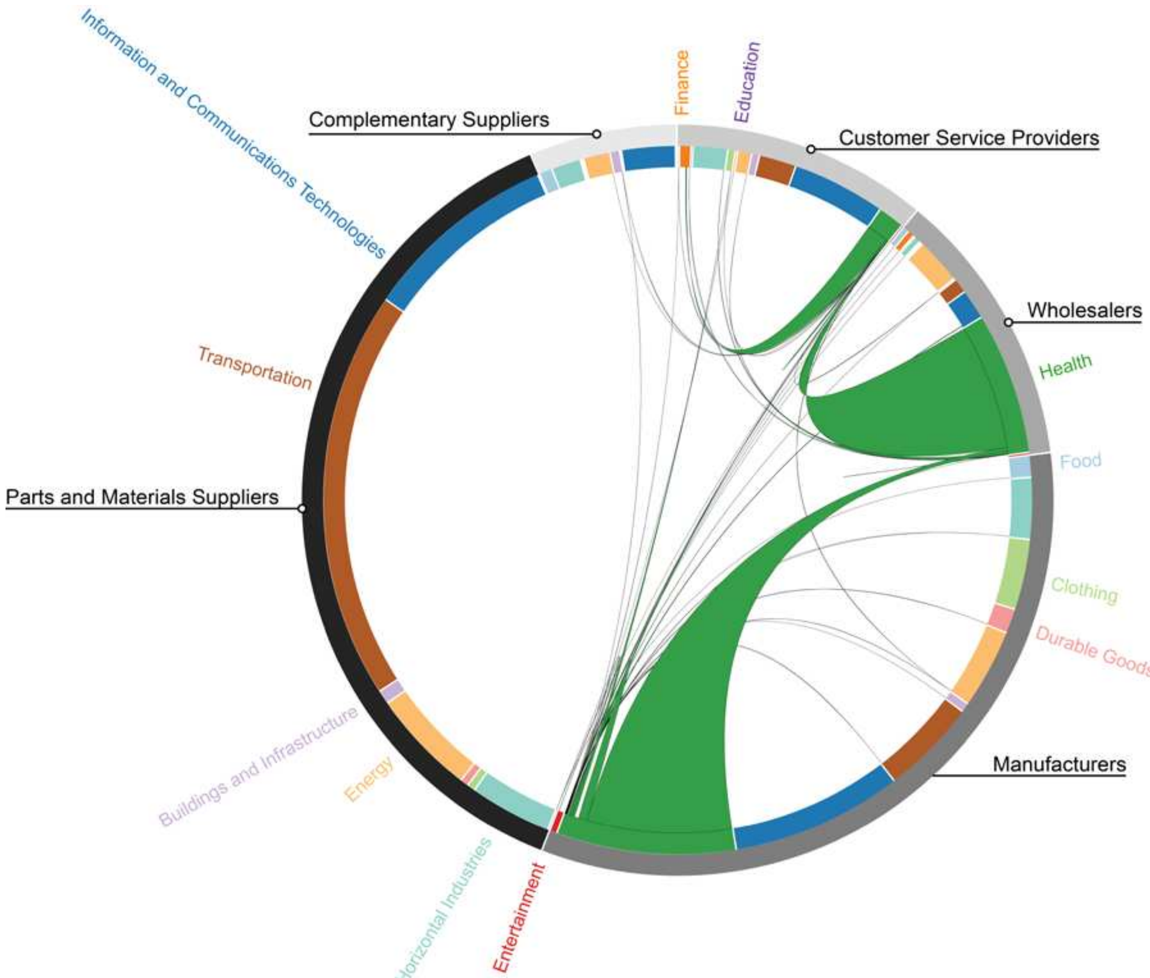


Figure 9: Net transactions within the Health Care sector

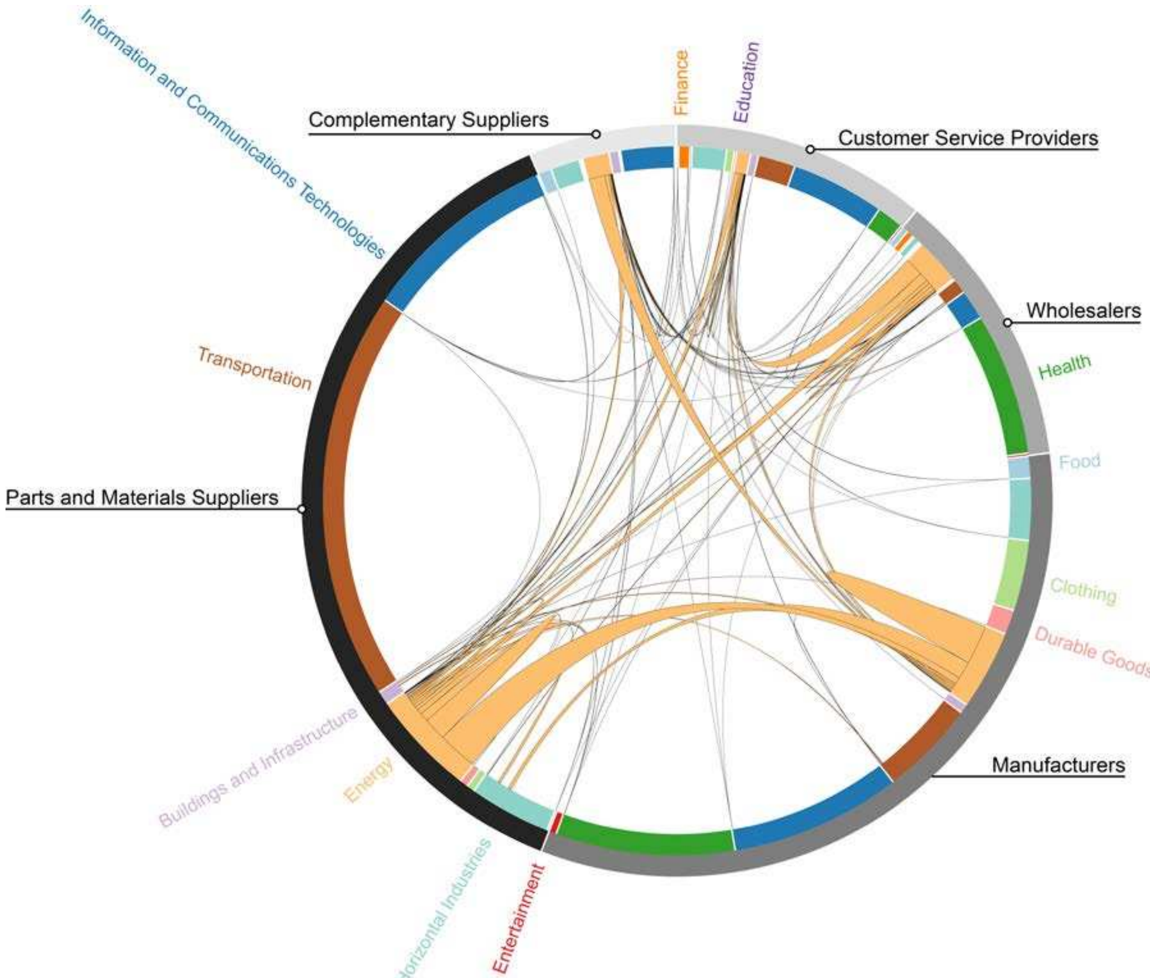


Figure 10: Net transactions within the Energy sector

Table 1 NAICS 2-Digit Sectors Mapped to Systems-Based Sectors and Roles

* NAICS * Activity- * Based * Sectors NAICS * Demand * Based * Sectors *		44-45 Retail Trade	42 Wholesale Trade	31-33 Manufacturing	11 Agriculture, Forestry, Fishing and Hunting 21 Mining, Quarrying, and Oil and Gas Extraction 22 Utilities	
	*** Systems- * Based * Roles Systems-* Based * Sectors ***	**Customer Service Providers**	**Wholesalers**	**Manufacturers**	**Parts and Materials Suppliers**	**Comple-mentary Suppliers**
	Food	72 Accommodation and Food Services				
	Clothing					
	Durable Goods					
	Energy					
	Buildings and Infrastructure	53 Real Estate and Rental and Leasing		23 Construction		
	Transportation	48-49 Transportation and Warehousing				
	ICT	51 Information				
62 Health Care and Social Assistance	**Health**					
71 Arts, Entertainment, and Recreation	**Arts, Entertainment and Recreation**					
52 Finance and Insurance	**Finance**					
61 Educational Services	**Education**					
	Horizontal Industries	54 Professional, Scientific, and Technical Services 55 Management of Companies and Enterprises 56 Administrative and Support and Waste Management and Remediation Services				
81 Other Services (except Public Administration) 92 Public Administration	**Public Administration**					