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# From Wireframe to Dashboard – Creating Transparency in Supply Chain Networks

**Penina Orenstein**
Stillman School of Business,
Department of Computing and Decision Sciences,
Seton Hall University,
400 South Orange Ave, New Jersey 07079
Email: Penina.orenstein@shu.edu

## ABSTRACT

**In this research, we take a wireframe network (tiered visualization of the nodes and edges in a supply chain network) and describe how it can be transformed into a dashboard. A dashboard is a form of data visualization which provides at-a-glance views of key performance indicators (KPIs) relevant to a particular objective or business process. We then identify several dimensions of information which should be included in the dashboard, such as structural, geographic as well as financial layers. The resulting dashboard tool is broad-based since, depending on the goal of the analyst, further layers may be applied to the structure. The information can then help improve the understanding of the supply network beyond confirming what is already known. This paper describes the information framework for the dashboard. The knowledge that is obtained through the analysis of the dashboard will yield areas for improvement and greater efficiency in the supply chain, reduce the chances of disruption and enable the supply chain to stay competitive.**

**Keywords:** *business analytics, data mining, digital visualization*

## 1. INTRODUCTION

Supply Chain Networks (SCNs) have in recent times evolved from simple sequential and linear process networks to highly dynamic processes that require information sharing and visibility to be available across the network coupled with decision making on a real time basis (Fiala, 2005). As such, it is important, not only, to identify the structure of a supply chain network, but also to understand what drives its success. Ideally, it would be preferred if the structure of a supply chain network could be derived using theoretic constructs, however, the nature of the supply network process is both interactive and dynamic. With the massive explosion in data availability, a data-mining approach is clearly a new avenue for research.

Data-driven supply chain network analysis is important because the analysis can help provide an understanding on the potential impact from events like Coronavirus (Zhu *et al.*, 2020), geopolitical trade tensions, and more. Recent developments surrounding the Coronavirus, have increased the need to understand the mechanism that drives global supply chains.

Supply chain network analysis has risen in prominence in recent years due to changes in the global economy that have contributed to an increasing need to capture and monitor the dynamic behavior of a supply chain network. This is a necessary step for managing, and controlling the flows between the firms in the network and understanding what drives its performance. Accurate maps are needed for supply chain performance management (Chae, 2009), and for supply chain re-design and improvement (Farris, 2010). A comprehensive discussion by McCarthy and Ivanov (2022) on the digitization of the supply chain, explains in detail the growing need for supply chain network analysis.

In this research, we consider how data visualization can be employed as a tool for supply chain network analysis. Data visualization is the representation of data or information in a visual format, essentially forming a bridge between the data and its graphical representation. We envisage that the knowledge which emerges can be used to understand trends and patterns in the data which may not be obvious from the actual data set.

The background for this idea comes from previous research in which we created graphical maps that essentially transformed supply chain financial relationship data extracted from Bloomberg and FACTSET, into visual images of the supply chain network (Orenstein, 2020). In addition to the visual component, we also provided structural metrics which helped explain the evolutionary nature of these networks. Unfortunately, the information obtained was limited in scope, providing an overall characterization of the network. The visualizations could not be used to make decisions about the supply chain because our understanding of its operation was impaired, for example, we could not trace an item through the supply chain network or explore the impact of disruption since we did not have sufficient knowledge of the supply chain underlying mechanism. In a certain sense, we had produced a collection of pretty pictures, but no actionable decisions could be made. Essentially, the graphical images helped confirmed what we already knew, that the global supply chain is complex, and that, even with the data visualizations, our understanding of the supply chain operation did not improve substantially. Our aim in this paper is to improve our understanding of the supply network so that recommendations about the supply network's operation and performance can be made, for example, where are key suppliers located, who are the key suppliers and how would the supply chain respond in the event of a disruption.

In this way, we could potentially use the visualizations to be able to trace individual parts to the exact site where they are manufactured. Ultimately, the mechanism could be used to help companies ensure sustainability practices from the production of raw materials through the finished goods, and possibly allow companies to identify and anticipate vulnerabilities in their supply chain. More importantly, we expect that layered visualizations can be applied to unlock predictive analytics capabilities and help supply chain managers act proactively. In addition, the visual mapping coupled with the layers of information will then improve the comprehension of the supply network operation and ultimately contribute to the decision-making process as to how to improve its efficiency. This is the primary goal of this research: to improve the comprehension of the supply network operation through actionable, quantifiable items.

The paper begins with a review of the literature which covers the definition of what constitutes a supply chain map, including which information sources should be targeted, examples of existing supply chain maps and some of the challenges that arise from developing supply maps. We highlight the need for a comprehensive framework of supply chain mapping which will enable a broad classification of supply networks via their visual maps. We then describe how this could be achieved using the data source applied in this study. We demonstrate the proof of concept using the AMGEN network to explain the key features of this research. We discuss some results emerging from the study. The findings of the paper are then summarized in the conclusions section along with some pointers to future research.

## 2. LITERATURE REVIEW

Supply chain models have been developed and studied heavily over the last several decades. Before approaching the concept of supply chain maps, it is important to develop an understanding of the more recent models to identify the key components of what constitutes a supply chain (Liao, *et al*., 2021). Building on this, we can identify the elements of a supply chain map (or visualization) which essentially is a visual representation or diagram that details the steps and components involved in the production and distribution of a product. It provides a comprehensive picture of the entire supply chain network, from raw material sourcing to the finished product.

A seminal article which extensively explores supply chain mapping from multiple angles, is provided by Mccarthy *et al*. (2022), who explains the key components of supply chain mapping including a clear definition of why there is a growing need for supply chain mapping, the fundamental elements needed in a supply chain map, and some examples of existing supply chain maps. It appears that historically, supply chain literature has shied away from providing guidance on the supply chain mapping process, making the need for direction in this area even more urgent. With the fragmentation of global supply chains coupled with the impact of COVID-19 on the global supply chain economy as well as geo-political instabilities, the need for supply chain mapping has become crucial (Demirel *et al*., 2019).

Aside from the need to develop supply chain maps, one needs to be mindful of the primary and secondary data sources that are required for a detailed map. This includes going beyond the first tier of information. Moving down the hierarchy from the global value chain to the process map requires more detailed and granular information, which will typically require the involvement of more stakeholders and the deployment of more resources in the data collection process to capture the desired mapping elements. This is fraught with difficulties, because of ownership and privacy concerns, see (Farris, 2010; Gardner and Cooper, 2003).

The study by Choi and Hong (2002) and by Kito *et al*. (2014) demonstrates how multi-tier information (which used differing primary data sources to obtain information on three auto supply chains) could be used to create a comprehensive network analysis. Primary data sources include, for example, interviews with manufacturers on site, or a detailed study of actual documents in the company. The comprehensive nature of the study by Choi and Hong (2002) was subsequently used in follow-up work by Kim *et al*. (2011) as well as Demirel *et al*. (2019). Related to these articles, is a discussion of the complexities associated with the auto supply chain and its map, see Armie, *et al*. (2022). Aside from primary sources, a supply chain map can be enriched using secondary data sources. Secondary data is defined as quantitative or qualitative data that has been collected by someone other than the researcher(s) for a different purpose than its intended use in research. Some of the more commonly used are existing literature, census data, governmental information, financial data, organizational reports, and records (Lind *et al*., 2012).

Regardless of the data source, it is clear from studies of both primary and secondary data, that whether the focus is on primary or secondary sources – creating a solid supply chain map, still presents a huge challenge for researchers in this area. The multiple sources of primary and secondary data implies that the resultant map will only be as good as the input to the model. Our research falls into the category of secondary data sources (financial data) applied in a hierarchical manner. This technique essentially provides a digital trace of all suppliers that comprise the supply network.

To date the scope of visualizing a supply chain network via digital tracing has mostly been restricted to first tier primary suppliers (International Labor Organization, 2019). As supply chains become more complex, tracking a vast number of suppliers to trace the origins of products, particularly the raw sources from upstream in the supply chain, remains a significant challenge (Cernansky, 2020). The fragmentation and global dispersion of supply chains across international borders may obstruct the visibility of certain suppliers, making some areas of a supply chain opaque (Norton *et al*., 2014). Additionally, traceability requires investment in technologies and processes that track goods along the supply chain and require coordination and information sharing across different actors in the supply chain. These efforts can be costly and require time and willingness from all the respective actors, some of whom may be reluctant to share information due to legitimate business concerns about competitiveness (Fair Labor Association, 2017).

It appears, that while there is also no uniform agreement on what constitutes a reliable supply chain map, researchers agree, that once the data for the map has been ascertained, there is a need for good visualization tools to view the components of the map. Some of the desired visual properties of supply chain maps have been discussed in now somewhat extant literature (Farris, 2010; Gardner and Cooper, 2003). Farris (2010) illustrates the decoration of graphs by changing the sizes of nodes and the widths of edges reflecting their attributes, using different node symbols for different types of entities. However, the goal of this paper is not to discuss the visual merits of different maps, rather, to highlight the need for a clear visualization of the resultant map.

The broad question which supplies chain visualization seeks to address is "do you know who is in your supply chain?" Clearly, not all supply chain visualizations are equal. There are several approaches that can be employed to produce a comprehensive supply chain mapping. Ideally, a supply chain map should include all the supplier sites as well as the sub-tier information. Collecting sub-tier data is more difficult due to its proprietary nature. The ability to drill down in the supply chain will depend on the extent to which the information can be obtained.

Through the anecdotal evidence in Meiklejohn (2015), we can understand the need for a comprehensive supply chain mapping. She traces clothes from the field to factory. Data from her conversations is collected and mapped to produce a digitally transparent, traceable map of the supply chain. She explains that inefficiencies in the supply chain can be highlighted through the mapping being created. In this example, information from the visualization is used to make decisions about supply chain performance, for example, Can the supply chain be re-engineered to make improvements and lower the carbon footprint? This is a key aspect of traceability.

Using the age-old adage, "you cannot manage what you cannot see", the goal of the mapping/tracing in this study is to increase the level of visibility in the supply chain, in order to be able to trace products from source to destination and use this knowledge to improve its performance and make suggestions about re-engineering the supply chain to make it more efficient, less prone to disruption, and increase sustainability. These are all areas which have not been addressed until now (Frost and Sullivan, 2019).

The time is ripe for developing a mechanism to affect these extensive supply chain tracings (Vakil, 2020). With the impact of Covid-19, reliance on Chinese suppliers has been identified as a critical weakness in manufacturing supply chains. The time has come for companies to focus on building a detailed supply chain mapping (trace), not only of first-tier suppliers, but also of second and third tier suppliers. The tracing will allow companies to track goods from source to destination as well as identify which countries form part of the path. It appears that companies that invested in this level of visibility appeared to be in better shape after the pandemic hit.

In a follow-up article, Vakil *et al*. (2021), expands on this point and highlights that when the pandemic hit, "70% of organizations did not have a sense of what parts of their supplier networks were affected." A large portion of these companies were focused on data collection and assessment mode trying to identify which local suppliers in China were impacted by the lockdown. By contrast, companies that had invested in supply chain risk management tools, particularly supply chain mapping appeared to have a different experience." According to Choi *et al*. (2020), "by having visibility into their supplier networks, companies such as GM, Cisco, IBM, and Amgen were able to quickly ascertain what parts and materials originated in Wuhan and Hubei and fast-track their responses".

It turns out that to map a supply chain one can obtain an overarching picture of the supply chain, but to really trace things properly and understand where the product traverses geographically, one needs to collect the data about the product. How it is manufactured, who are the suppliers? That is a lot more complex and requires attention to detail.

From this discussion, it follows that the focus needs to shift towards creating transparent supply chains. The contribution of this paper to the existing literature is to explain how a secondary data source (financial data) can be employed to create a visual understanding or digital trace of a generic supply network. Unlike some of the other examples which are limited to the supply chain under study, the contribution of this paper is to provide a mechanism for tracing the supply chain map of any public supply chain. By utilizing this subset of financial data, we can develop an extensive supply chain map which can then be used to understand, for example, who the key suppliers are, where they are located, the impact of a disruption on the entire supply chain as well as specific questions on the performance over a given timeframe. In the rest of this paper, we explain the data source, and via an example, show how the information presented in the tool can support some basic supply chain decisions.

# 3. DATA SOURCE

We assume that we can represent a supply chain network as an unweighted directed graph G=(N,L) with N nodes and L links or edges. We assume there are no cycles in the graph. In the context of this work, the nodes represent individual companies, which connect through edges. We use only supplier relationships. i.e., the degrees are all one directional. In the paper, we refer to G as the focal company, or focal node. Each edge represents a financial relationship between a pair of companies, essentially a binary relationship. As such, we can denote the network as an adjacency matrix (A). Any element of the adjacency matrix $A=a_{ij}$, is given as:

$$a_{ij} = \begin{cases} 1, if\ i \neq j\ and\ i\ and\ j\ nodes\ are\ connected\ by\ an\ edge \\ 0, if\ i \neq j, and\ i\ and\ j\ nodes\ are\ not\ connected \\ 0, if\ i = j \end{cases}$$

To create a dynamic visualization map of a particular supply chain network, we first acquired financial relationship data for a prototype company and organized the data by calendar quarter and tier for a period of ten consecutive years (2005-2015). In a supply network structure, it is not uncommon for a given company to appear in different tiers. Each time the said company appears in a particular tier, it is recorded. Aside from the prototype company described in this paper, we have separately collected financial relationship data for approximately sixty companies that span various industry sectors including Energy, Health Care, Industrial, Communication and Information Technology for the ten-year time span. The sector classification is derived from Yahoo Finance (https://finance.yahoo.com/industries/), which extracts the information from the GICS classification system (https://www.msci.com/gics). The data set that has been created is extensive.

The goal of this research is to develop a dashboard structure, essentially a proof of concept. Hence, we choose to spotlight a single company from the healthcare sector: AMGEN. We also chose AMGEN since it was highlighted by Vakil *et al*. (2021), as a company with traceability capabilities. With the information displayed on the dashboard, we can then apply the technique to any network in our collection (Orenstein and Tang, 2021).

### *3.1 The AMGEN Data Set*

AMGEN (Applied Molecular Genetics Inc.) is one of the world's largest independent biotechnology companies. Amgen was established in Thousand Oaks, California, in 1980. Amgen's Thousand Oaks staff in 2017 numbered 5,125 (7.5% of total city employment) and included hundreds of scientists, making Amgen the largest employer in Ventura County. Focused on molecular biology and biochemistry, its goal is to provide a healthcare business based on recombinant DNA technology (Wikipedia, retrieved April 27th 2021).

Before analyzing the AMGEN network, we examine some financial data about the company. The information was obtained from Compustat. As can be seen in **Figure 1**, AMGEN has seen a remarkable growth in both their total assets as well as in their sales and market capitalization. The reports highlight 2013-2014 as a milestone year, in the sense that for the first time in AMGEN's history, the total company revenue surpassed $20 billion. From the graphs, one can observe that AMGEN's sales is on an upward growth curve contributing to strong financial health. The years post 2013 appears to be a turning point for AMGEN.

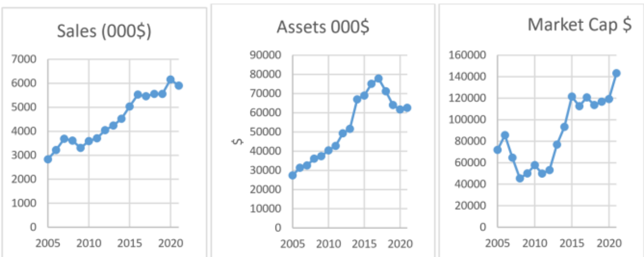


**Figure 1** AMGN Total Sales, Total Assets and Market Cap: Source AMGN Compustat Data

## 4. RESULTS

In this section we describe the framework which has been created to trace supply chain networks. The analysis starts with the basic network map and describes the stages leading to the detailed dashboard structure which can then be applied to help the analyst gain an understanding of the underlying supply chain operation. Throughout the discussion, we highlight how the information presented in the tool can support some basic supply chain decisions.

### *4.1 Creating the Basic Network Map*

The first stage of this analysis is to create a map of the network with no information other than the connections and the arcs that link the nodes together. An example of this is shown in **Figure 2** which displays the AMGEN network in 2005, quarter 1. One can observe a sparse structure which spans from a core of nodes (hub) at the center of the network. The data source is FACTSET, but the imaging method may be applied using Bloomberg data in a similar fashion, (Orenstein, 2020).

The map represents an important part of digital tracing since it highlights the nodes in the network by tier. Although not shown for simplicity, node names can be added to the map. One can examine the proportion of Tier 1 companies that comprise the network, and how the number of nodes within each tier changes as the network expands. The color indicates how many jumps it takes to reach focal company.

An important aspect of this visualization is the tiered information that can be seen. To gain an overview of the supply network structure, the supplier tickers have deliberately been omitted. However, in examining the data, one can easily obtain the names of the key suppliers which act as a bridge to the sub-supplier network. In this AMGEN diagram, ENTX (Entera Bio – red bridge node) emerges as a critical supplier as there is a sub-network that is dependent on it. Using the tool to identify critical suppliers can help supply chain managers make decisions about switching suppliers. One can also use this supply chain map when considering the question of re-shoring, (Soroka, 2016). If a key node (like ENTX) is replaced, what impact will this have on the suppliers in the sub-network?

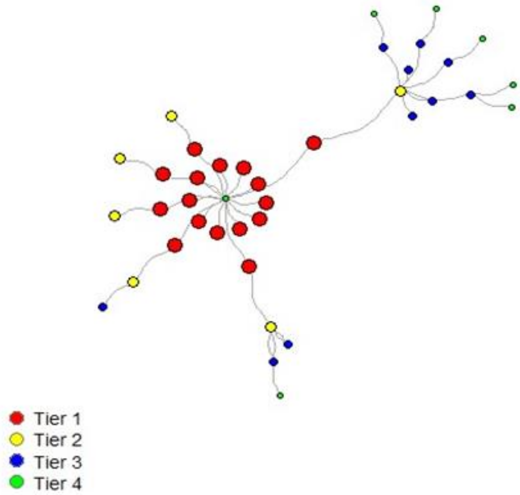


**Figure 2** Visual map of the AMGEN network in 2005, Quarter 1, highlighting the tiered information; Source: FACTSET.

One can also extend the mapping technique to compare how the supply network changes with time. This extension is applicable to FACTSET data only. The evolution of the network can be obtained by examining the historical financial relationship information by specifying the window of interest. Unfortunately, while Bloomberg data provides a detailed snapshot of the suppliers in the network at a particular point in time, one cannot look back to obtain a dynamic overview.

To explore the dynamic evolution we highlight **Figure 3**, which shows the AMGEN network in 2005, along with snapshots from 2009 and 2015. One can see how the structure of the core network evolves and note the expansion of the network at the upper tiers. There appears to be a correspondence between AMGEN's structural complexity and AMGEN's financial growth highlighted in **Figure 1**. This visualization highlights the importance of identifying critical suppliers to explain the supply chain operation.

The next phase of our analysis takes the existing network structure (**Figure 2**) and applies additional layers of information to the visualization. We begin with three dimensions: financial, structural, and geographic. These dimensions, when superimposed on the existing network enable the user to gain further insight into the network's operation and explore beyond the pretty picture. The first step in this process is shown in **Figure 4**. One can see how a layer of financial data (firm size) depicted by the relative size of each company within the supply network. When a company within the supply network exhibits a significant revenue relative to the focal company, a label for that company is displayed. This enables the user to easily identify the key suppliers within the supply network. For example, in **Figure 5**(a), SAP, a Tier 2 supplier is a significant player in the AMGEN network. In subsequent Figures, (b)-(d) we can track the top suppliers and examine their influence.

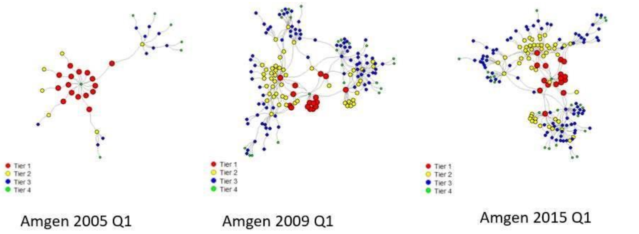


**Figure 3** Dynamic evolution of the AMGEN network, as time progresses the structure of the network evolves into a more complex pattern; Tier 1 structure changes – impacts upper tiers

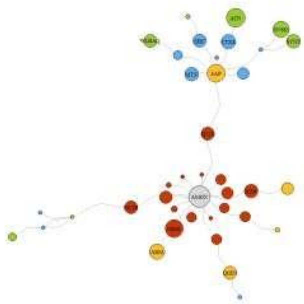

**Figure 4** AMGEN 2005, Q1, companies in the supply network highlighted by tier and sized by revenue – top ten companies highlighted by name on the map

### *4.2 Building Layers in the Network Data*

In addition to the general visualization of the node structure and the tiered relationships, we also wanted to understand the operation of the supply chain, hence the need for a geographic layer. In this visualization, we superimpose the nodes in the supply network (colored by tier) over a geographical map and use this map to explore node location and as an example relative size (revenue). One use of this aspect of the model is for re-shoring, (Soroka, 2016). If the geographic location of a node is known, one can consider replacing it with a more local supplier. The impact of this replacement can then be analyzed via the map. This is another example of how this tool can be used to aid in supply chain decision making.

An example of the basic geographical layer of the network is shown in **Figure 5**. The blue node on the west coast is AMGEN, the focal node. Tier 1 suppliers are distributed mainly on the west coast with some presence on the east coast. The nodes are sized by revenue, and tier. By manipulating the information from the geographical dashboard, we can then answer questions like, who are the key suppliers in the supply chain network and where are they located? What proportion of suppliers are located in a particular geographical region, and what would happen if the operations were moved closer to the focal node.

We can also provide additional layers of information which can be added to the basic dashboard shown in **Figure 5**. These include a financial dashboard (**Figure 6**) and a structural dashboard (**Figure 7**). For the financial dashboard, we provide three aspects of financial information including firm size measures, measures of financial performance as well as profitability. For the structural dashboard, we provide structural data such as the number of suppliers arranged by tier as well as node/edge characteristics. In addition, we have incorporated several measures to explain the centrality of the nodes in the network. These include degree centrality, eigenvector centrality, closeness centrality and betweenness centrality. The centrality measures are used to provide a ranking of critical suppliers. In this way, visualization is used to highlight who the key players are in the network, and how the entire network might be impacted in the event of a disruption. This is discussed in more detail in forthcoming research.


**Figure 5** Geographical overview of the AMGN (blue node) network, 2005, Quarter 1


**Figure 6** Financial dashboard of AMGN network, 2005, Q1


**Figure 7** Structural dashboard of AMGN network, 2005, Q1

## *4.3 Network Structure Analytics*

For the focal company's visualizations, we also calculated the corresponding structural metrics and recorded them by quarter and tier. We use several network metrics to characterize the topology of the supply network. These include the number of nodes, number of edges, average degree, network diameter, average path length and graph density. In the results section we provide a selection of the results for the structural component. A sample construct of the quantitative data used in this research is shown in **Table 1**. The definition for each metric is provided in Appendix 1.

**Table 1** Sample of Structural Metrics for the AMGEN network, for a single snapshot in 2005, Quarter 1, Tier 1-4.

| Year 2005 | Node Count | Edge Count | Average Degree (Edge/Node) | Average Path Length | Network Diameter | Graph Density |
|---|---|---|---|---|---|---|
| Tier 1 | 16 | 16 | 1 | 1 | 1 | 0.059 |
| Tier 2 | 6 | 6 | 1 | 1 | 1 | 0.045 |
| Tier 3 | 10 | 10 | 1 | 1 | 1 | 0.064 |
| Tier 4 | 7 | 8 | 1.14 | 1 | 1 | 0.051 |

To analyse the supply chain operation, we provide a series of visual images which demonstrate the evolution of these sample metrics over time. By combining the graphical images from Figures 2-4 with the structural metrics, it is possible to gain insight into the supply network evolution. Ultimately, when the financial, structural, and geographical information are synthesized, a true picture of the supply network can emerge.

In **Figure 8**, we view the relationship between edge and node counts by examining the average degree of the network as it expands. For Tier 1, these statistics coincide since typically the nodes are connected to the focal node in a concentric circle. But, as the network expands, the relationship between edge count to node count diverges. This is particularly noticeable from 2013, where the edge count is approximately double the node count. The graphs show that there is a correspondence between the growth in AMGEN's revenue, highlighted in **Figure 1**, (2013 onwards), and network growth as shown in **Figure 8**. Thus, by monitoring the structural growth of a supply network, one can obtain an idea about the fiscal health of the focal network.

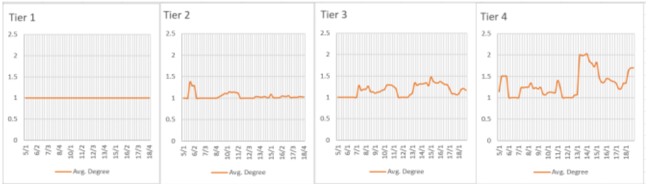


**Figure 8** AMGEN Average Degree by Tier 2005-2018; Source – FACTSET

Since the average degree reflects the ratio of edge count to node count it follows that to some extent, average degree can also be used as an indicator of supply network expansion. When the average degree increases, this implies stronger interconnectivity among the firms in the network. In fact, our previous research (Orenstein and Tang, 2021) indicated that in general, average degree is negatively correlated with firm performance, and that the overall performance of the Supply Chain Network (SCN) decreases as more connections form in the SCN. In **Figure 8**, we can confirm that, the average degree reaches a high in 2013 and then appears to fall. This decrease might be an indication of the sharp increases in financial performance highlighted in **Figure 1**, and the negative correlation we observed in our earlier research (Orenstein and Tang, 2021).

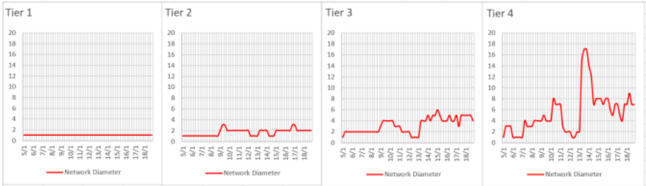


**Figure 9** AMGEN Network Diameter by Tier 2005-2018; Source – FACTSET;

The diameter of the network is the largest distance between any two firms in the network. As this number gets larger, it may be difficult to govern the supply network under a centralized regime. The diagrams in **Figure 9** show the network expansion from this perspective; one can observe that with the addition of each tier, the network expands and the largest distance between any two firms in the network grows proportionately. In 2013, at tier 4, the diameter is at its largest at 17 hops but then scales back. This statistic is important since it has implications for network control in a centralized network. As the network diameter increases, it may be more difficult to control the network in its entirety. If the network diameter remains stable, (or within the same range of values), then network control may be achieved.

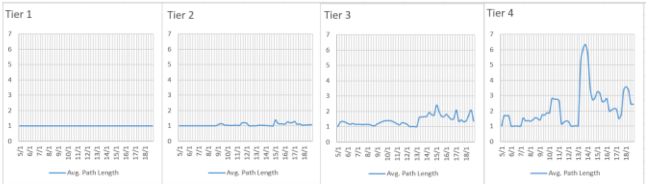


**Figure 10** AMGEN Average Shortest Path Length by Tier 2005-2018; Source – FACTSET;

The average shortest path length provides a measure of how close the firms are to each other. The average shortest path length increases as more tiers are included in the SCN. When the network is small (Tier 1 and Tier 2), this statistic remains stable hovering around 1, which implies that the firms in the network are closely located. As more tiers are included in the network, the average shortest path length grows commensurately indicating a more complex architecture among firms. If one compares **Figure 3** with the data in **Figure 10** one can deduce that the more complex structure in 2015 corresponds to an increase in the average shortest path length most noticeably as we examine the higher tiers. In terms of supply chain decisions, a disruption in the network on a lower tier has less impact than when one occurs in a higher tier. By examining the average shortest path length, managers can determine which suppliers are critical to ensuring smooth operation.

The density of a Supply Chain Network (SCN) indicates the level of interconnectivity between the firms involved. SCNs with high density indicate good levels of connectivity between firms which can be favourable in terms of efficient information exchange and improved robustness due to redundancy and flexibility, (Sheffi and Rice, 2005). In **Figure 11**, the overall graph density increases as more tiers are included in the SCN. However, unlike the other statistics of average degree and average path length, network diameter, the graph density appears to be declining especially at the higher tiers, aside from an increase in 2011-2013; This suggests that as the network expands, it may be more difficult to ensure full connectivity between the nodes, and supply chain managers might want to strive to keep the network of connections simple.

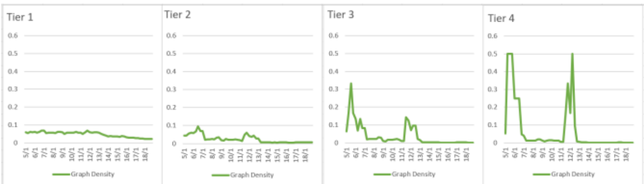


**Figure 11** AMGEN Graph Density by Tier 2005-2018; Source – FACTSET.

### *4.4 Discussion of the Results*

The analysis presented in this paper highlights the importance of performing supply network analysis using a layered approach. Using a basic visual map of the supply network one can then apply different constructs to explore the network's performance.

First, the map can be used to identify the critical nodes in the network as well as understand its dynamic evolution. This is an important aspect of supply chain mapping since data sources do not always lend themselves to the dynamic nature of a supply chain. In this tool, one can view the expansion of the supply chain, not only at the tier level but also over time.

Second, one can apply the geographical layer to explore the location of key nodes and the distribution of nodes in the network, across a geographic region. One can examine what proportion of nodes are in one region and how many are dispersed nationally or abroad. This aspect of the tool can help network managers make decisions in terms of re-shoring as they can use the model to explore the impact of removing or re-distributing key nodes.

Third, financial metrics can be collected and examined to explain which nodes are more significant in terms of the overall network performance. This helps managers in understanding disruption, for example, a node whose financial contribution is significant will have a higher impact on the entire network if it fails.

Finally, structural metrics can provide detailed insight into the performance of the supply network. For example, we can observe the dynamic nature of the supply chain operation by recording the average degree. Likewise, by observing the rise and fall in network diameter, managers can determine when control of the network is more feasible. As the network diameter increases, it may be more difficult to control the network in its entirety. If the network diameter remains stable, (or within the same range of values), then network control may be achieved. As the average shortest path increases this implies more complexity in the network, and this implies that managers will find it harder to control. In terms of supply chain decisions, a disruption in the network on a lower tier has less impact than when one occurs in a higher tier. By examining the average shortest path length, managers can determine which suppliers are critical to ensuring smooth operation. The density of a Supply Chain Network (SCN) indicates the level of interconnectivity between the firms involved. SCNs with high density indicate good levels of connectivity between firms which can be favourable in terms of efficient information exchange and improved robustness due to redundancy and flexibility.

## 5. CONCLUSIONS AND FURTHER WORK

In this paper, we described a framework which can be applied to the existing visual form of any generic supply network. The mechanism enabled us to obtain some insight into the network operation.

The central idea for this research was to introduce additional layers of information, including structural, geographic as well as financial. By superimposing these three dimensions on the existing network map, we can provide an understanding of the network that goes beyond the picture. Essentially, each dimension contributes a layer of knowledge to the visualization, thereby creating a measure of transparency in the original, somewhat opaque visualization. Using this three-pronged approach, the result is a comprehensive visualization of the supply chain network under consideration. In addition, the technique can easily be extended to study the dynamic behaviour of the network.

In the paper, we used the AMGEN network to develop the overall mechanism which can then be applied to study the operation of the supply network. We started with a basic network map which highlighted the tiered relationships in the supply chain. The map was then enriched with geographical information which highlighted the locations of each of the firms in the network. Structural relationships were then calculated to provide a quantitative overview of the dynamic evolution of the networks. This information was then supplemented with financial data which helped identify the dominant (critical) nodes in the network. Both strands of information (financial and structural) are presented as part of the visualization resulting in a meaningful understanding of the supply chain network's operation. The framework that was developed in this paper is easily applicable to other supply network structures for which tiered relationship data is available.

The tool that is showcased in this paper can aid supply chain managers in their decision-making process. For example, we showed how the graphical visualization of a basic tiered network helps managers identify critical nodes in the network that act as bridges or gateways to a sub-network. This has implications, particularly in the event of a disruption. What happens to the supply network connectivity if a critical node fails. Using the tool to identify critical suppliers can help supply chain managers make decisions about switching suppliers. This is a fertile area for research, and the tool provides a way of highlighting such issues. Work is underway as to how to rank these critical suppliers using centrality measures. This will be reported in a follow-up paper.

We evaluated the evolution of several structural metrics over a ten-year time span across multiple tiers. Each metric demonstrated different aspects of the supply chain network operation. For example, we showed how the average degree doubles as one expands to the higher tiers, suggesting that the web of connections, particularly at the higher tiers, gets more complex. Similarly, we showed how network diameter, which represents the largest distance between two firms increases by tier. This feature can make the government of the overall supply chain more challenging.

Average path length measures how close firms are to each other, and like network diameter, this statistic becomes more variable as the network expands. Like the network diameter, it is wise to keep the average path length low, as the network is then more robust to disruption, suggesting that supply chain managers should monitor these statistics to ascertain the overall network health. Network density suggests how much interconnectivity there is between firms. When this number increases, it may be more difficult to control the network. We have observed that the network density of the SCN may increase at the higher tiers, but this increase is not uniform. There are instances when the network density falls, even at the higher tiers. When the network density is low, it might be wise to target control strategies since the impact of change will be less significant. This is an area for future research.

In summary, using the sample structural metrics obtained from the tool, managers can make decisions about control of the network to target in terms of disruption and maintaining the overall health of the network. As indicated, managing disruption at the lower tiers has fewer negative implications than at the higher tiers where the network can get more complex, and the removal of a node has implications to maintaining connectivity.

One can also use the tool as a stepping-stone in understanding the impact of re-shoring. The geographic information, coupled with the visual structural map, can help managers analyse the impact of re-shoring a supplier. There are clearly implications especially when examining the impact of re-shoring a supplier that acts as a gateway node. This is a topic for future research.

Using the research tool developed in this paper, we would also consider to what extent, when there is growth and the network expands continuously by the addition of new nodes, do these new nodes attach preferentially to nodes that are already well connected? Is a large, well-known company more likely to attract new nodes or suppliers at a faster rate than a small, less-known company? Additionally, we plan to use the maps to explore the impact of COVID-19 on supply chains. For example, how does the COVID-19 pandemic affect the financial performance of companies with different supply chain networks.

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# APPENDIX A

These metric definitions are summarized below along with supply network context.

**Table A1** Node and network level metrics used to describe the supply network topology.

| Mathematical Representation | Contextual Definition |
|---|---|
| Network Size *(N,L)* | The size of a given network is defined as the number of nodes and links and characterizes the overall scale of the network. |
| Degree $k_i = \sum_j a_{ij}$ where $a_{ij}$ is any element of the adjacency matrix *A*. | Represents the number of connections a company has. For example, in a network, the company with the highest degree will likely be a key operator in the network. |
| Average Degree<br>$\langle k \rangle = \frac{\sum_i k_i}{N}$ where *N* is total number of *N* nodes in the network. | Indicative of how many connections a firm has. A high average degree implies strong interconnectivity among the firms in the network. |
| Network diameter (*d*)<br>$diameter = max_{i,j} l(i,j)$ where *l* is the | The diameter of the network is the largest distance between any two firms in the network. As this number gets larger, it may be difficult to govern the supply network under a centralized regime. |

| | |
|---|---|
| Average Path Length is defined as $$m = \frac{1}{N(N-1)} \sum_{i \neq j} d(v_i, v_j)$$ Where $d(v_i, v_j)$ is the shortest path between nodes *i* and *j*. | The average path length is defined as the number of hops traversed along the shortest path from node *i* to node *j*. The average shortest path length provides a measure of how close the firms are to each other. |
| Graph Density is defined as $\frac{<k>}{N(N-1)}$ where $\langle k \rangle$ is the mean degree of all nodes and $N$ is the number of nodes in the network with $0 \leq D \leq 1$ | Density of a SCN indicates the level of interconnectivity between the firms involved. SCNs with high density indicate good levels of connectivity between firms which can be favorable in terms of efficient information exchange and improved robustness due to redundancy and flexibility, (Sheffi and Rice, 2005). |
| Degree Centrality | The number of direct neighbors a given firm has. A firm with the highest degree is deemed to have the largest impact on operation decisions and strategic behaviors of other firms in that network. |
| Eigenvector Centrality | Measures firm's influence in the network by considering the influence of its neighbors. |
| Closeness Centrality | The measure of time it takes to spread the information from a particular firm to other firms in the network. |
| Betweenness Centrality | Number of shortest path relationships going through it, considering the shortest path relationships that connect any two given firms in the network. It signifies importance in the network; |

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**Dr. Orenstein** is an Associate Professor in the Department of Computing and Decision Sciences, Stillman School of Business, Seton Hall University. Dr. Orenstein is the Academic Director of the Master's in Business Analytics graduate program and maintains the undergraduate and graduate curriculum in Supply Chain Management at the Business School. Dr. Orenstein's current research interests center on data visualization and the structure of supply networks. Her research, which includes both contributions to theory and practice and to the scholarship of teaching, has appeared in the Journal of Networks and Spatial Economics and INFOR. She has also presented her work at DSI, POMS, INFORMS, MSOM and the SCMA. An earlier paper "Supply Networks: An Empirical Analysis of Topological Structure" won Best Paper Award at the Supply Chain Management International Symposium (SCMA), held in Niagara Falls, Canada, June 14-15, 2016.