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Visual analytics for supply network management: System design and evaluation

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ABSTRACT

We propose a visual analytic system to augment and enhance decision-making processes of supply chain managers. Several design requirements drive the development of our integrated architecture and lead to three primary capabilities of our system prototype. First, a visual analytic system must integrate various relevant views and perspectives that highlight different structural aspects of a supply network. Second, the system must deliver required information on-demand and update the visual representation via user-initiated interactions. Third, the system must provide both descriptive and predictive analytic functions for managers to gain contingency intelligence. Based on these capabilities we implement an interactive web-based visual analytic system. Our system enables managers to interactively apply visual encodings based on different node and edge attributes to facilitate mental map matching between abstract attributes and visual elements. Grounded in cognitive fit theory, we demonstrate that an interactive visual system that dynamically adjusts visual representations to the decision environment can significantly enhance decision-making processes in a supply network setting. We conduct multi-stage evaluation sessions with prototypical users that collectively confirm the value of our system. Our results indicate a positive reaction to our system. We conclude with implications and future research opportunities.

1. Introduction

In an increasingly global, complex, and information-rich economy, decision makers are continuously challenged to effectively manage their supply chains. While there are many analytical and empirical models that have guided decision making, most have adopted a simplified linear perspective of supply chain relationships. One classical example includes the MIT beer game [61], which provides a comprehensive understanding of the bullwhip effect [19] commonly found in multi-echelon supply chain settings. Each player in this game represents an echelon and is responsible for ordering and maintaining inventory in the respective echelon of the linear supply chain [42]. While widely used and valuable to certain decision making contexts, it has been argued that such models inadequately capture and address the rapidly growing interdependent nature between firms.

One approach that has gained significant traction in addressing this issue are network-centric models. Popular across many fields—from natural to human systems—networks have been proven to be highly useful in describing and understanding many different complex socio-economic systems [11,62], and in particular supply chain systems [13,21]. We should note that while closely related and often synonymously used terms, *supply chain* and *supply network* fundamentally emphasize different relational aspects. Specifically, we posit that "supply chain" emphasizes the classical linear, unidirectional view of buyer–seller relationships, while "supply network" emphasizes the bidirectional, interconnected, and complex nature of supply relationships. We adopt this terminological differentiation for the remainder of the paper.

As supply networks grow in scale, scope, and complexity, a decision maker's cognitive capacity to search, monitor, and manage them is strained immensely [14,22]. With significant advancements in information technology and the underlying communication infrastructure, almost every aspect of an enterprise is instrumented and large amount of data is accumulated daily, further amplifying the challenge. These challenges, however, present fertile ground for applying and integrating novel business analytic capabilities

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to support decision-making processes [25]. Investing in analytic capabilities is costly [26], but recent empirical evidence suggests that such investments improve supply chain performance specifically [66], and operational performance in general [18]. While business analytics is welcomed by many scholars and practitioners alike in operations management, one part of business analytic solutions that is often overlooked is interactive visualization [68].

Visual analytics, the fusion of information visualization with analytical capabilities, is a notable emerging methodological approach that can help cope with complex environments by augmenting a human's visual cognitive ability in examining large-scale data [64]. There are many different ways of visually representing supply networks, with some techniques used more frequently than others. According to cognitive fit theory, choosing the right visual representation that corresponds to the mental model of decision makers is an important factor in improving task performance [69,70]. Each visual representation (or layout) has strengths and weaknesses, emphasizing different structural aspects of the network [6]. Moreover, it has been shown that the use of multiple different layouts for the same underlying supply network data can potentially enable decision makers to gain novel and important complementary insights [9]. On the other hand, however, even if different visual representations are presented, much of the potential value is lost if the visual representations do not share a similar point of reference or context. While multiple coordinated views are common practice in the information visualization community [27,35], this principle is just gaining traction in business applications [2,8]. Following well-established principles of information visualization, successful system designs require mindful curation of how to unfold in-depth information triggered by user's needs without overloading the user's cognitive bandwidth. Similarly, carefully integrated analytic and predictive capabilities with interactive visualization has the potential to significantly enhance and transform decision making capacity [52].

This paper introduces a visual analytic system and then describes the design and implementation of a corresponding interactive prototype for understanding and managing supply networks. We begin by identifying a set of design requirements drawn from an extensive review of the SCM and information visualization literature and refined through discussion with expert scholars and practitioners. The three design requirements are as follows: (1) to support multiple views in an integrated interface, (2) to enable interactive investigation of supply networks, and (3) to provide data-driven analytic capabilities. Next, we develop a prototype equipped with such capabilities. We illustrate our prototype system using real-world multi-echelon supply chain data collected from a number of different industries [72]. Finally, we evaluated our prototype system using a multi-phase approach. We first presented and received feedback on our visual representations and interactions from leading scholars and experts at a leading information visualization conference. Integrating this feedback into a significantly revised design, we next held private in-person sessions with two SCM experts with significant years of experience to evaluate the practical utility and appropriate domain functionalities. Integratively, these two sessions provided a form of external validation of our approach from both methodological and practical perspectives. We also received invaluable feedback on content and visual encodings which we incorporated subsequently. Finally, we conducted a focus group user study to test the efficacy of our prototype with potential target users—supply chain managers. Participants were asked to complete a set of tasks using the system prototype and rate its utility and usability. The results of our focus group study reveal that while managers are not necessarily familiar with certain types of visualization, participants found the tool incredibly useful for discovering insights and asking insightful questions about the underlying data.

Our study makes three contributions to the decision support system (DSS) literature. First, the development process of our system provides a set of guiding principles for building data-driven visual DSSs. Second, our system prototype provides fully functional instantiations of the three engines proposed in our system architecture, featuring various network layouts, visual encodings, and real-world supply network data [72]. Third, we provide evaluation results on the value of our prototype based on a series of three evaluation sessions. The results collectively affirm that our prototype suggests sound ways to build a visual analytic DSS for supply chain and operations management issues.

2. Related literature

2.1. Decision support systems for supply chain management

Supply chains consist of a series of buyers and sellers connected in tandem. Managing these relationships across multiple abstraction layers called echelons requires a number of complex decision tradeoffs involving multiple and potentially conflicting objectives [30]. For this reason, SCM continues to be a very suitable application domain for DSS. Typical decision problems in SCM, in a broad sense, include inventory management, facility location, vehicle routing, and supply chain coordination, just to name a few. An exemplar DSS that aims to assist in solving the location-routing problem is presented by Lopes et al. [46]. The location-routing problem requires solving two NP-hard problems in combination: facility location and vehicle routing. This tool adopts a geographical representation of transportation networks. It does not, however, coordinate different views of this network for helping decision makers understand its topological nature and provide additional insight into the problem context. Similar real-world DSS applications for SCM [51] have been developed across various industries including pharmaceuticals [55] and energy [39].

While the foundational decision-making framework in SCM does not presume whether the supply chain is subject to a single- or multi-echelon model, several studies including Liang and Huang [45], indeed have built systems accommodating multi-echelon supply chains. Still, many studies have assumed a single node for each echelon highlighting interactions only across echelons rather than within an echelon. One way to model multiple interacting agents in supply chains is through a simulation. For example, van der Vorst et al. [67] modeled a multi-echelon food supply chain for a simulation study. Simulations are often used to support SCM scenario planning decisions [68]. Although simulation is a powerful tool to develop prescriptive business intelligence, the human-in-the-loop piece is often missing. There may be a rift between the developed simulation models and reality. Thus, incorporating an visual interactive engine into simulation models is of significant importance [67]. Although their framework was intended for simulation-based decision support systems for SCM, we extend their argument by demonstrating that sophisticated visual analytic support can boost the benefits that their conceptual framework can bring to analysts, supply chain members, and the whole system.

2.2. Managing complexity of supply networks using visualization

As the conceptualization of business relationships has transformed from sequential and linear to network-oriented and interconnected, network visualization has come to play a significant role in providing business intelligence in navigating and managing such a complex network of competitive and cooperative relationships [15,32]. This phenomenon is exemplified by the recent booming app ecosystem in the mobile platform business [3] and by the information and communications technology industry in general [9]. Thanks to large and rich data accumulation over time [20], identifying temporal pattern changes in networks using the visualization approach has received increasing attention [54]. For instance, visualization helps explain ecosystem-level transformation activities particularly around the cases involving key industry events such as mergers and acquisitions [12]. Moreover, the visualization approach is more frequently equipped with interactivity as technologies for rich interaction are burgeoning. One example is applying the interactive analytic approach to enhance traditional system modeling diagrams for manufacturing systems [10].

SCM is not an exception from this trend of interconnectedness. A supply chain is traditionally modeled as a bilateral relationship between suppliers upstream and customers downstream, but these days, such relationships have become increasingly bidirectional and involve many other third-party suppliers and external stakeholders. Accordingly, it is increasingly harder for managers to be vigilant to the events in their surrounding supply network environment [4]. Although game-theoretic, optimization, and simulation modeling approaches of supply chains emphasize the essential characteristics of SCM, helping practitioners grasp a holistic picture of the actual supply network that they manage calls for an approach that can summarize and describe the network in a succinct yet rich manner. Because of the complexity imposed by the network structure, objectives that managers strive to monitor and optimize may diverge and conflict. For example, reducing total costs and obtaining reliability of supply networks can be two conflicting objectives [73]. DSS can be particularly helpful for providing a big picture and helping managers interpret and make decisions in such a network context [63]. Thus, more scholars are embracing the rich visualization capabilities to diagnose the current state of supply networks.

Yet, static visualizations are primarily used to describe supply networks in order to disentangle complexity and aid the cognitive process of managers [6]. To support effective decision-making needs of managers, cognitive fit theory presupposes that the congruence between the mental model of a decision maker and the visual representation is critical [69,70]. The modern challenge is that many decision problems are dynamic and rapidly changing, thus the representation needs to be updated accordingly in a timely manner. Visual interaction techniques regulate the speed at which decision makers need to absorb and process information. Designers of a DSS need to think through the information needs of decision makers in the stages of a decision-making process and provide sufficient yet not overwhelming interaction methods that supply the right amount of information. Moreover, DSS should ideally help decision makers in all points in the loop of the decision-making process [58]. In their seminal paper, Shim et al. [58] conceptualize the iterative decision-making loop as starting from problem recognition to alternative generation, analysis, and implementation. According to this conceptualization, many current decision support systems in SCM help in the problem recognition stages, while leaving a gap in the alternatives exploration stage. Future visual analytic applications are expected to be equipped not only with visualization capabilities that assist managers in recognizing latent problems in supply networks, but also with analytic capabilities that help formulate feasible alternative solutions to the problems.

2.3. Visual analytic support for data-driven decision making

In addition to supply chains being increasingly modeled as networks, another notable trend is the explosive digital availability of daily operations data. Commonly referred to as the big data phenomenon, the increasing abundance of data is leading to a desire for more data-driven decision making [47]. Not surprisingly, data analytics has emerged as an important subfield for decision science and information systems in part to generate insights and to enhance business performance [20]. There is an increasing body of work that has found empirical evidence on the positive influences of analytical capabilities on firm-level operational performance. Trkman et al. [66] showed that analytical capabilities measured in four areas of operations—make, plan, source, and deliver—positively impact supply chain performance. Chae et al. [18] examined the positive influence of accurate data collection and advanced analytics on operational performance of a firm. Despite such evidence on the positive relationship between business analytics and firm performance, not much attention has been given on how to facilitate the managers' understanding and adoption of sophisticated analytic engines for improved decision making. Operations managers are domain experts making difficult decisions based on heuristics from their knowledge and experience, but they do not necessarily understand what value analytic engines can offer for data-driven recommendations [31]. Visual analytics aims to bridge this gap for managers by fusing data analytics and information visualization [10].

The common misperception in the business domain is that visual analytics is simply providing "pretty" visual representations of some underlying data. Mindfully curated visual elements such as composition of shapes and choice of visual elements that represent abstract quantities are indeed important constituents of successful visualization applications [48]. Since the groundbreaking cognitive fit theory for decision making [69,70], a number of recent studies in DSS still embrace, adopt, and implement the theory in different ways [44,50,57]. However, interaction is an equally critical—and often overlooked—part of visual analytics in DSS. Interaction allows users to dynamically explore and manipulate the data. When interaction is combined with visual representation, the full potential of visual analytics for decision making can be achieved [53]. Accordingly, the mode of interactions used in SCM application should be carefully curated and designed.

We acknowledge that many DSSs have already incorporated some form of visualization into their user interface design. For instance, the integrated DSS developed by Hunt et al. [39] for the UK energy sector provides a sensitivity analysis interface that allows visual inspection of different scenarios given varying key parameters. However, in most cases, visual representations and interactions are chosen by researchers without a grounded basis of which representations are most suitable to their context. Not much attention is given to how decision makers respond differently to alternate visual representations of the same underlying data. We aim to highlight the strengths and weaknesses of certain visual representations for a given SCM task and propose a useful set of design guidelines for scholars and practitioners who want to incorporate visual interactive elements into their own DSS development contexts.

3. Design requirements and system architecture development

We derived three salient system design requirements from the supply chain management and information visualization literature. We also conducted informal interviews and engaged in discussions with expert scholars in SCM to further propose our system architecture and visual analytic approach. The resulting refined design requirements are as follows:

- **Support multiple views in an integrated interface.** According to the DSS literature, data representation has an important impact on decision-making processes [59] and performance [69,70]. When multiple complementary views are present, coordination between views is important since users can lose context when switching between views. In the network visualization domain, a few studies have attempted to blend different network layouts to enhance strengths of each individual layout [35,36]. These studies show that, for example, fusing node-link diagrams and matrix layout can result in two representations that are valuable complements to the decision making process. Following this line of reasoning, we choose several important layouts that highlight different aspects of supply networks and provide techniques to switch between them easily.

Depending on the focal issue of interest, supply chain managers can make better-informed decisions by investigating the same elements of interest using different representations. For example, if distinguishing central nodes from peripheral ones is important, then the force-directed layout highlighting the underlying clustering structure may provide more direct insights than other layouts. Visualizations using other representations even on the same network data can provide additional intuition not seeing in the former ones that were generated. Therefore, a desired system must allow switching between different views to ultimately integrate the discovered insights.

- **Enable interactive investigation of supply networks.** Social networks or information communication networks have been traditionally depicted in static images [65]. Interactive visualization has quickly become the new norm for network visualization [16]. One of the benefits of interactive visualization is to provide detailed information on demand [48]. Users do not have to be overloaded with all data and information at once. Visualization helps provide an overall big picture, while interacting with the visualization provides visual cues and shows additional details when needed.

  Properly designed interaction techniques built in DSS suggests at least two implications for the modern decision-making research and practice. First, dynamic decision problems unfold subsequent problems based on earlier decisions. According to the cognitive fit theory [69,70], visual representation should be updated accordingly to reflect such dynamic changes in the decision space. Visual interaction techniques help orchestrate the updating process. Second, a manager's decision-making cognition is often overloaded due to increasing amount of data for making informed decision [20]. Interaction techniques again help managers cope with such decision complexity by feeding the right amount of necessary data in a timely manner. In sum, a desirable DSS for SCM should allow interactive exploration of the supply network.

  The current use of network visualization in the SCM and other management literature in general is primarily static, while the information visualization community is swiftly shifting towards interactive visualization. We expect supply chain managers to learn much more about the data through various modes of interaction with visualization such as clicking, dragging, hovering, and filtering. Reflecting this need and expectation, we implement interactive mechanisms to provide detailed information about supply network activities on demand. This details-on-demand approach reduces clutter of the overall visualization and helps manage user attention. Smooth interactive transitions between views also allow managers to understand the effect of different visual encodings based on different metrics.
- **Provide data-driven analytic capabilities.** There has been a continuing research effort to leverage visualization in predicting the future state of a system or its evolutionary trajectory [28]. Decision makers are often interested in exploring alternative scenarios by varying key parameters [49]. Thus, a desirable DSS should provide analytic and predictive capabilities beyond a descriptive portrayal of the supply network. For instance, managers may want to understand how disruptions (e.g., unexpected costs or delays due to natural disasters) in some parts of the supply network impact the performance of the entire network.

  In addition to helping understand the supply network as-is through visualization, our system needs to allow managers to explore potential alternative configurations such as inflated or deflated costs or delays at a certain stage in their supply network. Such functionality is useful to foresee gain or loss from managing mission-critical joints in the network. Monitoring risks and provisioning sufficient capacity to such critical points can lead to performance gains for the whole network, while working on peripheral activities may only result in minimal impact on overall performance. Exploring different configurations of costs and delays helps managers focus on mission-critical activities in a complex supply network. One way to address this need is to provide sensitivity analysis that shows how changes in costs and delays at certain nodes impact the entire supply network performance.

Based on the above three design requirements, we develop a conceptual system architecture for building a visual analytic application for supply network management (shown in Fig. 1). Specifically, we propose that a visual analytic system should contain three main engines corresponding to each design requirement. The visual representation engine should handle how to represent numbers and abstract concepts in visual forms in a way that facilitates the interpretation process for supply chain managers. The interaction engine takes in user input and estimates the underlying user intention of the current analysis. The descriptive and predictive analytic engine parses in accumulated data and builds models using sophisticated computational and mathematical methods. Together, we proposed that our human-in-the-loop centric visual analytic architecture can help improve human decision making [23].

4. Data and research context

To instantiate and validate our visual analytic system architecture, a real-world SCM context and corresponding supply network is required. One challenge is that extensive supply network data across different industries let alone different companies is rarely obtainable, as supply network operations are one of the core functionalities that a company engages in and data pertaining to them are often considered proprietary. To overcome this issue, we leveraged a well-documented supply network dataset offered to researchers by Willems [72]. This data source contains supply network data for various industries ranging from food preparations to semiconductor to aircraft engine manufacturing. Perhaps the most important feature of this dataset is that cost, delay, and demand data are included for each stage in the supply network. Such data elements are generally considered sensitive sources of information, making this dataset unusually particularly valuable as it captures the characteristics of real-world supply networks across multiple industries.

The dataset covers 38 supply networks from 21 different industries. The network size varies greatly across cases. The smallest network consists of 8 nodes and 10 edges, while the largest has 2025 nodes and 16,225 edges. Nodes in a network represent particular stages within the whole supply network context and fall into one of five types: procurement, manufacturing, transportation, distribution, and retail. It is rare for one supply network to contain all node activity types. In most cases, only three or four activity types are present in a given network. Some of the nodes are also marked as demand-facing stages. The demand-facing stages are often either retail or distribution activity types. They are, by definition, downstream activities from which we can trace back upstream activities following edges between nodes. Since this data clearly indicates source and target nodes, we can construct a series of directed graphs for each supply network.

In order to mask the actual identity of companies involved in the supply network, the numbers are purposely shuffled while aggregate statistics of the network are preserved. Beyond this, an additional worksheet has been published as a supplementary material that

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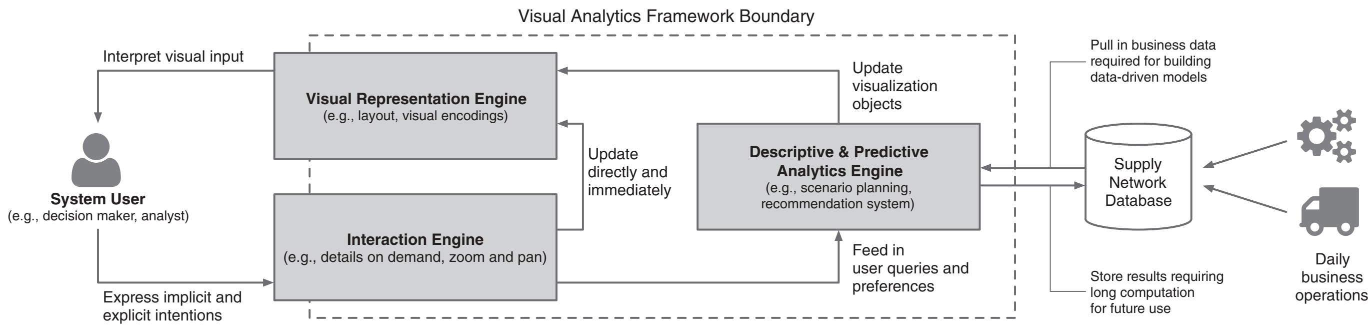

Fig. 1. Visual analytic system architecture for supply network management.

explains how to compute supply-network-level aggregate measures such as average cost of goods sold (COGS) or average cycle time. Table S1 in the supplementary material section presents a simplified schema of the dataset adapted from Willems [72]. Both mean and standard deviation are reported for stage time and demand, while only the mean value is reported for stage cost.

Although there are an extensive number of industries covered in this data source, we acknowledge that significant heterogeneity may exist across them. We would argue that certain industries in our dataset are high velocity in the sense that they are characterized by short product lifecycles and high rates of change in technology and market conditions whereas low velocity industries, such as the automotive industry, exhibit high levels of specialization and tightly integrated production [29]. This clockspeed of industry dynamics can have a fundamental influence on the likelihood of adoption of our system to the practice. Moreover, the dataset does not provide any time-varying information or timestamps of SCM activities. We thus note that we neither demonstrate nor test our system in a time-varying SCM context, but it is certainly possible to have our system adapted to such a context if time-stamped data is available. Applying visual analytics to a dynamically changing network is an active area of research in information visualization.

Several operations management studies have used this dataset to validate analytical models, including the impact of radio frequency identification (RFID) adoption and implementation [24], the value of real-time information in SCM [56], and a safety stock inventory policy [38]. As the original intention of this dataset was to study inventory optimization, studies that utilized the dataset also focused on inventory management issues. To the best of our knowledge, there is no study that extensively applies visual analytics to this dataset. Our visualization effort thus also contributes to operations and SCM domain because our prototype can help future researchers interested in this dataset understand the various facets of this data.

5. System

5.1. User interface

Fig. 2 shows the main user interface (UI) of our web-based system. The UI consists of three major parts: data selection tool, main canvas, and detailed information panel. The top bar contains the data selection tool and allows users to select which supply network data to visualize using a dropdown menu. The dropdown menu displays a chain serial number, a company serial number, and the numbers of nodes and edges, which allows quick identification of the supply network of interest. Whenever a user selects a different dataset from the dropdown menu, the main canvas shows the chosen supply network in a force-directed layout by default.

The large area below the top bar is the main canvas where the interactive visualization is rendered. The color legend is drawn on the top left corner of the canvas. Depending on the coloring scheme, colors are depicted in either a categorical list or continuous spectrum. Depending on the layout selected, the canvas may be panned by dragging with mouse and zoomed by scrolling the mouse wheel.

On the right-hand side of the UI is the detailed information panel which contains detailed information of the selected supply network and interactive controls governing which visualization to be shown in the main canvas. This pane can be slid out and hidden in case maximal size of the main canvas is needed. It also contains explicit navigational control buttons of panning and zooming if the chosen layout supports navigational functionalities. Furthermore, this pane contains several collapsible boxes inside. The first box provides the detailed information and summary statistics about the selected supply network. In-depth information includes network and company identifiers, industry classification, network size (i.e., the numbers of nodes and edges), average COGS, and average cycle time. At the bottom is a bar-shaped pie chart showing the composition of activity types for a given supply network. Below the first box is a second box that selects which layout is to be applied for network visualization. We provide users with five layout options: force-directed, circular, treemap, matrix, and substrate-based. The third box below allows the user to select the visual encoding scheme, i.e., which variables are to be visually encoded for shape, color, opacity, etc. The last box lists available interaction options that vary with each layout selection.

We implemented the prototype using d3.js [16] in JavaScript and HTML. The d3.js visualization framework provides excellent libraries of popular network layouts and supports rich interactive functionalities and smooth graphical transitions. One of the advantages of implementation using web technology is easy deployment. Our prototype is deployed on the web (URL hidden for review purposes) using Heroku, a platform-as-a-service company.

In the following subsections, we explain the various layouts, visual encodings, interactions, and what-if analysis panel incorporated in our system. We use the same supply network throughout our description to provide a consistent view of using our system. The chosen supply network is from the “Arrangement of Transportation of Freight and Cargo” industry and its identification number given by Willems [72] is 14. This network contains 116 nodes and 119 edges.

5.2. Visualizations and interactions

5.2.1. Layouts

We implemented five well-known network layouts to highlight different structural aspects of the network: force-directed, circular, treemap, matrix, and substrate-based. We allow supply chain managers to easily transition between layouts using a dropdown control. While there are many other sophisticated and advanced

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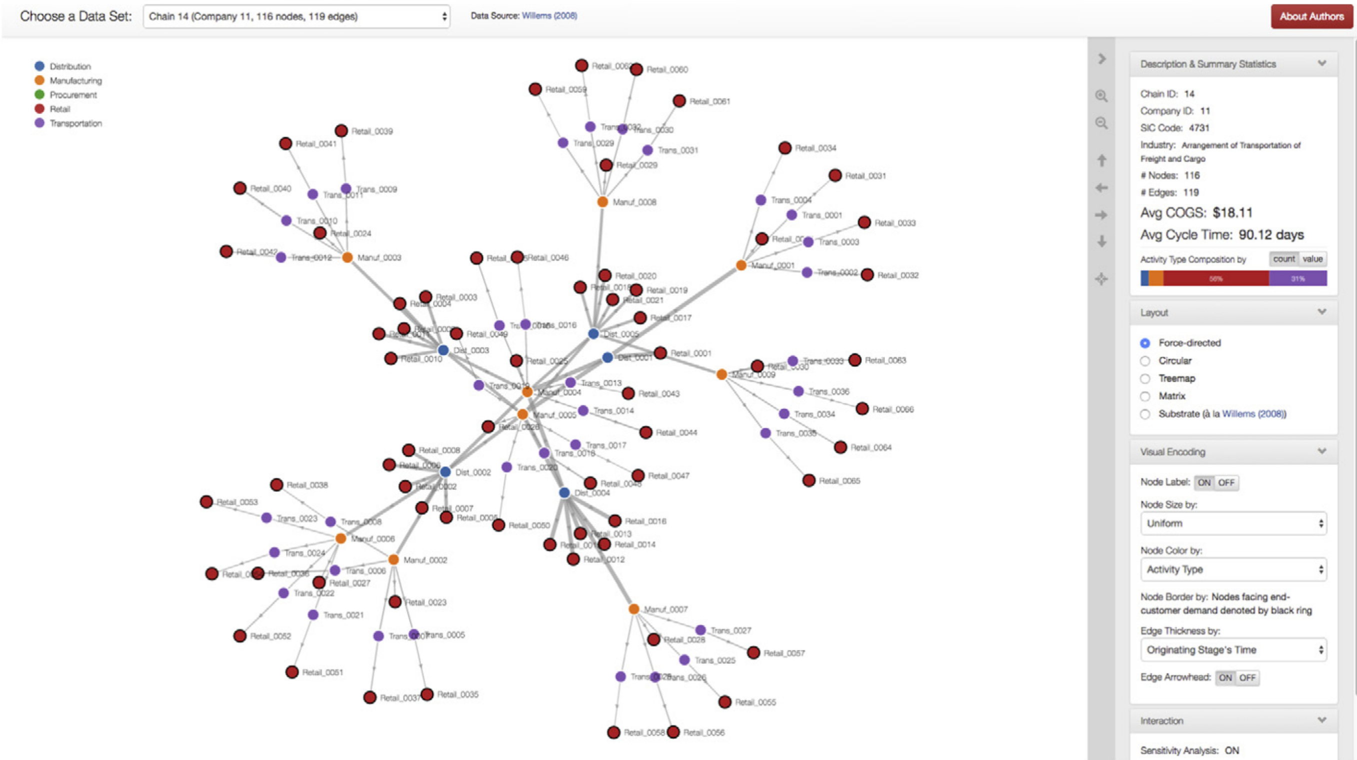


Fig. 2. Visual depiction of main user interface, showing force-directed layout of supply network from the transportation industry.

layouts other than those employed in our system, this set is purposefully chosen for several reasons. First, we wanted the chosen set of layouts to individually cover different aspects but collectively cover a comprehensive set of aspects of networks. For instance, the treemap layout focuses on node attributes and the matrix layout highlights edge structure. Both force-directed and circular layouts are good at showing an overview of the network, but the force-directed layout emphasizes clusters and hierarchical structure. In contrast, circular layouts highlight flows within the network. On the other hand, the treemap layout shows only nodes and the hierarchical structure of them, disregarding edges. Lastly, we chose the substrate-based layout because it is the default layout that was published along with the dataset itself. This substrate-based layout is the classic depiction of supply networks. We use this layout as a reference for comparison with other layouts. In the subsequent paragraphs, we explain each layout in detail from the perspective of how each layout uniquely helps decision makers navigate and manage supply networks.

5.2.1.1. Force-directed layout. This layout applies the laws of physics for forces and motions to determine the node positions. We employ the d3.js implementation of the layout. Details of physical simulations are found in Jakobsen [40]. Essentially, the force-directed layout regards all nodes as charged particles repelling each other. Edges of various thicknesses and gravitational forces hold these particles together and keep them from diverging indefinitely. The layout takes in parameters such as amount of charges, strength of gravitational forces, and friction in movements. The layout then computes with these parameters the positions of all nodes in an iterative and recursive manner. As the iterations go on, all node positions convergence. The d3.js program shows the iterative process of convergence via an animated visualization.

The force-directed layout has been extensively used to identify and emphasize clusters, modules, and connectivity structure of the whole network. Fig. 2 shows the advantage of this layout in understanding the chosen supply network from the transportation industry. Red, purple, orange, and blue nodes represent retail, transportation, manufacturing, and distribution activities, respectively. We can visually identify the recurring module of one manufacturer connected to four retailers through transportation services as well as one retailer directly linked to the manufacturing itself. We can find these one-to-four patterns recurring seven times in the peripheral areas and once in the center area of the supply network. This layout also highlights the hierarchical structure of this supply network. Two manufacturing nodes at the center are primary sources for the whole network. These two sources supply to regional distribution centers, which in turn supply to regional manufacturing centers. Transportation services are often used to deliver items from manufacturing stages to retail points. Thus, this force-directed layout fluently and succinctly describes the entire structure, connectivity, and hierarchy.

5.2.1.2. Circular layout. This layout places nodes on the circumference of a large circle. The generic version of circular layout depicts nodes as circles of various size and edges as lines of various thickness. In this system, we adopt and implement a modified version of the circular layout called chord diagram [43]. The key aspects of the chord diagram that depart from the generic circular layout are that nodes are depicted as arcs around the encompassing circumference and edges are drawn as filled Bézier curves among arcs. Tick markers outside the arcs denote scale of visualization. We employ the d3.js implementation named as chord diagram.

Fig. 3 (a) shows the same supply network in the circular layout. Arcs around the large circle denote aggregated activities. For example, each colored arc in this figure denotes aggregate distribution, manufacturing, retail, and transportation activities. The way it denotes directionality of flows warrants further explanations in detail. In principle, each activity type has two arcs: a source and a target. For example, there are two orange arcs in this figure. The larger one denotes the manufacturing activity as the source; the smaller one as the target. The flows are colored by the originating activity type's color. For instance, the largest flow is from manufacturing to transportation, and is colored orange in the middle.

The strength of this layout is that it gives a good summary of overall flows between different types of activities. We can see from the figure that manufacturing is the primary source stage for the whole network along with distribution that plays the role of a minor source. Simply put, items come into the supply network via distribution. Some of these inputs are directly forwarded to retail and others go through manufacturing stages. A small portion of manufacturing outputs again go directly to retail, while a major portion is delivered to retail through transportation activities. As such, this chord diagram narrates the summary of flows within the supply network.

5.2.1.3. Treemap layout. Invented by Johnson and Schneiderman [41], the treemap layout is used to visualize hierarchical information structure. This layout is popular across many fields and several business domains have adopted it depict hierarchical business information data [1] and daily stock market movements [71]. The treemap layout highlights node composition in the network, while ignoring connection structure between the nodes. One advantage of the treemap layout is that it utilizes full rectangular space given as a canvas (and is thus considered a space-filling technique). The algorithm to draw a treemap is as follows. A treemap divides a given rectangle into sub-rectangles based on the top hierarchy classification. This process is performed repeatedly until the algorithm hits the bottom of the classification hierarchy. Terminal nodes that do not contain any sub-hierarchy are called leaf nodes and they become the building blocks of the whole treemap.

Fig. 3 (b) shows the same supply network in treemap layout. Node rectangles are scaled by individual stage cost. Manufacturing incurs most costs. Transportation and distribution follow as the second and the third cost sources. Comparing with the composition bar on the right, manufacturing and distribution account for only a small portion in terms of the number of nodes. That is, a small number of manufacturing and distribution activities take up most of the costs in the supply network. On the contrary, more than a half of all nodes consist of retail stages, but they cost little. As such, a treemap layout provides a quick summary on composition of the network.

5.2.1.4. Matrix layout. This layout specializes in visualizing edge connectivity and adjacency, while ignoring node attributes. In this sense, it is a mirror opposite side of aforementioned treemap layout. In a matrix layout, nodes are not explicitly rendered. Columns and rows implicitly stand for nodes. Cells represent the edges between nodes corresponding to the row and the column. The intensity of a cell fill (e.g., darker shading in color gradient) denotes the strength of the edge. The matrix layout is capable of showing directionality of edges. In our implementation, rows represent sources while columns represent targets. In case of an undirected graph, a matrix layout would look symmetric. One limitation of the matrix layout is that the utilization level of canvas space is low for a sparse network having a smaller number of edges compared to the number of nodes. Due to this limitation, a matrix layout can hardly accommodate more than hundreds of nodes simultaneously. Certain features can be built into a matrix layout to mitigate this limitation such as scrollable matrix layouts or space-warp techniques which enable visualization of larger networks.

Fig. 3 (c) demonstrates a matrix layout of the same reference supply network. The first thing to learn from this figure is that the supply network is very sparse. Recall that rows represent source nodes. The empty part in the middle thus means that no edges start from retail stages. The insights gained from this figure are in essence similar to those from circular layout. The difference is that matrix layout portrays connection structure in greater detail.

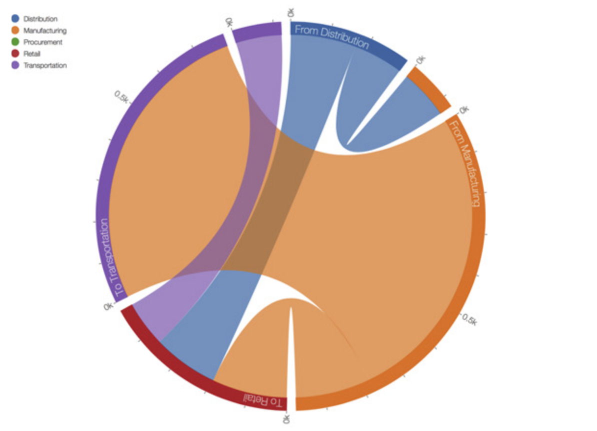
5.2.1.5. Substrate-based layout. This layout is particularly useful in cases where flows among the nodes are largely unidirectional and only a few finite node classes exist. Since these criteria match the structure of many supply networks in our datasets, the substrate-based layout can be a powerful tool for understanding the network structure when used appropriately. This layout was initially used in Willems [72] to visualize the supply networks when the datasets were published. It works nicely for a network of small size, up to about 20 nodes, but fails to provide immediate insights even for moderately large networks of tens of nodes due to its most constraining limitation: clutter and crowdedness. We implement this layout as a reference point for comparison with other layouts. Note that the purpose is not to disprove the utility of this layout. One improvement we make for this layout upon the original version is the panning and zooming capabilities, which mitigate a key limitation of this layout.

The substrate-based layout imposes implicit layers on which nodes are placed. In the case of this dataset, a natural set of substrates would be the type of stage: procurement, manufacturing, transportation, distribution, and retail. Depth from the root node of each network could be another set of substrates. Fig. 3 (d) shows the same supply network in a substrate-based layout. We scaled the nodes of the supply network based off of the x–y positioning of nodes provided in Willems [72]. At first glance, one can realize it is impractical to accommodate all nodes in one canvas screen unless the number of nodes is less than about 20. One advantage of this layout is that users can follow logical flow from source to destination. For instance, users can naturally understand items flow in this supply network from distribution to manufacturing, transportation, and finally retail stages. One limitation would be that users may easily overlook other flow possibilities. As shown in previous examples, a non-negligible amount of items flow from distribution to retail directly. This layout may not necessarily portray such non-standard flows appropriately.

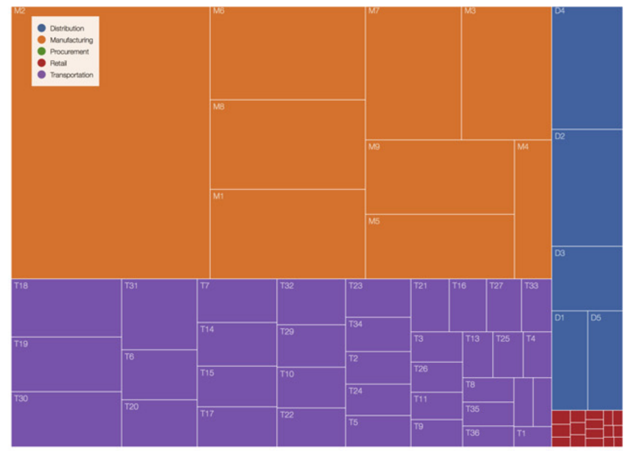
5.2.2. Visual encodings

While layouts highlight different structural aspects of the supply network, choice of visual encodings determine which variables are to be visualized on the canvas. Elements of visual encodings for network visualizations fall into two categories at large: nodes and edges.

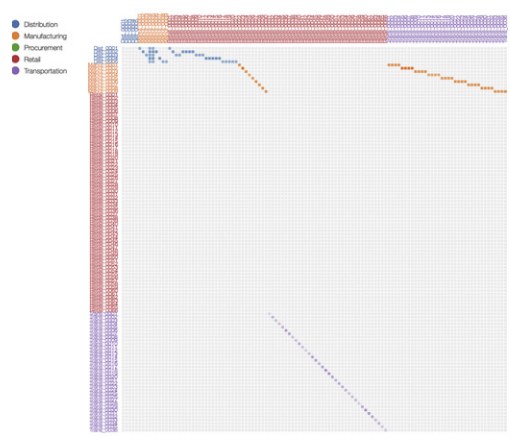
- **Node attribute encoding elements** include size, shape, fill color, fill pattern, border line color, border line thickness, and border line pattern. Some elements are better suited to visualize continuous variables, while others are better for discrete or categorical variables. For instance, size is a natural encoding element for a continuous variable. Some nonlinear transformations such as a logarithm or square root may be needed when a highly positively skewed variable is encoded into node size. Usual candidates for shape include circle and rectangle. Other shapes such as star or triangle may also be used, but using too many different shapes can potentially overload users' cognition. Colors are in general good for encoding both types of variables. When using color to encode continuous variables, choosing a right set of colors from a spectrum is important and there are online tools that help select such color sets [34]. Fill pattern refers to hatch patterns that shade the fill of the chosen shape. Border line can also encode different variables independent of node shape and fill.
- **Edge attribute encoding elements** include line thickness, line color, and line pattern. Since an edge is usually rendered as a line, there are relatively fewer encoding choices using edge rendering. In addition, edge length is determined by node placement imposed by the layout choice, which makes edge encoding limited further. Line thickness is suited for continuous variables and line pattern is good for categorical



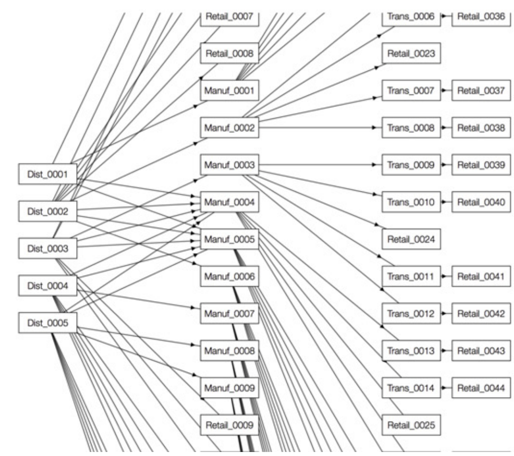
(a) Chord diagram: a special variant of circular layout with arcs and curves. Stages are aggregated and abstracted into activity type level.



(b) Treemap layout: highlights node compositions in the network. Edges are not rendered in layout, leaving out connectivity structure.



(c) Matrix layout: focuses on visualizing edges in relatively equal weights. Node attributes are hardly encoded in this layout.



(d) Substrate-based layout: reconstructed from visualizations published in [72]. Useful when intuitive layers of nodes are clearly present in the network.

Fig. 3. Various visualization layouts.

variables. Line color is again a good way to encode both types of variables.

Table S2 in the supplementary material section lists the strength of each encoding element for different types of variables. However, utilizing all possible visual encodings simultaneously is not necessarily desirable given the inherent limits in human cognition. Node size, node fill color, and edge thickness are often used in combination for a single visualization. Since there can be many different node and edge attributes users want to encode, the system needs to allow users to quickly switch and apply visual encodings on different variables. In addition, some elements may not be available to be rendered in the visualization due to limitations imposed by the chosen layout.

Table S3 in the supplementary material section summarizes the list of visual encodings implemented in our visual analytic system. It clearly indicates that layout can be a constraint to choose available set of encoding elements. The treemap layout has no edge encoding scheme as it does not render edges at all, while the matrix layout only provides a limited set of node attribute encoding.

Fig. 4 (a) shows an example of applying different node attribute encoding schemes in the force-directed layout example in Fig. 2. In this updated example, node size encodes the average delay of a supply network stage, node fill color encodes the downstream cumulative cost, and edge thickness encodes the originating stage's cost. Since node fill color now encodes a continuous variable, the legend on top-left corner of the main canvas turns into a spectrum scale. Colors become stronger towards terminal downstream retail nodes, while central manufacturing nodes are large in size. In particular, the modular cluster on the right-hand side of the network is darker than other clusters. Managers may want to investigate into this cluster and focus on this cluster to figure out how to improve overall chain's cost structure.

5.2.3. Interactions

Interactivity is increasingly becoming a norm for today's visualization applications. It allows decision makers to highlight a part of visualization following user attention and show in-depth information only on demand so as to keep the overall visualization experience from becoming overcrowded. Since most major operating systems employ a graphical UI, there are standard interaction elements accepted by many people familiar with those mainstream operating

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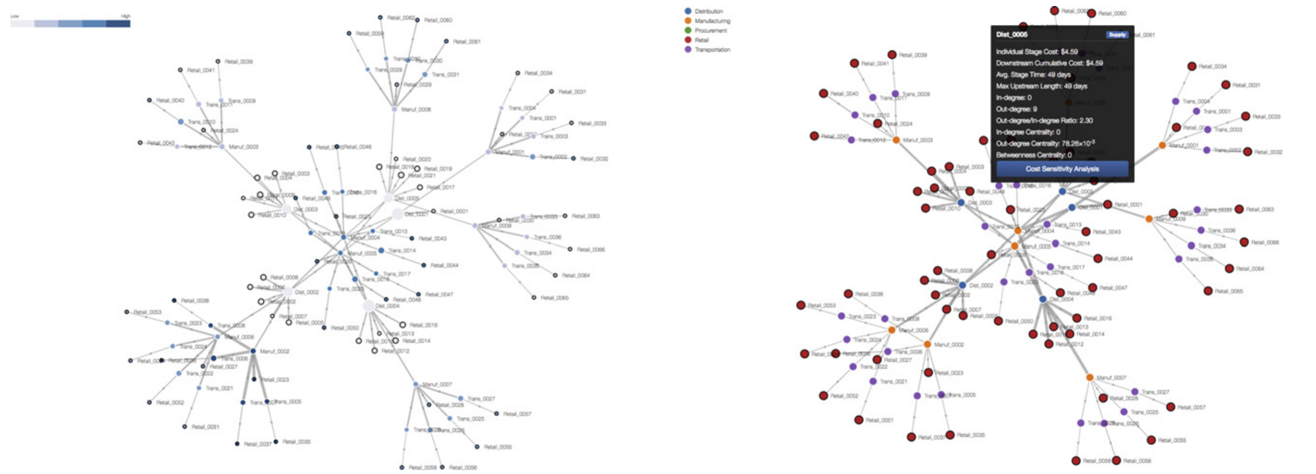

(a) Color and size can encode different attributes of nodes and edges. In this figure, node size, node color, and edge thickness encode average stage time, downstream cumulative cost, and originating stage's cost, respectively.

(b) Popup box shows further detailed information about the selected activity on demand.

Fig. 4. Depiction of how system users can interact with visual objects and alter their visual characteristics based on data attributes.

systems. Major interaction elements include hover, click, double-click, drag-and-drop, and mouse wheel scrolling. Hover refers to the feedback the system provides when a user moves the mouse pointer over a certain object. Click is often associated with explicitly selecting an object, while double-click is associated with executing a certain task. Drag-and-drop is usually used for moving around an object in the canvas. Mouse wheel scrolling is frequently linked with moving the canvas viewing frame or adjusting the zoom level.

Like visual encodings, interactions are also constrained by layout choice. For example, force-directed layout locates nodes in different places depending on the random seed for initialization, while preserving overall structural characteristics. Thus, it is possible to allow users to temporarily displace certain nodes by drag-and-drop interaction. However, such displacement interaction is not possible for rigid layout such as treemap. Another example is zooming and panning functionalities. These functionalities are particularly necessary for those layouts that render visualization in a boundless area. Examples of such layouts in our system include force-directed layout and substrate-based layout. Force-directed layout determines node positions based on simulation of physical forces, so some nodes can be repelled to a far location. Substrate-based layout, on the other hand, has predefined layers and places nodes along with those layers. When there are excessively many nodes for one layer, it is imperative for visualization grow boundlessly large in size. Thus, we implement zooming and panning functionalities for these two layouts.

Common interaction elements that are available across different layouts are the hovering and clicking actions. Hovering is useful to highlight a visual object where the mouse pointer is located so as to provide a visual cue as feedback for a user's intended action. For instance, Fig. 4 (b) shows the in-depth information box that appears when a user moves the mouse pointer over a node. The box contains detailed numerical information about the node and a button that launches the sensitivity analysis that will be explained in the next subsection. In the circular layout example, when user moves mouse pointer over an arc, the system fades out all other arcs and flows but the focal arc and relevant flows. This way, the system provides visual cues and feedback about which object the user is dealing with. The pop-up box not only shows performance and network metrics for the node but also provides a way to execute further what-if analysis on the node.

5.3. What-if analysis capabilities

The focus of many emerging analytic tools is shifting from describing and summarizing complex phenomena to incorporating model-based predictive capabilities. There are many predictive modeling techniques ranging from regression to machine learning. We implement the scenario-based what-if analysis functionality into this system. Often times, supply network managers want to learn about how improvement or deterioration in one node impacts the performance of the entire supply network. We allow managers to visually inspect the impact by running sensitivity analysis for each node in the network. The sensitivity analysis is launched by clicking the button in the in-depth information box. To facilitate understanding of the necessity of the sensitivity analysis, we present a usage case scenario as follows. Suppose that a supply network manager is tasked with monitoring sales at retail shops. The manager is evaluating an option to run a sales promotion at one of the retail points. The demand will be instantly increased at the participating retail stores when a promotion starts and the manager wants to know how the change in consumer demand impacts overall supply network performance. Will running such a promotion campaign increase or decrease the average supply network costs or delays?

Following Willems [72] we include two performance measures for the entire supply network. The first measure is the average cost of goods sold (*COGS*) per unit measured as "the volume-weighted average cumulative cost at each demand stage," which is a dollar-wise performance measure. The other is the average supply chain length (*Length*) measured as "a dollar-volume weighted average of each demand stage's maximum length," which is a time-wise performance measure. More formally, these measures can be computed as follows:

$$\text{COGS} = \frac{\sum_{n_i \in \mathcal{N}_d} f(n_i, G) d_i}{\sum_{n_i \in \mathcal{N}_d} d_i} \quad \text{where} \quad f(n_i, G) = c_i + \sum_{n_j \in \mathcal{P}(n_i, G)} f(n_j, G), \tag{1}$$

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$$\text{Length} = \frac{\sum_{n_i \in \mathcal{N}_d} g(n_i, G) f(n_i, G) d_i}{\sum_{n_i \in \mathcal{N}_d} f(n_i, G) d_i} \quad \text{where} \quad g(n_i, G) = t_i + \max_{n_j \in \mathcal{P}(n_i, G)} g(n_j, G). \tag{2}$$

where G is a given supply network represented as a directed graph, $\mathcal{N}_d$ is a set of demand stages, d_i is the number of units handled in a demand-facing stage n_i, and t_i is the individual stage delay at n_i. $f(n_i, G)$ is the cumulative cost function at n_i in G defined recursively. Similarly, $g(n_i, G)$ is the cumulative maximum supply chain length (or time) at n_i in G. $\mathcal{P}(n_i, G)$ is a set of predecessor stages of n_i in G. One immediate feature of the functional form of Eqs. (1) and (2) is their recursive definition. Although both performance measures are computed across demand-facing stages in the network, this calculation process eventually requires recursive computation of f and g based on the supply network structure. Moreover, because of the nonlinearity in the functional form, computing the response surface is not straightforward when c_i or d_i changes at node n_i. Obtaining the derivative in a closed form is not necessarily straightforward particularly when the number of nodes increases, so a numerical approach is helpful to visualize the response function over scenarios with varying c_i or d_i.

Fig. 5 shows a typical sensitivity analysis result window. The selected node is a retail stage, which faces the final consumer demand. This analysis shows the sensitivity of cost and time performance of the entire supply network when demand on the focal retail node is varying from 0% to 200% of the current level. Since both performance metrics—average cost of goods sold per unit and average chain length (in days) per unit—are computed as weighted averages across nodes facing final demand, changes in demand influence the weighting scheme for the formula. In this particular case, increasing or decreasing demand faced by the focal retail node poses a trade-off between money and time. A surge in demand at this retail node would lead to a reduction in average cost but inflation in average cycle time for the network, and vice versa. This is not always the case and sometimes sensitivity of both metrics moves in the same direction. If increasing demand at a certain retail node is predicted to reduce both cost and delay, managers can take actions such as launching promotion campaigns to boost demand at that node based on the sensitivity analysis.

6. Evaluation results and discussions

The previous figures are merely an illustration of one supply network example from the transportation industry. Our actual system provides visual analytics for all of the other 37 supply networks included in the dataset provided by Willems [72]. Throughout our evaluation studies and irrespective of supply network chosen, we received confirmation that we achieved to meet all three design requirements gathered from the literature and expert interviews. The force-directed layout is particularly useful to showcase and highlight diverse structural patterns of different supply networks. All other layouts provide complementary perspectives and additional insights as we had initially expected.

Implementing a visual analytic system is one thing; validating its usefulness is another. Validation is becoming increasingly important in the visualization literature [17]. There are a few standard ways to validate a new DSS in an actual work context. Consulting with domain experts and methodological experts is one approach to obtain face validity of a DSS. Alternatively, user studies with practitioners are often conducted to provide additional external validation. These different evaluation approaches complement each other in that they collectively shed light on the value, strength and weakness of a system.

We planned and conducted evaluations of our prototype in three phases. First, we presented and received feedback on our prototype from approximately 40 data visualization and visual analytic experts at the 2015 BusinessVis Workshop in Chicago. Specifically, we received extensive feedback on the rigor and usability of our system as well as whether our prototype complies with fundamental principles of information visualization and visual analytic design. Some of the key comments we received included a clearer graphical depiction of edge directionality and simpler view transition capabilities. We revised our prototype corresponding to these suggestions. In particular, we implemented directed edges for the force-directed layout, which clarifies supply flow directions.

Second, we organized a private interview session with two SCM experts. Drawing on their vast experience developing supply chain analytic tools and working with companies, we expected to gain valuable feedback on our system from a practitioners' perspective. In addition to providing insight into the essential needs of supply chain managers for decision support systems, the two experts also confirmed that our interactive prototype would be a unique and useful addition if positioned as a supply chain decision dashboard. They stressed that there is a growing need for SCM DSS to be complemented by visual analytics since both the complexity of decision making problems and the amount of data to digest have been increasing in parallel. Moreover, they confirmed that practitioners are looking for useful, interactive, and actionable ways to cope with the overwhelming process of data-driven decision making processes and our tool appeared to fill this gap. The comments received from this phase provided further assurance of the potential practical value of our prototype system.

Lastly, after incorporating the feedback from the previous two evaluation phases, we conducted a broader expert user study. Following prior work, there are two options of pursuing a user study. The first approach is to conduct a controlled laboratory experiment with treatment and control groups. This approach tends to measure quantitative performance metrics such as task speed and accuracy. The second evaluation approach is more value-driven [60], focusing on whether a system successfully implemented and conveyed built-in core values. In this study, we took the latter approach. One advantage of this approach is that users can be recruited that closely resemble the target users [37]. We decided to include each individual participant's verbal feedback as part of the evaluation of our system. Quoting such direct feedback is a common way to confirm and validate the value of the system [33]. We observe such a value-evaluation approach not only in the DSS literature but also in the information visualization literature [7]. In the end, our aim was to get a broader understanding of the usability and utility of our system. One challenge for such a user study, however, is to recruit a representative sample of managers with diverse backgrounds and industries. For our context, we needed people who have had SCM work experience and some exposure to analytical tools. We thus recruited senior and executive MBA students from a major U.S. business school to participate in our evaluation study. 11 MBA students (4 female and 7 male) voluntarily participated in the session and 10 participants completed the task answer sheet and the post-use evaluation survey. The average work experience of our sample was 5 years while the average operations and SCM experience was 2.7 years. Their job titles prior to joining the MBA program included purchasing and product specialist, business analyst, application support analyst, global plan manager, and process integration engineer.

For the user study, we developed specific tasks and post-use surveys. The tasks articulated different goals of different visual representations and the survey was expected to help us evaluate the overall usability of the system in a quantitative way. We derived questions based on the value-driven evaluation approach proposed by Stasko [60] and Park and Basole [48]. Questions included whether the system helps reduce time to perform a certain task, whether the system can generate insightful questions, whether the system can provide useful take-aways from the underlying data, and whether

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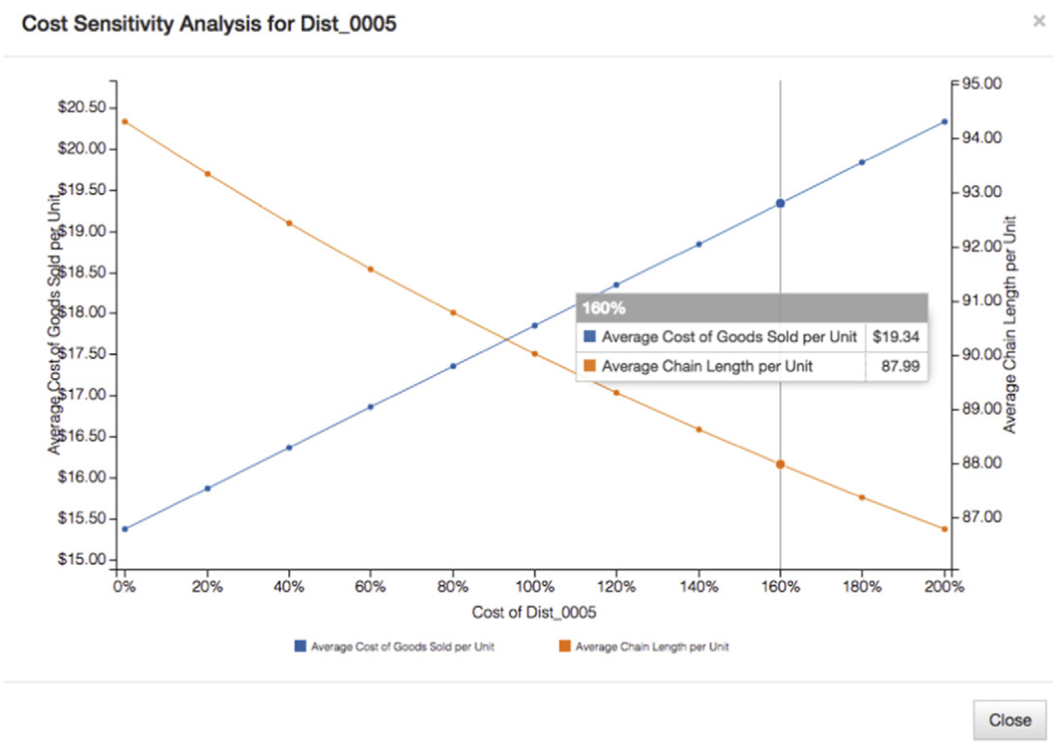

Fig. 5. Sensitivity analysis chart providing extent that performance of entire network is affected when individual node's demand, cost, or delay changes.

the system can boost users' confidence in the data. We also asked study participants to explore the system freely and report back any patterns of interest in free text format.

Table 1 shows the tasks list that participants were asked to perform using each visual representation and interaction techniques. We developed seven sets of tasks labeled from T1 through T7. Gray bars on the right show the bar chart whose horizontal length is proportional to the score for the corresponding subtask. These bar charts facilitate comparison across different tasks. Each task set lays out the specific purpose for the testing of different parts of the system. T1 only required reading the right-hand side panel. It is designed to be as straightforward as possible to obtain baseline face validity that participants can understand the overall structure of the system. As we expected, most participants performed T1 subtasks correctly. Each of T2 through T6 aimed to test the utility of different visual representations: force-directed, circular, treemap, matrix, and substrate layouts. Not a single task was done correctly by all participants, which suggests potentially wide variability of visual literacy among prospective supply chain managers. Participants particularly suffered in utilizing force-directed and matrix layouts compared to others. According to the scores for T2(2) and T5(2), many participants did not seem to understand some of the core concepts such as path and average out-degree of a network, although we explained these concepts in a tutorial session prior to the user study. T7 aimed to test the understanding of the sensitivity analysis chart. T7(1) shows that participants were able to identify the relationship direction, while T7(2) shows that many of them failed at reading a specific numerical value for varying cost of a stage. Lastly, T8 asked participants to freely explore the datasets with the tool. One comment we received was as follows: "Different chains have different structures. Chain 16 looks like a manufacturing cluster, probably Shenzhen in China with no retail level. Chain 11 looks like a local manufacturing network with retail channels, probably food manufacturing for perishable goods." These comments display that the participant could indeed develop insights mapped to the real world context by visually examining the network structure. Another notable comment was "Force directed and circular are easier for comprehending relationships, values and costs are better depicted through the tree map." Here, the participant clearly noted the trade-offs between different visual representations. Participants were given approximately 20 min to complete these tasks.

Upon task completion, participants were then asked to answer 10 questions in the post-use survey. Table 2 tabulates the survey results. Q1 through Q9 were asked based on a 5-point Likert scale with 1 being "Strongly disagree" and 5 being "Strongly agree". The higher the score, the more agreeable participants found the question to be. Participants gave relatively high scores about insight and take-away sense generated by the system (Q3 and Q6), while they found that the tool did not improve their confidence about the data (Q7). One contrasting pair of answers is Q1 and Q8. Participants found the system easy to use (Q1), but they also found that using this system does not necessarily reduce the time for completing the tasks (Q8). This contrast suggests that a DSS powered by visual analytics may look intuitive and easy to use in the beginning, but completing a certain task still takes time to accurately perform. Fig. S1(a) shows the distribution of scores for Q1 through Q9. It reveals that a few outliers exist in the lower end. Q10, on the other hand, asked participants to rank order the five layouts to assess their preferences on visual representations. It was not surprising to find that participants preferred the force-directed layout as it is generally considered the go-to layout for a network structure because its ability to highlights high-level structures such as clusters. The interesting finding is that participants also found the substrate layout to be highly useful and desirable for understanding a supply network. This answer reflects that the classic depiction of supply networks based on echelons makes intuitive sense to participants. The other three layouts are similarly ranked behind the top two choices. Fig. S1(b) also shows the histograms for Q10. After these 10 questions, we asked three

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Table 1
Results on task performance (N = 10).

Task set	Question	Score
T1	Choose chain 18.	
	(1) How many stages (i.e. nodes) are there in this network?	10
	(2) What is the average cycle time of this network?	10
	(3) Which type of activities is most prominent by the number of stages in this network?	9
T2	Choose chain 9. Use the force-directed layout to answer the following questions.	
	(1) By adjusting visual encodings of node size by out-degree, name a stage that has the highest out-degree centrality in this network?	5
	(2) Name any path from a procurement stage to a distribution stage.	3
T3	Choose chain 11. Use the circular layout to answer the following questions.	
	(1) How large is the flow from manufacturing to transportation?	7
	(2) Which of the two aggregate flows is larger: “manufacturing to transportation” or “procurement to transportation”?	7
T4	Choose chain 12. Use the treemap layout to answer the following questions.	
	(1) Which type of stages incurs highest costs in total?	7
	(2) Which individual stage incurs highest costs?	8
T5	Choose chain 11. Use the matrix layout to answer the following questions.	
	(1) What is the average out degree of a procurement stage in this network?	4
	(2) What is the average out degree of a manufacturing stage in this network?	3
T6	Choose chain 11. Use the substrate layout to answer the following questions.	
	(1) How many echelons are there in this network?	7
	(2) Name the echelons in order.	6
T7	Choose chain 16. Use the force-directed layout to answer the following questions.	
	(1) Does average cost of goods sold (COGS) per unit increase or decrease when you have to increase the cost of Manuf_0001?	6
	(2) What is the average COGS per unit when you have to increase the cost of Manuf_0001 by 20%?	3
T8	Browse and explore the software freely now. Find any patterns of interest to you and report back on what insight(s) you may find.	N/A
Aggregate	Mean	6.37
	Std. dev.	2.25
	Min	3
	Max	10

additional free-form questions: the strengths and weaknesses of the system and general comments. Participants for instance noted that the tool enabled them to see the complexity of supply networks more clearly (i.e. “It shows how complex the supply chain network really is.”; “[The system] helps visualize the complexities of supply chains.”) Many of the participants found the tool easy to use and commented that the system was “very interactive.” On the other hand, they called for the necessity of proper training before deployment by stating, “[One weakness is] lack of user guide.” and “More training is required for first time users.” They also noted the problem of having a cluttered visualization when the network becomes too large. In general, reducing such clutter in network is an active area of research in information visualization. Overall, our prototype system was very well-received by participants and the feedback we received suggests that we have a substantive basis for deploying this visual DSS into real-world settings.

7. Conclusion

Supply chains are increasingly viewed as complex networks of business relationships, evolving in a bidirectional and nonlinear fashion. The classical logic for SCM based on unidirectional and linear relationships can be significantly crippling in such a complex decision-making context that demands a better understanding of the structural characteristics of supply networks [5]. Accordingly, the emerging network perspective of SCM requires a novel approach for designing DSS and tools for key decision makers—from front line managers to top management—to stay informed about their supply network and business relationships in general.

Visual analytics, a new field and a new approach fusing information visualization and data analytics, can boost human cognition for disentangling patterns from a seemingly complex underlying phenomenon [63]. In this paper, we present an integrated system architecture for designing and building an interactive visual analytic DSS for supply network management. Our system architecture includes three key engines: a visual representation engine, an interaction engine, and a descriptive and predictive analytic engine. These three engines have the system user—decision maker or analyst for SCM—in the decision-making loop and empower them to explore the supply network database that accumulates data from daily business operations. We implement a prototype system using a well-established scholarly supply network data source [72] to demonstrate the instantiation of the system architecture. We evaluate the prototype system over three stages that include a conference workshop of methodological experts, an interview with supply chain experts, and a user study with operations and supply chain managers. These evaluation sessions were designed to provide us valuable feedback from visualization experts, SCM experts, and potential target users. The evaluation results indicate positive confirmation regarding the value of the proposed prototype system applied in real-world SCM and operations management contexts.

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Table 2
Results on value-driven evaluation of the prototype system ($N = 10$).

Number	Question	Mean	Std. dev.	Min	Max
Q1	The visualization system was easy to use.	4.10	0.54	3	5
Q2	The visualization system was easy to learn.	3.70	0.90	2	5
Q3	The visualization system enabled me to discover insights about the data.	4.10	0.83	2	5
Q4	The visualization system enabled me to ask insightful questions about the data.	3.70	0.90	2	5
Q5	The visualization system helped me generate knowledge about the data.	3.80	0.87	3	5
Q6	The visualization system conveyed an overall essence (or take-away sense) of the data.	3.90	0.70	3	5
Q7	The visualization system helped me generate confidence about the data.	3.50	1.02	2	5
Q8	The visualization system helped me complete the given tasks quickly.	3.40	1.02	1	5
Q9	The visualization system helped me complete the given tasks effectively.	3.80	0.98	2	5
Q10	Please rank order your preference of visualization layout. (1=highest, 5=lowest)				
	(1) Force-directed layout	1.80	1.60	1	5
	(2) Circular layout	3.30	1.19	2	5
	(3) Treemap	3.60	0.80	3	5
	(4) Matrix layout	3.80	1.33	1	5
	(5) Substrate layout	2.50	0.92	1	4

Note: Q1–Q9 scores are asked based on 5-point Likert scale. 1 is "Strongly disagree" and 5 is "Strongly agree". Only Q10 is asked based on rank order, so 1 is most preferable and 5 is least preferable.

There are several future research opportunities. The first and immediate extension of this study would be to deploy a visual analytic DSS into a real-world organization and investigate how the adoption influences near- and long-term operational decision-making quality and firm performance. Second, the visual representations shown in this paper are rather basic, highlighting essential structural properties of a network. The information visualization field, however, is actively developing novel visual representations and interactions designed for specific problems. Looking for a suitable place for these advanced visualization techniques in operations and SCM analytics will be a productive line of research. Lastly, our current prototype implements only cost and demand sensitivity analysis functionality. A future study may extend this list by incorporating various sophisticated analytic methods such as optimization and simulation modules into a visual analytic DSS. Each of these limitations provide exciting extensions for building sophisticated visual analytic DSS for SCM and operations management applications.

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Appendix A. Supplementary data

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