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Supply chain vulnerability assessment: A network based visualization and clustering analysis approach

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Abstract

Supply chains are large, complex, and often unpredictable. Purchasing and supply managers and supply chain risk managers need methods and tools to enable them to quickly understand how unexpected disruptions in the supply chain start and grow and to what extent will they negatively impact the flow of goods and services. This paper introduces a methodological approach that can be used by both researchers and managers to quickly visualize a supply chain, map out the propagation path of disruptive events from the supply side to the end customer and understand potential weaknesses in the supply chain design; taking into account the structure, connectivity, and dependence within the supply chain. The approach incorporates a Petri net and Triangularization Clustering Algorithm to offer insights into a supply chain network's vulnerabilities and can be used to efficiently assess supply chain disruption mitigation strategies, especially in complex and difficulty to analyze supply chain systems.

Keywords

Supply chain risk management, Supply chain vulnerability, Supply chain design, Petri net, Supply chain disruptions

Disciplines

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Comments

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ABSTRACT

Supply chains are large, complex, and often unpredictable. Purchasing and supply managers and supply chain risk managers need methods and tools to enable them to quickly understand how unexpected disruptions in the supply chain start and grow and to what extent will they negatively impact the flow of goods and services. This paper introduces a methodological approach that can be used by both researchers and managers to quickly visualize a supply chain, map out the propagation path of disruptive events from the supply side to the end customer and understand potential weaknesses in the supply chain design; taking into account the structure, connectivity, and dependence within the supply chain. The approach incorporates a Petri net and Triangularization Clustering Algorithm to offer insights into a supply chain network's vulnerabilities and can be used to efficiently assess supply chain disruption mitigation strategies, especially in complex and difficulty to analyze supply chain systems.

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INTRODUCTION

Globally competing firms have inherently large and complex supply chain systems that are particularly vulnerable to disruptive events (Blackhurst et al., 2005a; Craighead et al., 2007; Manuj and Mentzer, 2008; Giannakis and Louis, 2011). These complex supply chains have garnered much attention considering methods and means to understand their nature and their risk vulnerability (Tang, 2006; Sodhi et al., 2012). A disruption in the supply chain may lead to other entities failing and may even result in entire portions of the supply chain failing (Jüttner and Maklan, 2011). Supply chain vulnerability is the susceptibility or exposure to a disruptive event in the supply chain (Wagner and Bode, 2006; Bhamra et al., 2011; Ghadge et al., 2012; Wagner and Neshat, 2012). Prior literature has discussed steps for managing disruptive events in the supply chains as first identifying the potential disruptions, next assessing the likelihood and potential impact and finally selecting and implementing a mitigation strategy (Chopra and Sodhi, 2004; Manuj and Mentzer, 2008). The identification step can occur before the disruption occurs allowing managers to proactively avoid or reduce the impact of the disruption (Craighead et al., 2007;

Knemeyer et al., 2009). Conversely, the disruption may be unavoidable leading to more reactive planning (Craighead et al., 2007). When a supply chain is vulnerable to a disruption, the goal is to develop resilience in the supply chain, such that after a disruption has occurred the network can be leveraged to regain a desired service level as quickly as possible (Ambulkar et al., 2015; Pettit et al., 2013). Managing vulnerabilities is difficult because supply chains are interconnected with high levels of supply and demand uncertainty. Because of the complexity and interconnected nature of supply chains and their effect on disruption propagation, it is essential to understand the structure of the supply chain and its vulnerability to disruptions (Wagner and Neshat, 2010; Mizgier et al., 2013). When purchasing and supply managers restrict their focus solely on first tier suppliers they may not perceive disruption events moving in their supply chain until it is too late (Tang et al., 2009). Therefore, a method for understanding supply chain vulnerability would be useful to purchasing and supply managers to reconfigure the network structure and relationships or reposition capacity and resources to reduce the risk or effects of disruptions. While there are many types of disruptions that occur in supply chain networks, we focus on the specific disruption of node failure. That is to say, when a node in the supply network is no longer able to produce, ship, or transship products or services, the supply network has experienced a disruption.

Researchers employ various techniques including optimization, simulation, and regression to understand and explain supply chain networks. Recently, analytics methods have gained traction, creating greater diversity in approaching a very complex set of problems and giving supply chain research a fuller perspective (Waller and Fawcett, 2013a). These methods find their roots in World War II with Dantzig’s simplex method but have expanded through ERP into business intelligence (Sahay and Ranjan, 2008), and most recently to supply chain analytics (Waller and Fawcett, 2013b; Souza, 2014). The challenge purchasing and supply managers face is to employ appropriate analytical methods to help decision making in the face of a supply chain disruption.

Statistics, optimization and simulation are commonly used by researchers and managers to understand characteristics, behaviors, and nature of supply chains. Techniques like regression are used to describe theoretical models (e.g. Chong et al., 2015) or predictive analytics (Lindsey et al. 2014). Optimization has been used to search a problem space for the best solution given a set of constraints, and simulation can model the behavior and dynamics of systems (Tomlin, 2006; Griffis et al., 2012). The choice of technique is often a function of the problem and the maturity of the organization (de Oliveira et al., 2012).

In addition to these approaches, many researchers use heuristics and other techniques to gain analytical insights into supply chain problems (e.g. Memari et al., 2015). However, each of these methods is not without its limitations (Chapman et al., 2002; Zhang et al., 2011). When considering supply chain vulnerabilities, the need to understand a particular structure, model, or set of variables can prove problematic. Tang (2006) suggests reducing the impact of disruptions on supply chain operations by proactively forming strategic alliances with multiple suppliers in different countries. Ghadge et al. (2011) reach the same conclusion arguing for systems thinking. However, true systems thinking is a challenging task given that purchasing and supply managers have difficulty in monitoring suppliers more than two tiers from a focal firm. As a result, purchasing and supply managers are often caught unaware when a disruption that began several tiers upstream can cascade to the focal firm (Scheibe and Blackhurst, 2017). In fact, recent research has called for studies that adopt a more systems based lens and look at network based models to understand how disruptions impact supply chains (Van der Vegt et al., 2015). A similar call to action had been issued by Nair and Vidal (2011) to investigate a way to understand which nodes in a network should be fortified for protection against supply chain against disruptions. Finally, Kirilmaz and Erol (2017) note that the use of quantitative methods in supply chain risk management is insufficient and call for more tools to address supply chain vulnerability.

In this paper, we answer these calls through the development an approach that helps visualize and understand supply chain structure and assess vulnerability in that structure to supply chain disruptions (Min and Zhou, 2002; Blackhurst et al., 2005a; Zsidisin et al., 2005; Skipper and Hanna, 2009). The contribution of this research is the combination of Petri nets with Triangularization Clustering Algorithm (TCA) to assess disruption vulnerability of a supply chain based on its the structure. This approach will map out the propagation path of disruption events, and uncover vulnerabilities stemming from the supply chain design: the structure, connectivity and dependence within the supply chain. Triangles are the basic unit for measuring network structure and redundancy (Cheng et al., 2009), and have been used to quantify structure and flow in networks. Network nodes are interconnected, and thus it is important to measure more than nearness as proximate distance may not convey the strength of relationship between nodes. Triangularized clustering approaches have been used to identify network redundancies (Schank and Wagner, 2004) and structural invariances across websites (Zhou et al., 2007). This approach, once applied, provides novel insights into how the structure of a supply chain can impede or enable a disruption to propagate. When a firm’s supply chain is hit with a disruption, it is not only important to know which node in the supply chain is directly hit, but it is also important to know all possible scenarios for disruption propagation. We combine the Petri net approach with a clustering algorithm, the Triangularization Clustering (TCA), which identifies clusters and other network characteristics in order to gain insights into the vulnerabilities of the system. By combining these two methods into a new methodological approach, we build upon prior research to develop an assessment of supply chain vulnerability based on the structure of the supply chain and analyze how the structure of a supply chain can facilitate or hinder the propagation of a disruption. This insight is lacking in the literature and offers new knowledge to assess and manage disruptions in the supply chain.

In the following sections we introduce and illustrate the utility of our proposed decision model by first considering an exemplar service parts supply chain for an automotive firm to illustrate the functionality of our approach. In section 2, we introduce a Petri net and clustering algorithm combination to identify structural and procedural vulnerabilities in the supply chain. We demonstrate the applicability of our approach with our automotive firm example. Next, we provide insights on vulnerability for the service parts supply chains, and finally, we provide interesting extensions to our methodological approach with respect to supply chain disruption mitigation. The model presented in this research is appealing to both industry and the academy because it provides a road map for purchasing and supply managers to evaluate their supply base and network both in terms of connectivity and contractual agreements and processes.

METHODOLOGICAL APPROACH

The Petri net, developed originally by Carl Petri for modeling communication protocols, has evolved into a graphical and mathematical tool for representing and analyzing discrete event systems (Zurawski and Zhou, 1994), including manufacturing systems (e.g., Venkatesh et al., 1996; Yan et al., 1999; Yu et al., 2003) and supply chains (e.g., Blackhurst et al., 2004; Chen et al., 2005; Fridgen et al., 2015). As a graphical tool, the Petri net is a bipartite graph using nodes and arcs to visually map a system, while, as a mathematical tool, it can be embedded with mathematical functions for analysis of system properties.[1] Petri nets are proven tools for modeling complex and

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[1] A more complete discussion of Petri nets can be found in Murata (1989) and Zurawski and Zhou (1994).

dynamic systems as well as for evaluating network structure (Tuncel and Alpan, 2010; Zhang et al., 2011). It is essential to understand that the logic (or mathematical functions) that can be embedded in a Petri net can cause the model to become non-linear. This is both a strength and weakness intrinsic to the Petri net. It is a weakness because it prevents the network from being solvable in an optimization fashion, and it is a strength because it allows a network to more accurately represent reality in terms of contractual agreements, processes and procedures. We will describe this in greater detail and illustrate an example with the automotive firm.

To properly introduce fundamental concepts and terminologies related to the Petri net and how our methodological approach may be used to predict supply chain vulnerability, we present an example of how a supply chain can be represented by the Petri net. There are several open source Petri net tools available for research such as WoPeD (http://woped.dhbw-karlsruhe.de/woped/). Figure 1 shows a six-tier Service Parts Supply Chain for a U.S. heavy equipment manufacturer. This Service Parts Supply Chain is a subsection of a more complete supply chain; its structure was identified through interviews conducted with various supply chain managers employed by the U.S. heavy equipment manufacturer.

INSERT FIGURE 1 ABOUT HERE

As shown, the Service Parts Supply Chain is comprised of three U.S.-based distribution centers (DC 1, 2, and 3) belonging to the same firm. DC 1 and DC 2 supply items to DC 3, who supplies items to the Manufacturing Facility. DC 1 and DC 2 also supply items to each other as needed. The Manufacturing Facility serves four dealer locations (Dealers 1, 2, 3, and 4). DC 1 to DC 3 source items from seven suppliers – Supplier 7 supplies DC 3, Supplier 1, and Supplier 2; Supplier 6 supplies DC 2, DC 3, Supplier 1, and Supplier 3; Supplier 5 supplies DC 2 and Supplier

1; Supplier 4 supplies DC 1 and Supplier 2; Supplier 3 supplies both DC 1 and DC 2; Supplier 2 supplies Supplier 3 and Supplier 5; and finally, Supplier 1 supplies Supplier 4.

Figure 2 redraws the same Service Parts Supply Chain depicted in Figure 1 as a Petri net with two types of nodes: place nodes and transition nodes (Murata 1989). Place nodes, depicted by circles and labeled m_i's, generally represent locations or conditions (e.g., a distribution facility location in a supply chain or whether or not items are ready to be shipped or to be inspected at a location). Place node m1, as such, denotes Supplier 1. Transition nodes in a Petri net are depicted by rectangles, are labeled a_j's, and generally denote events (e.g., shipment of product, product assembly, or inventory receipt). Murata (1989, pg. 542) describes a transition as an event which has an "input and output places representing the pre-conditions and post- conditions of the event, respectively." Transition node a1, as such, denotes the shipping of items from Supplier 7. An advantage of a Petri net is the flexibility and granularity in defining what the place nodes and the transitions nodes can represent. Place nodes, besides denoting conditions, can also be defined to represent an entity within a Petri-Net represented system (e.g., a manufacturing plant or a warehouse) or a location within an entity (e.g., inventory storage within a plant). Transition nodes, besides denoting events, can be defined to represent actions (e.g., the steps in shipping materials) taken within the context of the system being modeled as a Petri net.

Table 1 summarizes and defines the place nodes and the transition nodes in Figure 2.

INSERT FIGURE 2 AND TABLE 1 ABOUT HERE

Finally, in a Petri net, the inherent relationship between pairs of place nodes is captured by directed arcs that connect one place node to a transition node to a second place node. Arcs within a Petri net, therefore, never link "like" nodes directly (i.e., arcs do not connect place nodes with place nodes or transition nodes with transition nodes), but rather multiple place nodes (which represent locations in our example) may feed into a single transition node (which represents events in our approach). Note also that the place node from which an arc emanates is typically referred to as the *input* place node; whereas, the place node to which an arc points is typically referred to as the *output* place node. Place node m_{11} in Figure 2 is, therefore, an input place node connected to the four output place nodes of m_{12}, m_{13}, m_{14}, and m_{15} through transition nodes a_{11}.

In addition to showing within-system interrelationships, the Petri net also facilities modeling of dynamic system behavior through the movement of "tokens" (tokens are shown in a Petri net as dots residing within place nodes). A transition node is "enabled" for token movement if the input place node contains at least one token. The movement of a token from the input place node(s) through the transition node to the output place nodes(s) will represent the initial *location(s)* or *condition(s)* in the input place node being transformed by an *event* in the transition node to a new *location(s)* or *condition(s)* in the output place node. Murata (1989) states that a token located in an input place node may be interpreted as holding "truth" for the condition associated with that place node, or a token may indicate that items or resources are available .For any place node, the number of resident tokens is a non-negative integer (i.e., $\{0, 1, 2, . . . \infty\}$). The movement of the token from the input place node, through the transition place node to the output place node is called the firing of the token (Murata 1989). A firing of an enabled transition removes tokens from the input place node(s) and places tokens to the output place node(s). An enabled transition may or may not fire, depending on whether or not the event actually takes place. Logic may be attached by embedding *attributes* into both the place nodes and the transition nodes and embedding of *algorithms* into the transition nodes (Blackhurst et al., 2005b; Wu et al., 2007; Zhang et al., 2011). *Attributes* are specific information relevant to the context being represented by a Petri net. For a supply chain context, relevant attributes to embed into the place nodes may include information such inventory level or processing time; attributes relevant to the transition nodes may include not only similar information or measures but others pertaining to occurrence of events (e.g., transportation time to ship from place node m_i to $m_{i'}$). *Algorithms* are the decision logic to dynamically update the attributes in the system. As tokens move through the basic Petri Net to reflect system changes, these attributes can be dynamically updated by algorithms embedded within transition nodes, with algorithms being mathematical operands or logical rules that, once executed, change the values of attributes embedded into a particular transition node. The passing of tokens through a transition node, therefore, triggers the execution of one or more of these algorithms, which, then, results in an updating of attributes of interest.

More formally, this can be stated as the following three steps:

Attributes and Algorithms Development

Step1 : For i = 1 to I, identify and define $C^i = \{c^i_1, c^i_2, \ldots, c^i_x\}$ for place node m_i, where $c^i_1 \ldots c^i_x$ are specific attributes of interest.

Step 2: For j = 1 to J, identify and define $D^j = \{d^j_1, d^j_2, \ldots, d^j_y\}$ for transition node a_j, where $d^j_1, d^j_2, \ldots, d^j_y$ are specific attributes of interest.

Step 3: For j = 1 to J, identify and define $F^j = \{f^j_1, f^j_2, \ldots, f^j_y\}$ for transition node a_j, where $f^j_1, f^j_2, \ldots, f^j_y$ are specific logical or mathematical algorithms to update attributes of interest for place nodes.

As an illustration, consider again the basic Petri Net in Figure 2. Suppose we are interested in monitoring processing times and inventory levels along the supply chain. Complying with Step 1 of the Attributes and Algorithms Development, let C^i = {Cumulative Processing Time$^{(i)}$, Inventory$^{(i)}$}, where Cumulative Processing Time$^{(i)}$ = Cumulative Processing Time (in hours) at m_i and Inventory$^{(i)}$ = Inventory Level (in units) at m_i. Following Step 2 of the Attributes and Algorithms Development, define D^j = {Activity Processing Time$^{(j)}$}, where Activity Processing

Time$^{(j)}$ = Processing Time (in hours) at transition node a_j. Finally, following Step 3 of the Attributes and Algorithms Development, let F^j = {Cumulative Processing Time$^{(j)}$, Replenishment $^{(j)}$}, where Cumulative Processing Time$^{(j)}$ = [∀ input place nodes i (i.e., m_i,'s) with arcs into transition node j (i.e., a_j), compute Maximum$\{c^{i}_{\text{Cumulative Processing Time}}\} + d^{j}_{\text{Activity Processing Time}}$] and Replenishment $^{(j)}$ = the rule: IF (Inventory$^{(i)}$ < reorder point at m_i) THEN (invoke replenish order operation for place node m_i (and update Inventory$^{(i)}$ accordingly).

An enabled transition nodes fire, the attributes are updated through the algorithms and the tokens move through the system. In this way, tokens can allow the user dynamically describe the behavior of a system in terms of states and changes to states (Murata, 1989; Zurawski and Zhou, 1994). Collectively, the distribution of tokens across place nodes within a Petri net at any time instance t can be said to describe or to mark the state of a Petri net represented system. This marking for the State at time S_t can, moreover, be written as an m-vector, with m being the number of place nodes within the Petri net and the numerical values in the vector denoting the number of tokens residing at the respective place nodes. Hence, the initial marking, S_1=[0,0,0,0,0,1,1,0,0,0,0,0,0,0,0,0], with respect to Figure 2, denotes the presence of one token in place nodes m_6, and m_7. For a Petri net, a dynamic change is modeled as the movement of token(s) and the corresponding change in the marking S. This movement of tokens is triggered by the firing of one or more transition nodes, during which tokens in one or more input place nodes are moved through corresponding transition nodes into one or more output place nodes. The Petri net shown in Figure 2 with S_1=[0,0,0,0,0,1,1,0,0,0,0,0,0,0,0,0], therefore, signals that items are ready to be shipped from Supplier 7 (m_7) to Supplier 1, Supplier 2, and DC 3 and items are ready to be shipped from Supplier 6 (m_6) to Supplier 1, Supplier 3, DC 2, and DC 3 and, consequently, triggers the firing of the corresponding transition nodes a_1 and a_7. Post-firing, tokens would move through the transition nodes and end up in the output place nodes, resulting in a new state at t=2 with a marking given by S_2=[1,1,1,0,0,0,0,0,1,1,0,0,0,0,0]. Logic may be embedded into the nodes allowing tokens to be added to indicate that the transition node (event) affected multiple output places nodes (locations). For example, in our application of Petri nets we are interested in the flow of products in the supply chain and how a disruption may propagate to all possible states, so the tokens in the initial state locations at Supplier 6 (m_6) and Supplier 7 (m_7) will be fired to *all possible output place* nodes (Supplier 1, Supplier 2, Supplier 3, DC2 and DC 3). The use of attributes and algorithms is limited in our application to understanding propagation paths resulting from the design of the supply chain. Future work may enhance the use of the attributes and algorithms as discussed at the end of this paper.

Supply Chain Vulnerability Assessment

For the Petri net to be useful in a supply chain disruption context, we create a Node Dependency Matrix and apply a clustering algorithm in order to understand vulnerability of the supply chain caused by the design of the supply chain. We extend the prior use of Petri nets from just looking at which nodes a disruption will impact as in Wu et al. (2007), to a deeper understanding of vulnerability in the supply chain. We also go beyond prior work using Petri nets to determine conflict in a supply chain using a hierarchical Petri net approach where entities in the supply chain are combined into a supply chain context (Blackhurst et al., 2008). The hierarchical Petri net developed by Blackhurst et al. (2008) determines if a marking is reachable from an initial marking giving the combination of entities in order to identify conflicts in the supply chain. In this work, we specifically examine how the structure, connectivity and dependence within the supply chain impact vulnerability. We develop a Node Dependency (ND) Matrix, a k×k incidence matrix ($G_{k\times k}$), is constructed to enumerate all dependencies between place nodes and transition nodes for a given

Petri net, with these dependencies being the input into the TCA. In other words, the ND Matrix re-represents the Petri net model in terms of a matrix, which allows the supply chain dependencies to be understood and manipulated though a clustering algorithm. TCA then aptly identifies clusters based on the sequencing or precedence among nodes (Steward, 1981; Kusiak et al., 1995; Kusiak ,1999), with the clusters being stipulated as either *levels* or *cycles*. We apply these understanding dependencies, levels and clusters to a supply chain in order to gain insights in the vulnerability of the system.

A level is a grouping of n place nodes and/or transition nodes where $n \geq 1$, with nodes within the level being connected to one another in a defined precedence structure. The set of nodes within one level can also be connected to the set of nodes of another level in a precedence structure. Hence, levels are numbered to indicate their sequence with a lower-numbered level being a precedent to the next higher-number level. For example, the set of nodes constituting Level 3 should precede the set of nodes constituting Level 4 which should precede the set of nodes constituting Level 5 and so forth. Moreover, the first level (Level 1) and the last level that TCA identifies are somewhat unique because they only contain place nodes with Level 1 place nodes all being input nodes that anchor the beginning point of a Petri net and the nodes in the last level all being output nodes that anchor the ending point of a Petri net.

A cycle, like a level, is a grouping of n place nodes and/or transition nodes where $n \geq 2$. Like nodes within a level, those within the cycle also have a defined precedence structure. A cycle differs, however, from a level in that the precedence structure connecting nodes in a cycle creates a closed loop of interconnected nodes. Cycles differ, moreover, from levels such that their numberings are for convenience and do not reflect a sequencing structure. Cycle 2, therefore, does not precede Cycle 3 nor does it follow Cycle 1. Finally, for some Petri nets, TCA may identify a set of nodes to be both a cycle and, concurrently, a level or to be a cycle subsumed within a level.

Procedurally, applying the TCA to a given Petri net involves the following steps:

Development of the Petri Net Model and Node Dependency (ND) Matrix and Application of the Triangularization Clustering Algorithm (TCA)

Step 1: Construct the Petri Net Model representation

[a] Represent place nodes as circles and transitions nodes as rectangles. Arcs, drawn as arrows, connect place nodes and transition node.

  - Arcs within a Petri net never link “like” nodes directly. Place nodes may feed into a single transition node.
  - The place node from which an arc emanates is typically referred to as the *input* place node; whereas, the place node to which an arc points is typically referred to as the *output* place node.

[b] Initialize the marking S_1 noting the initial placement of the tokens.

[c] Subsequent states of the network are influenced by the transition firing

  - A transition is enabled if the input place node has a token
  - An enabled transition may or may not fire depending upon the logic embedded in the node. In addition, the placement of the marking(s) into the output place node(s) is determined by the logic in the transition nodes.

Step 2: Construct the $G_{k\times k}$ ND Matrix:

[a] Let the rows and the columns of the $G_{k\times k}$ ND Matrix represent the k place and transition nodes, such that each cell (i.e., row-column combination) along the diagonal of $G_{k\times k}$ denotes the same k^{th} node and such that each cell off the diagonal of $G_{k\times k}$ denotes a pairing of the node in the row and the node in the column.

[b] In the cells along the diagonals of $G_{k\times k}$, enter a “+”; in the cells off the diagonal, enter a “1” if the node in the column is an output node for the node in the row.

Step 3: Identify and sorting of origin nodes and destination nodes:

[a] Identify either an origin node or a destination node.

<u>Note</u>: An origin node is a node for which no other node precedes it; a destination node is a node for which no other node occurs after it. In the ND Matrix, if the i^{th} column of the ND Matrix has only one nonempty entry (a diagonal entry), then i is an origin node; if the j^{th} row of the ND Matrix has only one nonempty entry (a diagonal entry), then j is a destination state.

- If no origin or destination nodes exist, proceed to Step 4.

[b] Underline the node identified in Step 3[a].

[c] Apply the **Sorting Rules** (below) to the underlined node.

- *If the identified node is an origin node*, then move it to the farthest **left** position before the sequence of the nodes that are not underlined.
- *If the identified node is a destination node*, then move it to the farthest **right** position after the sequence of the nodes that are not underlined.

[d] Repeat Step 3[a].

Step 4: Identification of Clusters:

[a] For any remaining nodes in the ND matrix (those that have not been identified as origin nodes or destination nodes), identify an existing cycle.
Note: A cycle exists if there is a path starting with the node and ending with the node (e.g., Place Node 2→Transition Node 3→Place Node 2).

- If no cycles exist, proceed to Step 5.

[b] Merge all the activities in the cycle into one node by merging the corresponding rows and columns in the cycle into a single row and column. Designate this node as a cycle and note the nodes within the cycle.

[c] Return to Step 4[a].

Step 5: Identification of Levels:

Assign the nodes and cycles in the ND matrix to levels (1 to n) from the upper left corner of the ND Matrix going to the lower right corner of the ND Matrix according to the precedence relationships (where level 1 precedes level 2 which is followed by level 3, etc.). Note that level 1 will be the node or nodes identified in the first pass of Step 3[c] of origin nodes moved to the farthest left position. Level n will be the nodes identified in the first pass of Step 3[c] of destination nodes moved to the farthest left position. Levels between 1 and n will be the nodes and cycles moved in subsequent steps.

Table 2 identifies the 26×26 ND Matrix (i.e., $G_{26\times26}$) corresponding to Figure 1; Table 3 reveals the 11 levels and 2 cycles embedded within the Petri net representation of the Service Parts Supply Chain. With the exceptions of Level 3 and Level 7, which also correspond to Cycle 1 and Cycle 2 respectively, the remaining 11 levels generally alternate between sets of place nodes and sets of transition nodes.

INSERT TABLE 2 AND TABLE 3 ABOUT HERE

Next, we discuss the results of this example using the proposed methodological approach to assess the vulnerability for the supply chain.

INSIGHTS FOR THE SERVICE PARTS SUPPLY CHAIN USING THE PROPOSED TOOL

By applying the approach to the Service Parts Supply Chain example, three insights about the structure of this supply chain, with implications how to manage supply chain disruptions, become readily evident.

Levels: Connected clusters vulnerable to disruption spread

The Service Parts Supply Chain depicted in Figure 1 has 11 levels, with each level having between 1 (e.g., Level 4 as show in Table 3) and 8 (i.e., Level 3 as shown in Table 3) place nodes and/or transition nodes. This insight provides some pragmatic advice concerning the magnitude of investments that would need to be made in order to actively manage all the entire Service Parts Supply Chain. Assuming a one-to-one match and that the number of place nodes and/or transition nodes for a level has negligible effects, this Service Parts Supply Chain would require at least 11 “monitors,” one for each level, with a monitor, in this case, being a human or a technology-based resource given the responsibility to keep watch over the set of place nodes and/or transition nodes for a particular level.[2] These monitoring resources contribute to the warning capability of a supply chain, allowing for the detection of a pending or a realized disruptive event and the subsequent dissemination of relevant information to all relevant entities within this Service Parts Supply Chain (Craighead et al., 2007). This would be of particular use to purchasing and supply managers who need to decide where and how to utilize limited resources in managing supply chain risk (Hoffmann et al., 2013).

The 11 levels, moreover, pinpoint a precise propagation path for a disruptive event occurring within this Service Parts Supply Chain. Since the levels are themselves sequenced (i.e., a level with a lower number precedes one with a higher number), a disruptive event affecting one or more place nodes and/or transition nodes within Level N would propagate and affect the place nodes and/or transition nodes within Level N+1, then those within Level N+2, and so on until an intervention successfully stops the spread. Hence, if Supplier 6 (i.e., place node m_6 in Level 1 from Table 3) were to experience a disastrous fire that shuts down its production capabilities, one or more nodes in Level 2 onwards would be negatively affected, with this disruptive event at Supplier 6 eventually affecting one or more nodes in all levels unless mitigation initiatives such as inventory and capacity buffering had been deployed or such as materials flow rerouting can be deployed. In this regard, understanding the number, as well as the sequencing, of levels for a supply chain can contribute to the development, within a supply chain, of what Pettit et al. (2010) refers to as anticipation capabilities.

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[2] Naturally, the number of place nodes and/or transitions nodes within levels should also play a role in determining how many monitoring resources are necessary. A level with a large number may benefit from more than one “monitor”; conversely, a single “monitor” may be able to keep watch over multiple levels, with each level having only a small number of constituent nodes (e.g., one).

Interestingly, there are six levels which only consist of one node: level 4 (m_3: supplier 3), level 5 (a_6: shipping from supplier 3); level 7 (m_{10}: DC 3), level 8 (a_{10}: shipping from DC 3); level 9 (m_{11}: the manufacturing facility); and level 10 (a_{11}: shipping from the manufacturing facility). While node m_{11} (the manufacturing facility) can be easily identified from Figure 1, the other 5 vulnerable points are not as obvious from Figure 1 (nor was it obvious to the supply chain managers of the U.S. heavy equipment manufacturer). We term these nodes and arcs “critical” to indicate they represent highly vulnerable points of the supply chain because these nodes represent a single node level (a level identified using TCA which only has one node) with multiple inputs and multiple outputs. In other words, if the node is compromised, it could potentially shut down entire portions of the supply chain. For example, level 9 which consists only of node m_{11} (Manufacturing Facility) or level 10 which consists of only a_{11} (shipping from the manufacturing facility). If the manufacturing facility was shut down due to a labor strike or fire, it could shut down the entire chain. Likewise, if the shipping lane from the manufacturing facility was shut down due to labor issues or an accident, this also has the potential to disrupt delivery to the customer. These single nodes may be viewed as a bottleneck which could affect ALL of the dealers.

This feature of the proposed methodological approach helps purchasing and supply managers to quickly understand vulnerable points in the supply chain. For example, Melnyk et al. (2010) call for tools to identify possible weak points in the supply chain and Knemeyer et al. (2009) discuss the need to identify “key locations” in the development of a proactive planning process. We envision the identification of critical nodes and arcs being used to help identify these vulnerable points in the supply chain. These bottleneck points in the network should be a red flag to supply chain managers indicating increased vulnerability to have a single node shut down large portions of their supply chain. These nodes should be monitored more closely and have extra resources on hand or close by. These nodes should also be identified as candidates for multiple sourcing or back up mitigation methods.

Cycles: Clusters with multiple nodes vulnerable to circular disruption impact

Besides the 11 levels, the Service Parts Supply Chain in Figure 1 also supports two cycles, with Cycle 1 (corresponds to Level 3) involving shipment of items between Supplier 1 (m_1) and Supplier 5 (m_5) that go through Supplier 4 (m_4) and Supplier 2 (m_2) and Cycle 2 (corresponds to Level 7) involving shipments of items between Distribution Center 1 (m_8) and Distribution Center 2 (m_9) and with neither cycle representing situations of rework (i.e., items being sent back up the supply chain to be fixed or repaired or disposed of). This insight raises questions regarding the design of the Service Parts Supply Chain product flow. One immediate question is why these cycles are present in the Service Parts Supply Chain? Why do these cycles even exist? Since the two cycles connect place nodes and/or transition nodes for the Service Parts Supply Chain in a closed loop. It is possible that supply chains will have cycles due to the additive nature of the product. Thus, a supplier may add value to a product, send it to a partner who, in turn, modifies the product and returns it to the supplier. Therefore, it may be argued that the product is no longer the same, but some supply chain networks may have inefficiencies and risk of disruption due cyclical nature of their supply networks. For example, Scheibe and Blackhurst (2017) describe cyclical risks caused by the structure of a supply chain network that allow disruptions to grow through a feedback effect.

Cycle 2 questions the need to maintain two Distribution Centers that are apparently quite involved in sending materials back and forth to one another and suggests that there may be an opportunity to redesign this portion of the Service Parts Supply Chain. Assuming no geographical restrictions, collapsing two Distribution Centers into one, perhaps at a more appropriately centralized location, can reduce not only the complexity in the Service Parts Supply Chain but also in monetary and physical investments of safety stock inventory. Cycle 1, for another, questions the possibility of a supply chain redesign so that supplier 1 ships to supplier 5 directly rather than going through supplier 4 and 2.

Cycles, from a pragmatic perspective, reveal potential issues about structure of a supply chain and the associated flow of materials with the supply chain. In other words, cycles show possible redundancies and poor supply chain design and may even be viewed as raising a flag indicating supply chain complexity. It may be beneficial to simplify the supply chain and eliminate unnecessary redundancies.

DISCUSSION

The importance of managing supply chain vulnerability cannot be overstated. A single disruption can halt not only the flow of material affecting the tier of the supply chain where the disruption occurs, but also the material flow across the entire supply chain (Rice and Caniato, 2003). The 10-minute fire in March, 2000 at a Philips semiconductor plant disrupted the supply of a critical part for cell phone manufacturing that resulted in a $400 million loss for Ericsson (Latour, 2001). Research has provided additional evidence attesting to the harmful effects of supply chain disruptions on operational and financial performance with both immediate and long term effects (Deane et al., 2009; Blackhurst et al., 2011). A single (and even seemingly minor) supply chain disruption can cause the failure of the entire supply chain (Kern et al., 2012), and firms affected by supply chain disruptions can expect a reduction in their operating income, return on sales, and return on assets by 107%, 114%, and 93%, respectively, with a consequent decrease in shareholder wealth by 10% in the short term and 40% in the long term (Hendricks and Singhal, 2003, Hendricks and Singhal, 2005a, Hendricks and Singhal, 2005b).

The ability to understand supply chain vulnerability allows for better decision making regarding risk exposure (Wagner and Bode, 2006; Wagner and Neshat, 2012). As such, we contend that negative impacts from supply chain disruptions are a manifestation of the vulnerability of the supply chain. To address this issue, we have proposed and illustrated the use of an approach to visualize the supply chain and analyze areas of vulnerability. By doing so, we are able to pre-emptively identify vulnerable locations in the supply chain before a disruption occurs by analyzing the network based on a deeper understanding of the network structure. Furthermore, it is critical to understand how factors like the connectivity and design of a supply chain affect supply chain vulnerability (Wagner and Bode, 2006; Pettit et al., 2010; Pettit et al., 2013). The methodological approach in this research enables purchasing and supply managers to visualize a supply chain, determine vulnerabilities to disruptive events, and expose the propagation path of a supply chain disruption without overly simplifying assumptions. Therefore, the contribution of our paper is that we combine Petri Nets with a clustering algorithm (Triangularization Clustering Algorithm) in order to assess the vulnerability of a supply chain to a disruption (and the disruption propagating through the supply chain) based on the structure of the supply chain. This combined approach provides novel insights into how the structure of a supply chain can impede or enable a disruption to propagate. The focus of our approach is with the structural view of the supply chain, and because it takes an agnostic view for disruption propagation (cf. Garvey et al., 2015), it is scalable to various sourcing scenarios. Additionally, the contribution of this research being grounded in supply network structure brings value to both purchasing and supply management as well as supply chain risk management.

The contribution of this research to purchasing and supply management may first be shown through enhancing the ability of purchasing and supply managers to test and implement strategies to mitigate the risk of disruption, especially in large-scale systems where the propagation path of a disruption is not intuitively obvious. Conversely, it will also show where there is a lack of dependency—that is, it helps purchasing and supply managers identify areas of the network that would not be affected by a disruption and hence do not need immediate attention. The closed-loop system design allows users to better identify sources and reoccurrences of disruptions, which enhances supply chain managers' ability to break the disruption cycle.

Second, in a supply chain disruption context, levels provided by the methodological approach illustrate which nodes in the supply chain are immediately affected by a disruption and how the disruption, if unchecked, will propagate through different entities in a supply chain. A purchasing and supply manager may use these levels and cycles to more accurately predict where the vulnerable points in the supply chain exist, given a disruption at any point within the supply chain, and to focus recovery efforts in those portions of the supply chain that are most vulnerable to that disruption given an expected propagation path. Understanding levels and cycles will help purchasing and supply managers better allocate limited resources such as buffer inventories. Use of the attribute and algorithm set briefly discussed in Section 2 will help purchasing and supply managers understand the depth of impact a disruption has and the effectiveness of a mitigation strategy on that disruption.

The contribution of this research to supply chain risk managers is also found in the levels and cycles. Levels are valuable in understanding where and how to allocate scarce resources to "shore up" vulnerable areas of the system, and cycles illustrate recursive loops in the supply chain design. Moreover, as tokens move through the Petri net reflect system changes, these attributes can be dynamically updated by mathematical operands or logical rules in the form of algorithms embedded within transition nodes, that once executed, change the values of attributes in specific transition nodes. The passing of tokens through a transition node, therefore, triggers the execution of one or more of these algorithms, which results in an updating of attributes of interest.

For example, adding safety stock may be investigated to understand the resilience of a supply chain to a disruption. The logic triggered could also be directed towards contractual negotiations. The Petri net may embed logic that would cause a supplier to also hold additional safety stock or contract for a quantity discount. These types of choices are representative of actual supply chains, but are very difficult or impossible to model in traditional network optimization methods. As such, it is common practice to constrain traditional models via assumptions, and while this allows for a network model to be solved, it becomes less realistic and therefore less useful. Additionally, points of vulnerability in the supply chain and hidden cyclical dependencies, where a disruption may self-propagate over and over within a loop of nodes, are exposed, allowing purchasing and supply managers to assess risk, understand supply chain structures, and make informed decisions on allocation of resources and supply chain redesign.

The levels and cycles provided by the methodological approach also help us understand that the design of a supply chain may impacts its level of vulnerability. Certainly, tradeoffs do exist, and managers need to be keenly aware that actions to reduce one risk may raise the impact or likelihood of other types of risk (Chopra and Sodhi, 2004). For example, while combining the two Distribution Centers into one (in our example application) may reduce the complexity of cycles in the supply chain design, it might not account for other risks like a natural disaster or a strike affecting the single Distribution Center. Our approach can be used as an input into predictive supply chain vulnerability analysis.

We envision our methodological approach being used by supply chain risk managers to perform pre-emptive analysis (as advocated by Chopra and Sodhi, 2004; Melnyk et al., 2010;

Kirilmaz and Erol, 2017) to determine how reconfiguring the design of the supply chain influences vulnerability. By using this approach, a supply chain and purchasing manager can better allocate resources and share information in a more informed manner as he or she has a better understanding of how nodes in the network (supply chain) are related. It is wasteful to allocate resources (e.g., extra inventory) to a node that is not immediately in the propagation path of disruption.

CONCLUSION

Hendricks and Singhal (2003) note that the negative consequences of a disruption amplify and grow the longer it is untreated. Thus, it is of great importance to reduce risk in the supply base (Blackhurst et al. 2008). This sentiment is echoed by Tomlin (2006, pg. 650) who said, "extra capacity is of little value if a disruption is nearly over by the time capacity is available." In fact, supply chain resources are often constrained and costly, so managers want to know where supply chains are most vulnerable in order to strategically place and effectively use scarce resources (Wagner and Bode, 2008; Kern et al., 2012). To that end, we developed a methodological approach using Petri net and TCA allowing purchasing and supply managers to evaluate a network and discover potentially vulnerable points. We envision the use of this approach as a supply chain vulnerability diagnostic tool to help supply chain managers analyze the supply network to discover vulnerabilities and adjust accordingly to avoid disruptions. When a disruption occurs, the manager needs to quickly determine what effects it will have on the network including the propagation path as well as the impact (Blackhurst et al., 2005a). Similarly, Melnyk et al. (2010) call for development of systems to map the supply chain and develop "what-if" or war room analysis. It is of utmost importance for supply chain members to cooperate to mitigate the risk of exposure in specific locations (Knemeyer et al. 2009). In this manner, our method can be used for proactive supply chain risk management as a way to understand where the structure of the supply chain may lead to exposure or vulnerability of the supply chain to disruptions. There may also be opportunities to use this approach for supplier selection purposes where purchasing and supply managers can better understand critical nodes and supply chain design (structure) issues when comparing multiple suppliers, deciding where and when to dual source, determining facility location and sourcing strategies. We encourage practitioners to use the method proposed in this paper to step back and examine the structure of the network as a whole and thus reduce risk exposure.

To gain more insights into the real world usefulness of our proposed method, we presented our findings to two additional companies to get feedback on application opportunities. One firm is in the same industry as our example firm and the other is a large furniture manufacturer. Both firms saw great value in understanding how the structure, connectivity and dependence could yield insights into the vulnerability of complex supply chains. The furniture manufacturer suggested future work could add a timing component into the model that would show how resources are consumed over time in the face of a disruption. The company termed it "the clock is ticking" approach and gave the example that if we added inventory levels to the transition nodes, one could see how many hours/days until the buffer resource was consumed, amplifying the disruption impact. The suggestion from the firm in the same industry was to use our model at an increased level of granularity -- within a single plant. The company described having many value streams within a single plant and wanting a way to understand how changing products (and flows) within their mixed model scheduling system would impact the overall network.

Effective use of level and cycles will yield better predictions of disruption propagation and, therefore, the vulnerability of the supply chain is better understood. However, we recognize that there is no one size fits all solution to managing supply chain vulnerability. Future work in this area should include the following issues: First is the potential for state explosion. The larger and more complex the supply chain, the more cumbersome the construction of the network and the more unwieldy its ND Matrix becomes. Additionally, the use of more tokens in the system increases the complexity of the analysis. Second, while the Petri net allows logic to better represent human decision making, trying to account for every contingency can make the transition node logic unwieldy or even self-contradictory, but that is intrinsic in the contractual agreements themselves, and not an artifact of the Petri net. However, it must be acknowledged to add to the potential complexity of our methodological approach. Generating stochastic continuous Petri nets will manifest as Markov processes, and it would be worth adding probabilities of failures at nodes and links to gain a richer understanding of the vulnerabilities of a supply chain network.

There are several interesting extensions to the methodological approach that could be developed. For example, Zhang et al. (2011) identify the need for future research to model uncertainty in the supply chain and propose the use of tools to augment Petri nets such as fuzzy logic. These extensions should be investigated to develop more informative results for supply chain managers and could influence how and when mitigation strategies are deployed. Another interesting topic worthy of exploration is mining the network structure to identify important patterns. Such patterns can identify a sub-network, which can allow the user to explore that portion of the supply chain in greater depth while helping to address the challenge of scalability. Yet another opportunity is to add dimensions of node criticality and timing (delays and stoppages of flow) into the Petri net model (as discussed in the discussion section) as well as using tokens to represent resources (Murata, 1989) as opposed to material flow. Another extension would be to run “what-if” scenarios with the model to test vulnerability under difference scenarios or circumstances (Hwarng and Xie, 2008). What if different locations or suppliers were added, for example? This research could also be used to investigate varying levels of node failure. Instead of a complete failure, what would be the effect if a node had a partial failure? In addition, the method proposed in this paper does not account for single versus multiple suppliers, volumes, costs, lead times, difficult to re-source suppliers and component criticality. A supplement to our method (extending beyond our focus on supply chain structure) would be to add additional nuances and complexity into the method. Finally, a backward tracing of the flow in the model can help with issues related to traceability and pinpointing the origin of risk occurrences in the supply chain.

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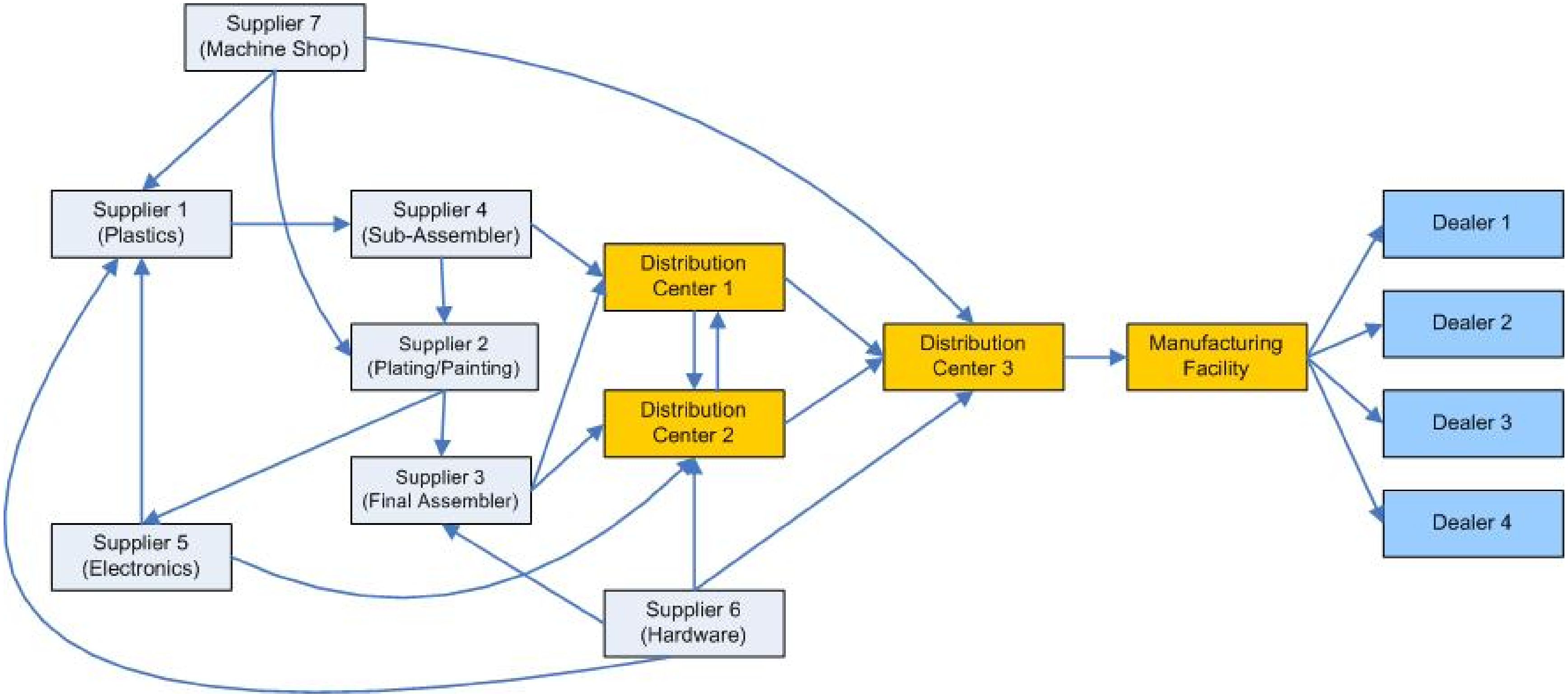

Figure 1. Service Parts Supply Chain Example

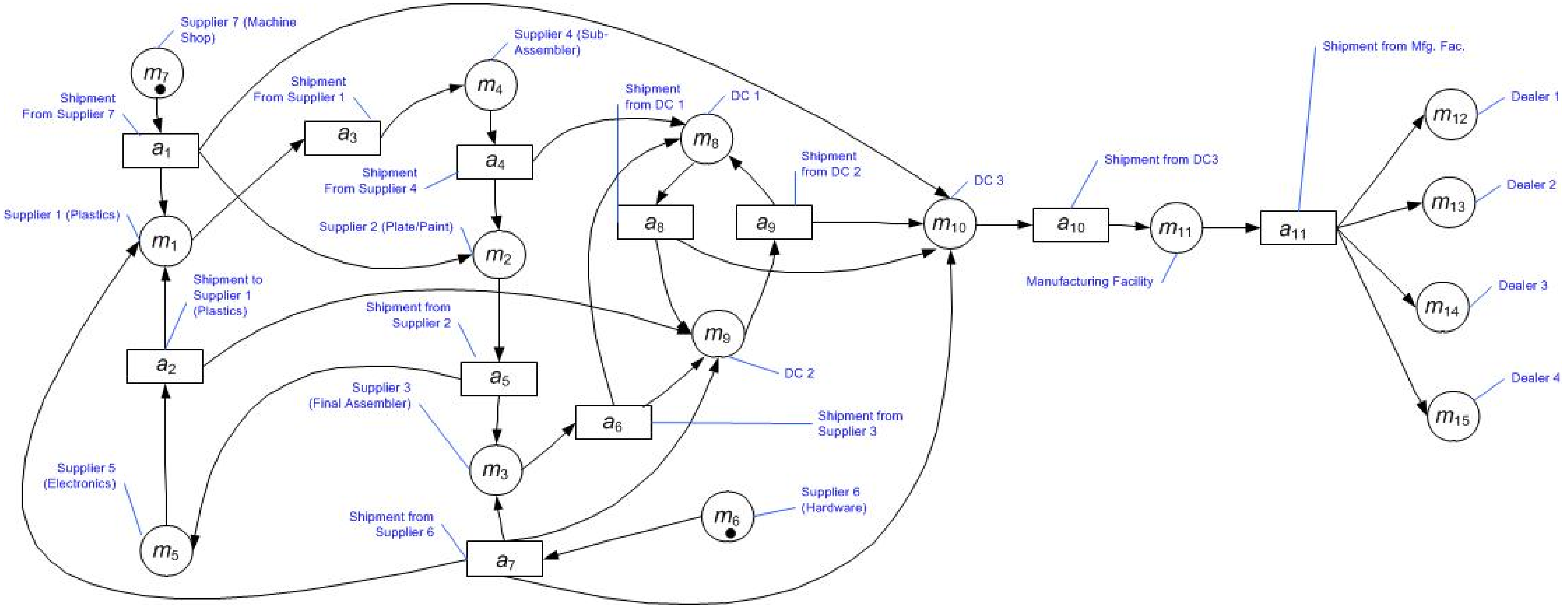

Figure 2. Petri net Representation for the Service Parts Supply Chain Example

Node Type	**Node Designator**	**Node Description**	**Initial Marking**	**Input Nodes**	**Output Nodes**
Place	m_1	Supplier 1 (Plastics)	0	a_1, a_2, a_7	a_3
Place	m_2	Supplier 2 (Painting/Plating)	0	a_1, a_4	a_5
Place	m_3	Supplier 3 (Final Assembler)	0	a_5, a_7	a_6
Place	m_4	Supplier 4 (Sub-Assembler)	0	a_3	a_4
Place	m_5	Supplier 5 (Electronics)	0	a_5	a_2
Place	m_6	Supplier 6 (Hardware)	1	–	a_7
Place	m_7	Supplier 7 (Machine Shop)	1	–	a_1
Place	m_8	Distribution Center (DC) 1	0	a_4, a_6, a_9	a_8
Place	m_9	Distribution Center (DC) 2	0	a_7, a_{12}, a_{16}, a_{17}	a_9
Place	m_{10}	Distribution Center (DC) 3	0	a_2, a_6, a_7, a_8	a_{21}
Place	m_{11}	Manufacturing Facility (MF)	0	a_{10}	a_{11}
Place	m_{12}	Dealer 1	0	a_{11}	–
Place	m_{13}	Dealer 2	0	a_{11}	–
Place	m_{14}	Dealer 3	0	a_{11}	–
Place	m_{15}	Dealer 4	0	a_{11}	–
Transition	a_1	Shipment from Supplier 7	0	m_7	m_1, m_2, m_{10}
Transition	a_2	Shipment from Supplier 5	0	m_5	m_1, m_9
Transition	a_3	Shipment from Supplier 1	0	m_1	m_4
Transition	a_4	Shipment from Supplier 4	0	m_4	m_2, m_8
Transition	a_5	Shipment from Supplier 2	0	m_2	m_3, m_5
Transition	a_6	Shipment from Supplier 3	0	m_3	m_8, m_9
Transition	a_7	Shipment from Supplier 6	0	m_6	m_1, m_3, m_9
Transition	a_8	Shipment from DC 1	0	m_8	m_9, m_{10}
Transition	a_9	Shipment from DC 2	0	m_9	m_8, m_{10}
Transition	a_{10}	Shipment from DC 3	0	m_{10}	m_{11}
Transition	a_{11}	Shipment from Manufacturing Facility	0	m_{11}	m_{12}, m_{13}, m_{14}, m_{15}

Table 1. Place Nodes and Transition Nodes for the Service Parts Supply Chain Example

	m_1	m_2	m_3	m_4	m_5	m_6	m_7	m_8	m_9	m_{10}	m_{11}	m_{12}	m_{13}	m_{14}	m_{15}	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
m_1	+																	1								
m_2		+																		1						
m_3			+																		1					
m_4				+															1							
m_5					+												1									
m_6						+																1				
m_7							+									1										
m_8								+															1			
m_9									+															1		
m_{10}										+															1	
m_{11}											+															1
m_{12}												+														
m_{13}													+													
m_{14}														+												
m_{15}															+											
a_1	1	1								1						+										
a_2	1								1								+									
a_3				1														+								
a_4		1						1											+							
a_5			1		1															+						
a_6								1	1												+					
a_7	1		1						1	1												+				
a_8									1	1													+			
a_9								1		1														+		
a_{10}											1														+	
a_{11}												1	1	1	1											+

Table 2. Node Dependency Matrix for the Service Parts Supply Chain Example

	Levels	**Cycles**
1	m_6, m_7	m_1, m_2, m_4, m_5, a_2, a_3, a_4, a_5
2	a_1, a_7	m_8, m_9, a_8, a_9
3	m_1, m_2, m_4, m_5, a_2, a_3, a_4, a_5 (also Cycle 1)	
4	m_3	
5	a_6	
6	m_8, m_9, a_8, a_9 (also Cycle 2)	
7	m_{10}	
8	a_{10}	
9	m_{11}	
10	a_{11}	
11	m_{12}, m_{13}, m_{14}, m_{15}	

Table 3. Levels and Cycles in the Petri net Representation for the Service Parts Supply Chain Example