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Developing a supply chain disruption analysis model: Application of colored Petri-nets

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ABSTRACT

As a result of globalization in the past two decades, supply chains are encountering more unknown conditions and risks. One important category of risks is disruptions that block material flowing through a supply chain and that may even result in end-product manufacturing failure. This paper uses a Petri nets-based model as a tool to understand the dissemination of disruptions and to trace the operational performance of a supply chain. The presented approach models how changes propagate through a supply chain and calculates the impact of disruptions on supply chain attributes by concluding the states that are obtainable from a given initial status in the supply chain.

1. Introduction

With regard to the complex and dynamic environment of supply chains, uncertainty (generally termed “risk”) has been raised as an important concern. The reported dramatic outcomes from risky events demonstrate the importance of proactively managing supply chain risk (Chopra & Sodhi, 2004).

Supply chain risks have been clustered into different groups, and these classifications differ between papers (Chopra & Meindl, 2007; Juttner, 2005; Tang, 2006b). Among the supply chain risks types are disruptions resulted from natural disasters, supplier bankruptcy, labor disputes, war, terrorism and social-economic-political instability (Chopra & Meindl, 2007; Craighead, Blackhurst, Rungtusanatham, & Handfiels, 2007; Hendricks & Singhal, 2005c; Kleindorfer & Saad, 2005). Naturally, different authors may suggest dissimilar sources for disruption risks, but disruption risks generally have a low probability and the potential for a large loss. Some papers refer to them as “catastrophic events” (Knemeyer, Zinn, & Eroglu, 2009). They can seriously disrupt or delay material, information and cash flows, which can ruin sales, increase costs or both. How a company gets along such threats depends on the type of disruption and the organization’s level of preparedness. Supply chains can use two complementary actions to respond (Pochard, 2003). They can secure their supply chain or they can develop resiliency. Both can be performed in many different ways, and it seems that there is no single best solution. The problem for mangers is to choose a good strategy and to quantify the benefits of various options. In order to determine the most effective method, mangers must be able to analyze disruptive events and their possible effects. Despite the importance of this issue, there is not a rich literature on supply chain disruptions and their effects. This may be due to the newness of this concept, which was primarily developed following the September 11 attacks. Existing studies for detecting the effects of disruptions on a supply chain are based on a single disruptive event, and the interrelationships between different types of disruptions have not been considered. Due to this lack of information, the current paper investigates a mathematical model for determining how disruptions of supply chain components are causally related to each other as well as finding out the way of disruptions’ propagation.

The remaining sections of this article are organized as follows: In following section, supply chain disruption studies and existing methods for analyzing a disruption are reviewed. Afterward, proposed model will be introduces, which is clarified using a numeric example and an empirical case study. Finally, the paper concludes with a brief summary.

2. Literature review

2.1. Supply chain disruption

Relative to the most business practices, the occurrence of a disruptive event is an extraordinary and unusual situation. While a significant amount of researches has been reported in the area of supply chains, there have been relatively little investigations conducted in the area of understanding the global impacts of supply chain disruptions (Wu, Blackhurst, & Grady, 2007). Fig. 1 shows the categories of published research in this field.

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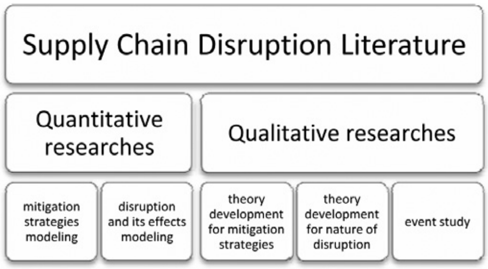

Fig. 1. Categories of disruption's published researches.

Along these lines, Lee and Wolfe (2003) presented strategies for reducing vulnerability to security losses that may cause disruptions. Kleindorfer and Saad (2005) introduced a conceptual framework to estimate and reduce the effects of disruptions. Norrman and Jansson (2004) studied a fire accident at Ericsson Inc.'s sub-supplier and the company's solution for mitigating the likelihood of such events as a proactive plan. Tang (2006a) proposed robust strategies for mitigating disruption effects, and Pochard (2003) discussed an empirical solution based on dual-sourcing to mitigate the likelihood of disruptive events. Marley (2006) discussed lean management, integrative complexity and tight coupling, as well as their relationships with disruption effects. Papadakis (2006), based on an empirical analysis, demonstrated the financial implications of supply chain design, particularly on the differences between pull- and push-type designs. Hendricks and Singhal (2005a) shed light on the effects of supply chain glitches that result in production or shipment delays and estimated their impact on shareholder wealth. In another report, Hendricks and Singhal (2003) showed that supply chain disruptions have negative effects on financial performance measures, as well as on operating income and return on assets. Craighead et al. (2007) illustrated the relationship between supply chain structure and disruption severity based on their observations from different case studies. Yu and Qi (2004) demonstrated mathematical models for demand disruptions while Qi, Bard, and Yu (2004) examined quantity discount policy when demand disrupts. Xiao and Yu (2006) developed a game model to study evolutionarily stable strategies (ESS) of retailers in quantity-setting duopoly situations with homogeneous goods and analyzed the effects of demand and supply disruptions on the retailers' strategies. Xiao, Qi, and Yu (2007) investigated the coordination mechanism of a supply chain with one manufacturer and two competing retailers when the demands are disrupted. Similarly, Xiao and Qi (2008) studied the coordination of a supply chain with one manufacturer and two competing retailers after the production cost of the manufacturer was disrupted. Tomlin (2006) suggested two different groups of strategies, mitigation and contingency, prior to a disruption and discussed the values of these two choices for managing a supply chain disruption. Chopra, Reinhardt, and Mohan (2007) focused on the importance of decoupling recurrent supply risk from disruption risk and of planning appropriate mitigation strategies.

All of the aforementioned strategies can be categorized into two main types, preventive and recovery, and preventive solutions can be categorized as follows:

- Robustness strategies (Tang, 2006a).
- Resiliency strategies (Rice & Caniato, 2003; Sheffi & Rice, 2005).
- Security-based strategies (Hale & Moberg, 2005; Lee & Whang, 2005; Rice & Caniato, 2003; Sheffi, 2001).
- Agility strategies (Chopra & Sodhi, 2004; Hendricks & Singhal, 2005b, 2005c; Li, Lin, Wang, & Yan, 2006; Tang, 2006b).

All these strategies to manage supply chain disruption, have a critical assumption that the supply chain managers are not aware of the time of disruption occurrences but experts can estimate vulnerable parts of the chain and the amount of disruption effects if it occurs, consequently they define some applicable policies. In general, because of the unpredictability and complex effects of disruption, some researchers (Knemeyer et al., 2009; Norrman & Jansson, 2004) choose proactive approaches. A catastrophic event has a very low probability of occurrence, but tremendous consequences if it occurs, and supply chains are increasingly susceptible to catastrophic events. So supply chain decision makers should put a priority for proactively planning these types of events (Knemeyer et al., 2009).

2.2. Supply chain disruption analysis

Despite the few papers on disruption analysis, some researchers have applied simulation models to predict supply chain behavior, and these simulations include models for tracing the effects of uncertainty (Petrovic, 2001), order release mechanisms (Chan, Nelson, Lau, & Ip, 2002), business processes and inventory control parameters (Jain, Workman, Collins, & Ervin, 2001). Kleijnen and Smits (2003) distinguish four simulation types for supply chain management (SCM): spreadsheet simulation, system dynamics (SD), discrete-event dynamic systems (DEDS) simulation, and business games, which are discussed and compared by Kleijnen (2005).

Some researchers have presented methods such as system dynamics (Wilson, 2006) and network-based procedures (Li et al., 2006; Liu, Kumar, & Aalst, 2007; Wu et al., 2007) to demonstrate disruptions effects. Wilson (2006) investigates the effect of transportation disruption on supply chain performance by applying system dynamics. Disruptions, however, are discrete events, and in order to scrutinize them, there is a serious need for discrete simulation methods. One creative method in this field is the use of Petri net approaches. Liu et al. (2007), Blackhurst, Wu, and Craighead (2008) and Wu et al. (2007) address Petri net-based models to illustrate and predict the propagation of disruptions through the supply chain.

Blackhurst et al. (2008) presented a methodology that extends the concept of basic Petri nets to discover supply chain conflicts before they occur. The approach involves linking hierarchical levels of the supply chain system and detecting conflicts that occur when single entities, each optimized for their own operations, are combined in a supply chain.

Liu et al. (2007) proposed Petri nets extended with time and color as a formalism for managing events. They designed seven basic patterns to capture modeling concepts that commonly arise in supply chains. They also showed how to combine the patterns to build a complete Petri net and analyze it using dependency graphs and simulation.

Wu et al. (2007) presented a network-based approach to model supply chain and the effects of a disruption and perturbation on it. The proposed approach (DA-NET) extends the concept of reachability analysis; and focuses on how disruptions can propagate through a supply chain and affect its performance. This model is a creative and practical approach, but it is independent of disruption type and does not consider interrelationships among different disruptions. It also does not consider that some disruptions are completely dependent on another or that one disruption may reduce the likelihood or severity of another. For instance, a sanction disruption may enhance the likelihood of unpredictable price decreases or labor disputes. Here, we propose a model that supports this condition as well as different disruptions. This feature allows decision makers to predict different situations in order to not only reduce response time, cost, inventory level and bullwhip effects, but also to increase flexibility and agility.

3. Proposed model

Although there are some researches on investigating supply chain risks through simulation (Chan et al., 2002; Kleijnen, 2005; Petrovic, 2001), these methods stands on the probabilistic nature of risks. Consequently, the main assumption is risks' patterns, can be estimated as different distribution functions, these estimations are based on previous risk experiences and existence of definable behavior. But, disruptions are partially or totally uncertain events (Klibi & Martel, 2008; Wu, Blackhurst, & Chidambaram, 2006) without any definable distribution functions. Hence, the best approach to manage such events is application of discrete events tracking based on cause and effect rules; and one such approaches for modeling a supply chain and its disruptions is a Petri net-based methodology. Because of its ability to demonstrate precedence as well as concurrent events, and furthermore its mathematical foundation and possibility of representing models in graphical way, this procedure has been shown to be an effective tool for modeling complex and dynamic systems (Wu et al., 2007). The concept of Petri nets was introduced by Carl Petri in 1962. A Petri-net graph is a bipartite graph, uses circles to represent place nodes and bars for transition nodes; directed arcs between place nodes and transition nodes are the symbols of input–output relationships. Tokens are located in places and travel along arcs; their flows through the arcs are regulated by transitions (Proth & Xie, 1997).

While Petri nets have been employed to model supply chains (Blackhurst et al., 2008), there has been a few researches investigating the application of Petri nets in supply chain disruption analysis (Blackhurst et al., 2008; Liu et al., 2007; Wu et al., 2007). Thorough understanding of disruption behavior would ease the design of contingency plans and operation strategies. This behavior can be explored by addressing creative approaches to apply reachability concept of Petri nets. While the model proposed by Wu et al. (2007) was a great step in disruption modeling, it is very general and illustrates the behavior of disruption regardless of its tacit effects on other disruptions. This paper attempts to overcome the drawbacks of their work.

The proposed model is sensitive to disruptions' type and interrelationships, so there is an essential need to choose an approach that could support this issue. Because of the capabilities of colored Petri nets (CPN) to handle this sort of problem, this model was selected. However, as a result of CPNs complexity, there are no analytical and mathematical tools for these sorts of networks. CPN is a graphical language for constructing models of concurrent systems and analysing their properties. It is a discrete-event modeling language combining the capabilities of Petri nets with the capabilities of a high-level programing language (Jensen & Kristensen, 2009). The main application of CPN has been in software engineering, though there are some papers exploring its capabilities in workflow modeling (Jun, Yong-Li, & Chang-Zheng, 2009) and manufacturing systems (Zhao, Cao, & Sun, 2009). Software applications exist that can trace the movement of tokens, but they are not capable to determine the effects of this movement in changing node attributes. Therefore, the proposed model makes new mathematical contributions to Petri nets concepts in addition to its application in tracking the effects of disruptions through supply chains. Hence, where most of the published works on CPNs are persisting on programing languages, the proposed model applies mathematical structure.

Table 1 details the basis for the CPN-approach for modeling supply chain systems. This model is referred to as CPND for the remainder of this paper. The definitions and the operation of the approach are described, illustrated by a numerical and an empirical example. Some of the definitions and variables are the same as Wu et al. (2007).

Definition 1 (*CPND*). A directed bipartite graph consisting of a set of nodes $P = \{p_1, p_2, \ldots\}$ and a set of arcs $L = \{l_1, l_2, \ldots\}$. The node set P is decomposed into two disjoint subsets M and A such that every arc in the graph joins a node in M with a node in A, and no arc joins nodes within the same subset. M is the set of place nodes and A is the set of transition nodes.

Definition 2 (*Place node*). Let $M = \{m_1, m_2, \ldots\}$ be a finite set of nodes m_i, where each mi consists of an attribute set $C^i = \{c_1^i, c_2^i, \ldots\}$. M is called a place node set, $m_i \in M$ is called a place node and is denoted by a circle in the graphical representation. Thus, for the CPND with m place nodes, the place node attribute set matrix is:

$$C = \left[C^1, C^2, \ldots, C^m\right] = \begin{bmatrix} c_1^1 & \cdots & c_1^m \\ \vdots & \ddots & \vdots \\ c_v^1 & \cdots & c_v^m \end{bmatrix}. \tag{1}$$

Definition 3 (*Transition node*). Let $A = \{a_1, a_2, \ldots, a_n\}$ be a finite set of objects, a_j, where each a_j consists of an attribute set $D^j = \{d_1^j, d_2^j, \ldots\}$ and an algorithm set $F^j = \{f_1^j, f_2^j, \ldots\}$

$$a_j = \left(D^j, F^j\right), \tag{2}$$

where A is called transition node set, and each $a_j \in A$ is called a transition node and denoted by a solid bar in the graphical representation.

Thus, for the CPND with n transition nodes, the transition node attribute set matrix is:

$$D = \left[D^1, D^2, \ldots, D^n\right] = \begin{bmatrix} d_1^1 & \cdots & d_1^n \\ \vdots & \ddots & \vdots \\ d_w^1 & \cdots & d_w^n \end{bmatrix}. \tag{3}$$

The algorithm set, F_j, is a set of operations on place node attributes sets and transition node attribute set. It is considerable that, the exact amount of attributes in place and transition nodes are not available before disruptions and they should be estimated based on previous experiences, experts' knowledge and similar cases in other supply chains.

Definition 4 (*Arc*). Let $L = \{(m, a) | m \in M, a \in A\} \subseteq (M \times A)$ be a finite set of arcs connecting place nodes and transition nodes. Each $(m, a) \in L$ is denoted by a uni- or a bi-directed arc in the graphical representation.

Definition 5 (*Marking vector*). Let T^i represent the marking vector for CPND at stage i, indicating the number of tokens of each color in each place. In the graphical representation, a marking $t_{k,m}^i$ is indicated by t small tokens of color k in the circle representing place node m. Note that T^0 indicates the initial marking of the CPND network:

$$T^i = \begin{bmatrix} t_{1,1}^i & \cdots & t_{1,m}^i \\ \vdots & \ddots & \vdots \\ t_{k,1}^i & \cdots & t_{k,m}^i \end{bmatrix}. \tag{4}$$

Definition 6 (*Input matrix*). Input matrix I: $A \times M \to \{0, 1\}$ shows the arc from M to A. If there is any arc from m_i to a_j then $I_{ij} = 1$ and otherwise $I_{ij} = 0$.

Table 1
Parameters and their descriptions in CPND.

Parameters	Description
$A = \{a_1, a_2, \ldots, a_n\}$	Transition nodes set
$a_j = (D^j, F^j)$	Elements of transition node a_j
$D = \left[D^1, D^2, \ldots, D^n\right] = \begin{bmatrix} d_1^1 & \cdots & d_1^n \\ \vdots & \ddots & \vdots \\ d_w^1 & \cdots & d_w^n \end{bmatrix}$	Attributes of transition nodes
$D^j = \left[d_1^j, d_2^j, \ldots\right]'$	Attributes of transition node a_j
$F^j = \left\{f_1^j, f_2^j, \ldots\right\}$	Set of algorithms in node a_j
f_k^j	One of the algorithms for a_j
$M = \{m_1, m_2, \ldots, m_m\}$	Place nodes set
$C = \left[C^1, C^2, \ldots, C^m\right] = \begin{bmatrix} c_1^1 & \cdots & c_1^m \\ \vdots & \ddots & \vdots \\ c_v^1 & \cdots & c_v^m \end{bmatrix}$	Attributes of place nodes
$C^i = [c_1^i, c_2^i, \ldots]'$	Attributes of transition node c_i
$X = M \cup A$	Set of all nodes
$I: A \times M \to \{0, 1\}$	Mapping of input matrix
$O: A \times M \to \{0, 1\}$	Mapping of output matrix
$G = O - I$	Incidence Matrix
$L = \{l_1, l_2, \ldots\}; L \subseteq (M \times A) \cup (A \times M)$	Set of all arcs
K	Number of color of tokens
$Q^j = \begin{bmatrix} q_{1,1}^j & \cdots & q_{1,k}^j \\ \vdots & \ddots & \vdots \\ q_{k,1}^j & \cdots & q_{k,k}^j \end{bmatrix}$	Relation matrix of tokens' color for entering tokens to transition a_j
$P^j = \begin{bmatrix} p_{1,1}^j & \cdots & p_{1,k}^j \\ \vdots & \ddots & \vdots \\ p_{k,1}^j & \cdots & p_{k,k}^j \end{bmatrix}$	Relation matrix of tokens' color for outgoing tokens from transition a_j
$T^i = \begin{bmatrix} t_{1,1}^i & \cdots & t_{1,m}^i \\ \vdots & \ddots & \vdots \\ t_{k,1}^i & \cdots & t_{k,m}^i \end{bmatrix}$	Marking matrix at stage i, indicating the number of tokens in each color in each place. T^0 indicates the initial marking
$t_{k,m}^i$	Number of tokens of color k in place m at stage i
$H^i = [h_1^i, \ldots, h_n^i] = \begin{bmatrix} h_{1,1}^i & \cdots & h_{n,1}^i \\ \vdots & \ddots & \vdots \\ h_{1,k}^i & \cdots & h_{n,k}^i \end{bmatrix}$	Transitions' firing matrix at stage i
$R(T^i) = \begin{bmatrix} rt_{1,1}^i & \cdots & rt_{1,m}^i \\ \vdots & \ddots & \vdots \\ rt_{k,1}^i & \cdots & rt_{k,m}^i \end{bmatrix}$	Reachable marking from initial marking T^i
$S^i = [s_1^i, s_2^i, \ldots]'$	State of the network at stage i

Definition 7 (*Output matrix*). Output matrix $O: A \times M \to \{0, 1\}$ shows the arc from A to M. If there is any arc from a_j to m_i then $O_{ij} = 1$ and otherwise $O_{ij} = 0$.

Definition 8 (*Incidence matrix*). If the network does not have any direct loop (there is no arc from a_j to m_i and from m_i to a_j) the incidence matrix is defined as:

$$G = O - I. \tag{5}$$

Definition 9 (*Firing transition*). Transition a_j is fired if for all input place m_i, $t_{k,i} \geqslant 1$.

Definition 10 (*Relation matrix of token color for tokens entering transition a_j*). This matrix indicates the relationship of input token color with existing token color in each transition node. In the other words, it shows which colors of tokens can be fired by entering a token with a specific color. This relationship can be shown as follows:

$$Q^j = \begin{bmatrix} q_{1,1}^j & \cdots & q_{1,k}^j \\ \vdots & \ddots & \vdots \\ q_{k,1}^j & \cdots & q_{k,k}^j \end{bmatrix}. \tag{6}$$

In this matrix if $q_{3,4}^2 = 1$, the entering token to a_2 with the third color would change its color to the fourth one before having any influence on transition a_2. Consequently if the third disruption occurs, the fourth disruption will be triggered from transition node a_2 but the third disruption would not have any impact on transition a_2.

Definition 11 (*Relation matrix of tokens' color for outgoing tokens from transition a_j*). This matrix indicates the relationship of output token color with created token color in each outgoing place node. It shows which colors of tokens can be created by entering a token with specific color. This relationship can be shown as follows:

$$p^j = \begin{bmatrix} p_{1,1}^j & \cdots & p_{1,k}^j \\ \vdots & \ddots & \vdots \\ p_{k,1}^j & \cdots & p_{k,k}^j \end{bmatrix}. \tag{7}$$

In this matrix if $p_{2,5}^3 = 1$, the outgoing token from a_3 with the second color would change its color to the fifth one. Consequently if the second disruption occurs, the fifth disruption will be triggered after firing transition node a_3 and the impact of both disruptions are felt in this transition node.

Definition 12 (*Firing matrix*). This matrix indicates which transitions and which tokens can be fired in each stage. This matrix can be shown as:

$$H^i = [h^i_1, \dots, h^i_n] = \begin{bmatrix} h^i_{1,1} & \cdots & h^i_{1,n} \\ \vdots & \ddots & \vdots \\ h^i_{k,1} & \cdots & h^i_{k,n} \end{bmatrix}, \quad \text{where} \quad h^i_{\alpha,\beta} \in \{0,1\}. \tag{8}$$

If token with color α is fired in transition β at stage i, then $h^i_{\alpha,\beta} = 1$, otherwise $h^i_{\alpha,\beta} = 0$, i.e., if at third stage, all input places to transition a_5 have at least one token of second color, the transition a_5 can be fired to transfer the token of second color and $h^3_{2,5}$ would be 1. It is notable that $H^0 = \{0\}$.

Definition 13 (*Updating marking matrix*). If T^i is marking matrix at stage i, G is incidence matrix and H^i shows the firable transitions and tokens, the updated marking matrix after firing is obtained by

$$\left(T^{i+1}\right)' = \frac{\alpha + ABS(\alpha)}{2}, \tag{9}$$

which reveals the number of tokens in each color in each place after firing progress, where $ABS(\alpha)$ returns the absolute value of α and,

$$\alpha = \left(T^i\right)' + G \times \left(H^i\right)' + \sum_{j=1}^{n} \left(\left(\left(T^i\right)' + G \times \left(H^i\right)'\right) \times \left(Q^j - Im\right) - \sum_{j=1}^{n} \left(T^i\right)' \times \left(P^j - Im\right). \tag{10}$$

where Im is Identity Matrix.

Definition 14 (*Updating attributes*). If T_i is marking matrix at stage i, G is incidence matrix, H^i shows the firable transitions and tokens, $C = [C^1, C^2, \dots, C^m]$ is attributes of places and $D = [D^1, D^2, \dots, D^n]$ is attributes of transitions; the updated attributes are obtained by following equation in which F is the suitable function depend on each case:

$$\begin{aligned} S^i &= [s^i_1, s^i_2, \dots]' \\ &= F\left\{\left[C^1, C^2, \dots, C^m\right] \times \left(T^{i-1}\right)', \left[D^1, D^2, \dots, D^n\right] \times \left(H^i\right)'\right\}. \end{aligned} \tag{11}$$

The result of this up-grading, shows the impact of disruptions during each stage of their spreading; and in final run it would be clear that which phase of this diffusion has the largest effect and summation of all stages exhibits the total influence. In addition, the effects of disruptions are calculated for each attribute separately which reflects different influences on each attribute, e.g. cost or lead-time.

Definition 15 (*Reachable marking from marking T^i*). This matrix indicates the reachable marking matrix from the initial marking T^i where $rt^i_{\alpha,\beta}$ is number of tokens with color α in place β:

$$R\left(T^i\right) = \begin{bmatrix} rt^i_{1,1} & \cdots & rt^i_{1,m} \\ \vdots & \ddots & \vdots \\ rt^i_{k,1} & \cdots & rt^i_{k,m} \end{bmatrix}. \tag{12}$$

If a disruption occurs in a supply chain, it will be shown by tokens and the path of its propagation can be obtained from marking matrix. In the proposed model, in order to distinguish different disruptions, each disruption is introduced by specific colors, and interrelationships of disruptions are addressed by relationships between colors of tokens. In addition, the effect of disruption on nodes' attributes is calculated based on Definition 14.

4. Numerical example

In order to clarify the proposed model, this section contains a numerical example based on reality, and the presented definitions are used in practice. This example contains a 4-stage supply chain with supplier tier-2, supplier tier-1, a manufacturer and a retailer (Fig. 2).

Supplier tier-2 and supplier tier-1-b are not local, but supplier tier-1-a, the manufacturer and the retailer are in the same country. Based on this assumption, relationships between countries can influence supply chain cooperation. This supply chain can be transformed to Petri nets as shown in Fig. 3, in which political instabilities and sanctions prevent material flow between supplier tier-2 and supplier tier-1-b. As a result of this disruption, production in supplier tier-1-a breaks off, and the supplier falls into bankruptcy, which launches a second disruption. Based on the Petri nets model (Fig. 3), the first disruption arises at place nodes m_1 and m_2. At transition a_2, a disruption is capable of initiating another (e.g., a sanction causes supplier bankruptcy), and in this network, the first disruptions in m_1 and m_3 causes some loss. This loss is measured by cost and time as two important performance factors.

This example tries to demonstrate the way in which disruptions spread among supply network members and one disruption's effect on other disruptions and supply network attributes. The parameters introduced in the previous section are as follows:

$$I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, \quad O = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad G = \begin{bmatrix} -1 & 0 & 0 \\ 1 & -1 & 0 \\ 0 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{bmatrix},$$

$$D = \begin{bmatrix} 5 & 1 & 1 \\ 7 & 1 & 0.5 \end{bmatrix},$$

$$C = \begin{bmatrix} 8 & 6 & 7 & 12 & 2 \\ 3 & 1 & 2 & 2 & 7 \end{bmatrix}, \quad T^0 = \begin{bmatrix} 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$H^1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad Q^1 = Q^2 = Q^3 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad P^1 = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix},$$

$$P^2 = P^3 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

where, matrix C represents the cost and lead-time effects of disruption in each place node as it attributes and in similar way, matrix D represents the attributes of transition nodes. In addition, the interrelationship of disruptions is reflected by matrix P^1.

It is notable that in order to standardize definitions of places and transitions, in this example all of the processes that are shown by places and transitions also show transportations.

Based on Definition 13, the updated marking matrix will be calculated as follows:

$$(T^1)' = \frac{\alpha + ABS(\alpha)}{2} = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

In this stage, T^1 is added to the set of $R(T^0)$, and updated attributes are obtained by Definition 14. The most regular function for integrating loss in different tiers of a supply chain is a simple sum, so as the starting point we use this function as F:

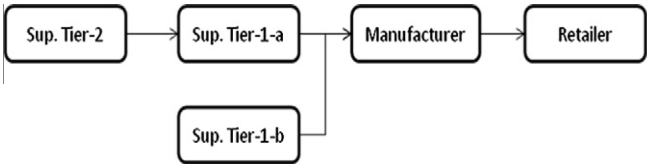

Fig. 2. Supply chain in numerical example.

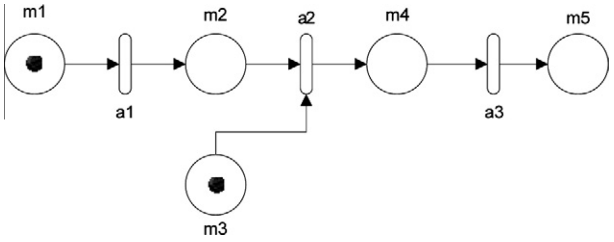

Fig. 3. Petri net model in numerical example.

$$S^i = [s_1^i, s_2^i, \ldots]' = \begin{bmatrix} 20 & 0 \\ 12 & 0 \end{bmatrix}.$$

At this stage, following to the occurrence of first disruption, the cost of 20 units and additional lead-time of 12 units (the first column in matrix S^i) have been imposed to the supply chain. Table 2 presents the results of each stage.

In order to compute final losses due to disruptions, S^is should be added, and forms the resulting status of the network in each attribute:

$$\text{resulted status} = \sum_i S^i = \begin{bmatrix} 20 & 0 \\ 12 & 0 \end{bmatrix} + \begin{bmatrix} 14 & 1 \\ 4 & 1 \end{bmatrix} + \begin{bmatrix} 13 & 13 \\ 2.5 & 2.5 \end{bmatrix} = \begin{bmatrix} 47 & 14 \\ 18.5 & 3.5 \end{bmatrix}.$$

This matrix shows that because of first disruption, the cost of 47 units and additional lead-time of 18.5 occur, and as a result of the second disruption, the imposed cost and lead-time would be 14 and 3.5, respectively.

5. An empirical case study

This section describes an application of the proposed model (CPND) based on data from an automotive spare parts manufacturer in Iran, a developing country. The main purpose of this case study is to demonstrate the application of CPND to a real-world environment. It should be noted that some details have been omitted or simplified to reduce the length of this case study.

Table 2
Results of computations at each stage.

Stage (i)	T^i	H^i	S^i
0	$\begin{bmatrix} 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$	–	–
1	$\begin{bmatrix} 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 20 & 0 \\ 12 & 0 \end{bmatrix}$
2	$\begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 & 0 \\ 0 & 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 14 & 1 \\ 4 & 1 \end{bmatrix}$
3	$\begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 13 & 13 \\ 2.5 & 2.5 \end{bmatrix}$

Suppose that there is a supply chain of 5 stages consisting of suppliers at tier-2, suppliers at tier-1, manufacture, retailers and customers. There is a pull policy from supplier tier-2 to manufacture and a push policy forward from manufacture (Fig. 4). In this arrangement, manufacture contacts suppliers for replenishment, but its order is not based on the direct orders of retailers. Rather, it is sent based on predicted customer demand and seasonal discounts. The distributors sell products to customers, and they normally ship customers' orders from stock. When there are several back-orders, this situation might be caused by a serious production delay. These sorts of situations would be considered as disruption. If the production delay was caused by material supply delay, manufacture would try to contact an alternative supplier for replenishment.

The illustrated supply chain purchases different products, but in this case study only a product is mentioned. First, the supply chain actions and rules should be identified. Then, it is possible to form a Petri net. These actions are summarized in Table 3, and each of them corresponds to a place in the Petri net.

As mentioned in Definition 9, transition a_j is fired if for all input place m_i, $t_{k,i} \geqslant 1$. So if there is a transition node that can be fired if at least in one input place m_i, $t_{k,i} \geqslant 1$, we have to transform that part of the Petri net as shown in Fig. 5(a) and (b). So, if this "or condition" is valid in transition a_1, then three dummy nodes (a_2, a_3, m_3) are added to the model.

Based on several interviews with top managers, different disruptions were discovered that caused production delays, and the most important ones are listed in Table 4. Managers were also asked to demonstrate the interrelationships of different disruptions and the effects one disruption had that trigger others. Based on their importance, interrelationships and their effects on supply chain outputs, sanctions and supplier financial inability were chosen for deeper investigation.

This cause and effect relationship is reflected in relation matrix of tokens' color. According to these dealings, the occurrence of some disruptions is just determined through these matrices. Consequently, the relation matrices have the significant role of revealing effects of secondary disruptions when the primary disruption reaches specific nodes in network.

It is notable that there are several rules that connect places to each other and also form the behavior of tokens in a Petri net. When a customer order arrives and there is no out-of-stock situation, the order is confirmed. When a customer order arrives but there is an out-of-stock situation, a back-order is generated; manufacture sets a production plan based on its prediction and sends orders to suppliers to provide material and parts. When an order is sent to the supplier that is not local, they negotiate the payment method. Under regular conditions, the supplier and manufacturer accept credit payment, but under sanction situations, the supplier prefers to receive cash instead. If payment is done on cash, bargaining meetings take place.

Transactions in supply chains are very vast and sophisticated; hence it is often difficult to see how changes or disruptions will be dispread through the network. In exploring the case study, even a small part of the supply chain can represent significant complexity. Fig. 6 shows processes by place nodes. These processes may indicate transportations, negotiations, payments, production, assembly steps, engineering steps or inspection steps. Note that each place node has an attribute set (in this case, cost and lead-time), and each transition node has an attribute set along with an algorithm set that represents calculations for cost and lead-time. The processes are initiated by a manufacture order for each part and material. In examining Fig. 6, it is not easily possible to realize how disruptions will propagate through the network or where they will have an influence on key attributes or performance measures. Thus, there is a need for using CPND.

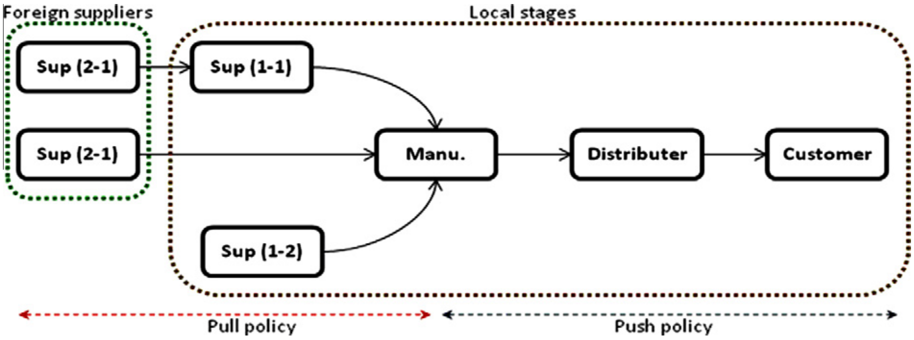

Fig. 4. Supply chain arrangement in empirical study.

Table 3
Places description.

m_1	Material transportation to sup (1–1)	m_{27}	Negotiation on payment method with sup (2–2)
m_2	Producing part $a1$ at sup (1–1)	m_{28}	Negotiation on credit payment with sup (2–2)
m_3	Part $a1$ quality control	m_{29}	Negotiation on cash payment with sup (2–2)
m_4	Recycling at sup (1–1)	m_{30}	Opening credit for manu
m_5	Wastes transportation at sup (1–1)	m_{31}	Cash payment for manu
m_6	Packaging at sup (1–1)	m_{32}	Material transportation from sup (2–2)
m_7	Order to sup (2–1)	m_{33}	Custom issues for manu
m_8	Negotiation on payment method with sup (2–1)	m_{34}	Bargaining on material price at manu
m_9	Negotiation on credit payment with sup (2–1)	m_{35}	Negotiation with intermediaries at manu
m_{10}	Negotiation on cash payment with sup (2–1)	m_{36}	Negotiation for alternative supplier at manu
m_{11}	Opening credit for sup (1–1)	m_{37}	Reducing cash at manu
m_{12}	Cash payment for sup (1–1)	m_{38}	Decision to production stop at manu
m_{13}	Material transportation from sup (2–1)	m_{39}	Order to sup (1–2)
m_{14}	Custom issues for sup (1–1)	m_{40}	Material transportation from sup (1–2)
m_{15}	Bargaining on material price at sup (1–1)	m_{41}	Financial procedures for sup (1–2)
m_{16}	Negotiation with intermediaries at sup (1–1)	m_{42}	Producing part $a3$ at manu
m_{17}	Negotiation for alternative supplier at sup (1–1)	m_{43}	Part $a3$ quality control
m_{18}	Reducing cash at sup (1–1)	m_{44}	Reworking on part $a3$ at manu
m_{19}	Decision to production stop at sup (1–1)	m_{45}	Assembly at manu
m_{20}	Part transportation from sup (1–1) to manu	m_{46}	Final product quality control
m_{21}	Material transportation to manu	m_{47}	Reworking on final product
m_{22}	Producing part $a2$ at manu	m_{48}	Distribution
m_{23}	Part $a2$ quality control	m_{49}	Purchasing
m_{24}	Recycling at manu	m_{50}	Dummy place
m_{25}	Wastes transportation at manu	m_{51}	Dummy place
m_{26}	Order to sup (2–2)		

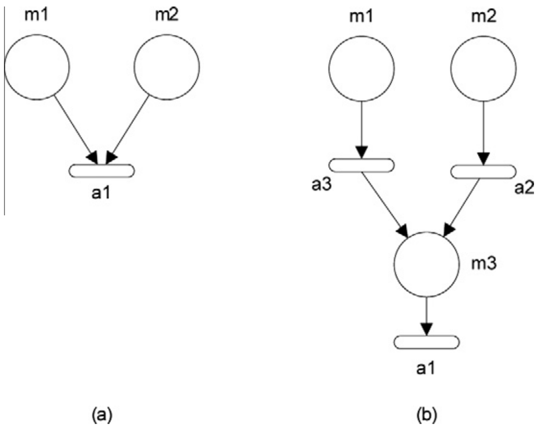

Fig. 5. Transforming Petri net with “or condition” in transition $\mathbf{a}_1$.

Table 4
Disruptions list.

Code	Disruptions	Probable outcome
*D*1	Sanction	*D*2, *D*3
*D*2	Supplier financial inability	–
*D*3	Inflation	*D*2
*D*4	Fluctuation of exchange rate	*D*3

The processes within the supply chain are vulnerable to disruptions. This study emphasizes problems due to sanctions. There are only a few countries encountering this problem, and it is not a well-known problem. However sanctions cause serious problems both directly and indirectly.

Let us use this disruption as an illustration of the application of CPND. Sanctions occur because of political problems, and international partners in the supply chain encounter restrictions on being in contact with each other. In our example, suppliers are prohibited from answering orders and providing after-sale services. This restriction causes several problems. Suppliers try to ask for cash payment instead of credit, due to some restrictions on financial institutes. Moreover, suppliers try to increase their price, and several negotiation meetings take place that add additional cost and lead time. By increasing limitations, some suppliers tend to prevent direct sourcing so that intermediaries must the part or material. This also causes increases in both cost and lead time. In the worst conditions, some suppliers prevent even indirect sourcing, and an alternative supplier will be selected that causes more cost and lead time in addition to decreased quality. In our case study, most of the local suppliers are small and a rise in cost for long periods of time would present serious problem for them.

Consequent to the lack of material supplied by foreign suppliers, the local suppliers may be forced to reduce production levels or even stop production. This lack of material can be the root of huge loss for local suppliers. Supplier financial inability has different meanings in the literature, and in this example, we use supplier financial inability as financial problems that block material flow in the supply chain. Based on this definition, sanctions may cause supplier financial inability and the bankruptcy of a local supplier. A m_{16}, tokens of the first color can fire token of a second color, and one disruption triggers the other; this effect is entered to the model through relation matrix of tokens' color as the critical components to start investigation on second disruption.

When sanction occurs, it causes a token from first color to appear at m_{10} and m_{29}. When these nodes are disrupted, how will this disruption affect the overall supply chain performance? Supply chain managers are eager to know the disruption's impact on the system as a whole. Disruptions at susceptible members and portions in the supply chain can have a significant impact on downstream supply chain entities, including final customers. The studied supply chain's managers declared that the cost and the lead-time are the key performance measures for the supply chain. Therefore, each place node (m_i) has the attribute set $C^i = \{c_1^i, c_2^i\}$, where c_1^i is the cost and c_2^i is the lead-time of that place node. Each transition node has an attribute set $D^i = \{d_1^i, d_2^i\}$, where d_1^i is the cost and d_2^i is the lead-time of that transition node. Also, an algorithm set $F^i = \{f_1^i, f_2^i\}$ exists, where f_1^i and f_2^i are applied to update the effect of disruption on cost and lead-time, respectively, when the transition node is fired.

For this example, let us assume that a sanction occurs, the supply chain is disrupted and the initial marking sets a token of first in node m_{10} and m_{29}. To detect the effects on the supply chain if the nodes m_{10} and m_{29} are disrupted; CPND operations shows the reachability set of m_{10} as $(m_{10}, m_{12}, m_{15}, m_{16}, m_{17}, m_{18}, m_{19})$ and the reachability set of m_{29} as $(m_{29}, m_{31}, m_{34}, m_{35}, m_{36}, m_{37}, m_{38})$. In addition to propagation of sanction disruption, the CPND operation shows the effect of sanctions on triggering other disruptions, including supplier financial inability, which is the secondary disruption in current study. This effect can be shown in node m_{19} by initiating second color token and its reachability set is (m_{19}, m_{20}, m_2).

Employment of CPND illustrates the reachable set of nodes, i.e., the nodes affected by propagation of the disruption. CPND is applied not only to illustrate the disruption propagation, but also to evaluate how the disruption impacts the system quantitatively, as explained in previous section. The studied disruptions are critical from political point of view, so the authors were not allowed to publish the exact cost and lead-time values. This paper can only report estimated amounts of these attributes rather than the real ones. By this assumption, if the operation of the network runs normally, each production batch will have a cost of 95,000 Tomans (the unit cost in Iran) with a lead-time of 19 days. The sanction

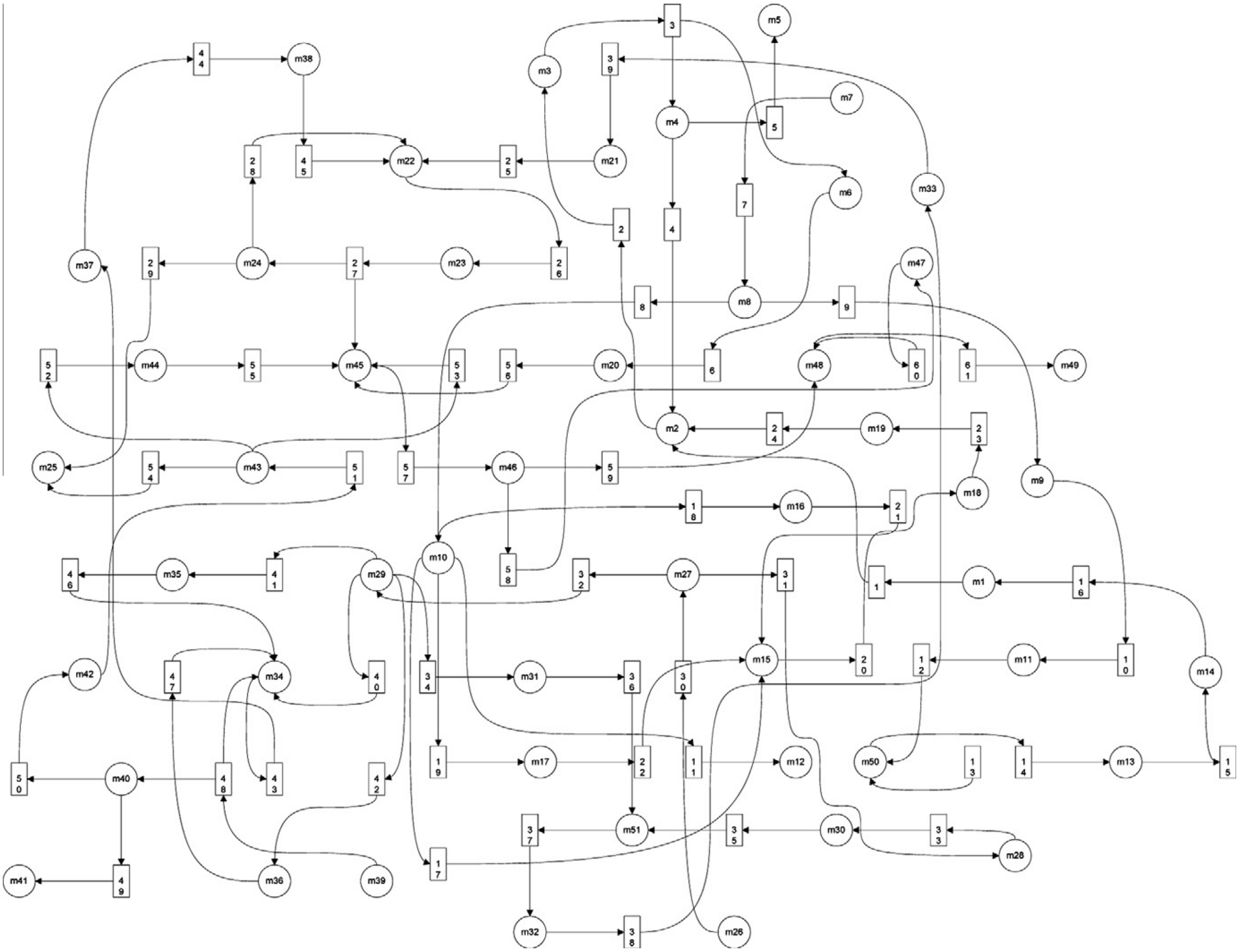

Fig. 6. CPND network for empirical case study.

disruption, however, will affect the key attributes. The first outcome of sanction is a restriction on the payment approach; international banks will not support open credit and the lone way is to pay by cash, which causes an increase in lead-time and overhead cost. If the restrictions go beyond the payment methods, it is probable that some companies will be prevented from direct sourcing, and additional intermediaries may enter the supply chain, generating an additional cost (28,500 Tomans) and lead-time (7 days). Conversely, the other option is to choose an alternative supplier and set it as the fixed supplier. In this situation the procurement lead time and cost should be negotiated, and this decision will cause additional costs and lead-time, depending on the selected alternative supplier. Because under normal circumstances this supply chain tries to select components with the lowest cost and lead-time, the alternatives offer worse conditions.

In addition to the direct effects of sanction, the other important side effect is its influence on other disruptions such as supplier financial inability. As mentioned earlier, supplier financial inability has different meanings in literature, in the context this work, we mention it as the supplier's inability to continue its role in the supply chain due to financial problems that block the material flow. Based on this definition, sanction may cause bankruptcy of a local supplier. Declaring bankruptcy in Iran has its own unwritten special rules that may not obey most international rules. One reason for this issue could be the governmental structure of most important industries. In this study, we define bankruptcy as an important result of financial inability that ends production. By this definition, harsh financial situations caused by sanctions lead to serious financial problems and cause a stop in production, so this problem can be shown as a token in m_{18} and m_{37}. Hence, the effects of a second disruption can also be calculated and illustrated by a CPND procedure that estimates an additional cost of 21,000 Tomans and 3 days of for lead-time. But the most important part in this procedure reflects the interrelationship of different disruptions, as explained in earlier part of this section.

The case study presented in this paper gives a special example of a couple of disruptions that could occur in a supply chain. The modeling approach (CPND) is able to investigate how changes disseminate through a supply chain and can assess the impact of the disruption on key attributes. This ability will permit better management of a supply chain and thus will allow the whole supply chain and each member to prepare quicker response against disruption or even plan for future unwanted events.

6. Conclusion

Supply chains are increasingly susceptible to disruptions; and investigating policies to control/mitigate disruptions becomes a necessity for companies and a crucial field of research. There are several examples by academics and practitioners on system-wide effects of supply chain disruptions, but there are only a few that consider their behavior in a supply chain. In order to propose effective solutions for mitigating disruptions, there is an essential need to track disruptions and their effects. This paper used Petri nets as a tool to trace the prevailing disruption. Based on the proposed model, the path of spreading disruptions, their interrelationships and their effects on performance factors can be determined. Determining the way events propagate along supply chains and the way they affect different elements will help decision makers to concentrate on vulnerable areas and to find more effective solutions. Based on this method, they can assess how much a solution may help to reduce disruption effects.

In line with this study, one important area for future research is to explore mathematical and analytical models to measure the amount of correlation and interdependence of supply chain disruptions. In addition to qualitative analysis of disruption interrelationships, it is crucial to estimate the quantitative amounts of these correlations. Consequently, this value would affect the development of mitigation and contingency plans for each disruption. Moreover, in evaluation of a supply chain's total disruption it should be considered that, a supply chain's total disruption may not be a simple sum of its parts, and correlation of different disruptions should be mentioned in any research. However, there is an essential need to find useful tools for evaluating a disruption's probability, something that has scarcely been mentioned by researchers.

Furthermore, as disruption's parameters (e.g., probability of occurrence and its impact) are very hard to estimate accurately, developments of disruption analysis tools with insensitivity to errors in such parameters can be mentioned as fourth area of future research.

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