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ASSESSING THE RESILIENCY AND IMPORTANCE OF A SUPPLY CHAIN NETWORK

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ABSTRACT

In supply chain management under disruption, definition of resilience is based on many factors, and a consensus is yet to be agreed upon. In addition, there is very limited quantitative research in the supply chain resiliency field. Therefore, we propose a mathematical formulation for constructing a resilient supply chain under disruption. Our goal is to design supply chain networks that are resilient under stress by incorporating the concept of node importance. For quantifying resilience, mathematical formulation is a new approach, and the objective function of the model is based on the idea of resiliency triangle and node importance. Solving this problem, allows evaluation of the resiliency of a supply chain as a whole, as well as the resilience of individual building blocks. Disruptions and recovery are stochastic processes in real life. The problem itself has non-polynomial many binary variables. Therefore, we have developed a simulation model for validating the mathematical model. Many realistic scenarios have been generated and the simulation model has been tested under those scenarios.

Keywords: Resiliency, Supply Chain Management, Simulation, Mathematical Modeling

1 INTRODUCTION

Supply chain is a critical component for a firm to stay ahead of its competitors. Disturbances cause reduction in the performance of the supply chain, and therefore a firm will lose competitiveness when a disturbance occurs. A worldwide survey of international businesses reported that 85% of firms experienced at least one major disruption in year 2010 (Business Continuity Institute 2011). Disturbances are difficult to anticipate and usually have negative consequences affecting many parties due to integrated structure of supply chains (Barroso et al. [1]).

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In recent years, many different forms of disturbances have been reported. Natural catastrophes whether small or large in scale have drastic impact on supply chain, such as the earthquake at central Taiwan in September 1999, Indian Ocean Tsunami in 2004, Haiti and Chile Earthquakes in 2010, and the 2010 eruption of Icelandic volcano Eyjafjallajokull. In addition, technical faults such as the oil spill that took place in the Gulf of Mexico and economic crises such as the one we are slowly leaving behind caused by the failure of Lehman Brothers are examples of what could go wrong (Barroso et al., Bhamra et al. [1, 2]). Natural disasters, pandemic diseases, terrorist attacks, economic recessions, worker strikes, wars, equipment failures and human errors can all pose severe threats to the continuity of an organization's operation, while they have a direct effect on an organization's ability to supply finished goods to a market and provide critical services to customers.

Blackhurst et al. [14] review literature on the quantification of cost of supply chain due to disruptions. In 1996, as a consequence of 18 day labor strike, quarterly earnings were reduced by $900 million at General Motors. In 1997, Boeing suffered from disruption of supplier delivery, resulting an estimated cost of $2.6 billion. Another consequence of supply chain disruption mentioned is on the impact to the stock market. Such announcements decreased the shareholder value by 10.28% with a recovery time of 50 trading days based on a different research. Because of these, it is essential that the supply chain is designed as resilient to disturbances as possible. We define resilience as *the supply chain's ability to react to disturbances and return to its original state* (Christopher and Peck, Ponomarov et al. [3, 4]). Therefore, the focus must be on reducing the probability of occurrence of a disruption, reducing the consequences of those disruptions once they occur, and reducing the time to recover (Falasca et al. [5]).

Supply chain resilience has been mostly studied in a qualitative manner. Therefore, this paper aims to develop a quantitative framework for assessing the resiliency of a supply chain. Our main purpose is to develop a model based upon the definition of supply chain resilience. We incorporate the idea of node importance into this evaluation. Within this framework, the criticality of a node can be evaluated in a more realistic manner, as a node with relatively low traffic does not necessarily have to be as resilient as a node with a high volume of goods flowing through it.

The model we propose allows decisions to be made related to network design and quantifying the resilience and importance of nodes, thus better evaluation on the criticality of nodes. In the problem we are solving, every node is either a supply or a demand node, and they all have different probabilities of being affected from various disruptions, which are often independent from each other. Similarly, the set of available arcs can be interrupted as a result of a disruption. Unfortunately, a disruption imposes a monetary consequence on the affected arc or node regardless of the magnitude. The monetary consequence faced represents both the deviation from the normal state of the disturbed component of the supply chain and the time it takes for the same component to get back to its original state. The demand must be satisfied, and the nodes and arcs must be chosen such that the available budget is not exceeded. While satisfying these conditions, our goal is to make sure that we design our supply chain in such a way that the weakest link (i.e. node) in the network is as resilient as possible. Node defined as the weakest link is either more likely to be affected from disruptions occurring at its incoming or outgoing arcs, or at itself. This could be related to the probabilities of disruptions, or the consequences faced due to these disruptions being high, and in some cases, both.

The remainder of the paper is organized as follows. In Section 2, we provide a review of the literature related to supply chain resilience, and summarize the idea of supply chain resilience. Then we build a mixed integer programming model that captures the definition of supply chain resilience in Sections 3 and 4. Section 5 describes the verification of the mathematical model via simulation. Finally, conclusion is given in Section 6.

2 LITERATURE REVIEW

We propose a mathematical formulation for building a supply chain, which is not common in the literature. The only formulation we came across is by Ratick et al. [6], who presents a formulation that allows them to decide the location of backup facilities or utilization of the existing ones for backup purposes in case of a disruption, while minimizing total cost. The formulation is similar to the set covering problem.

In this paper, we attempt to use our mathematical formulation to develop a quantitative framework for assessing supply chain resilience. Despite the increasing number of publications on supply chain resilience, only few studies have attempted to create a quantitative framework (Falasca et al., Ratick et al., Datta et al., Carvalho, Colicchia et al. [5-9]). Datta et al. [7] attempt to analytically assess supply chain resilience. The authors evaluated the impact of different strategies when considering the dynamics of demand, production and distribution functions. They considered the Customer Service Level (CSL), average inventory level and production change-over time to assess the operational resilience. They found that the flexibility of the production and distribution procedure is a key factor in coping with demand changes. However, their model does not consider any other factors (such as cost) that would enable trade-off analysis. Flexibility of the production and distribution allows a supply chain to be more resilient as it can cope with the changes due to disruptions more easily.

One of the few studies, aiming to develop a similar tool as us is by Pettit et al. [14]. They developed SCRAM™, which is based on a qualitative methodology, involving surveys with focus groups and for determining the link between disruptions, controllable factors and ways of improving resilience, and it gives a quantitative assessment of the supply chain under consideration as a whole.

We built our ideas on Falasca et al. [5], who developed a simulation based framework for helping managers to redesign supply chains to be resilient against environmental uncertainties. Despite being only a theoretical framework, the authors addressed the necessity of minimizing the immediate impact caused by a disruption and the time to recover, by utilizing resiliency triangle (Tierney et al. [10]). When designing supply chains, the authors argue that node criticality, complexity and density should be taken into account.

Focusing on supply uncertainties, Colicchia et al. [9] use the length and variation of the supply lead-time as indicators of supply chain resilience, which is different than what we do in this paper. They argued that a better understanding of the risk sources for specific supply chain settings can enable the design of a more resilient supply chain. Also based on the concept of the 'resilient triangle' (Tierney et al. [10]) and using exploratory case studies and empirical data, Carvalho [8] developed a model to create a composite performance measure: the *resilience index*. By applying structured interviews and calculating the resilience index, the authors could compare the performance of different companies in terms of resiliency. However, many of the metrics used depend on the qualitative perception and personal judgment of managers and are subject to possible bias. Moreover, this measure is suitable for analyzing the current state of the business processes, but not applicable to investigating what-if scenarios.

There are some studies that focus on the risk aspect, not necessarily towards evaluating resiliency or designing resilient supply chains. Lodree et al. [11] evaluated the impact of demand uncertainty and the occurrence of an extreme event (such as a disaster) on inventory levels and CSL by finding stock-out probabilities. They compared the inventory levels in the classic newsvendor solution with the levels needed in case of uncertain situations. Tomlin [12] determined economical choices of mitigation and contingency strategies in order to overcome unreliable supply. His model considered the supplier’s percentage uptime and the length of disruption which indicate the level of risk that supply chains are exposed to. Overall, some of these models are designed to evaluate the resilience of individual companies and not the supply chain as a whole, or the whole supply chain, but not its components.

Disaster resistance is more about pre-disaster mitigation. However, the concept of resilience also includes the stages both during and after a disaster. Therefore, supply chain resilience is the ability of a supply chain system to reduce likelihood and consequences of disasters. Therefore, a tool that incorporates the idea of resilience triangle should be used as it considers both time to return to and deviations from normal state. Based on this idea, resilience is not only about minimizing the risks of interruptions, but also getting back to normal state as fast as possible. Even though reducing risk leads to more resilient supply chain, mitigating one type of disruption may cause the likelihood or consequences of another disruption to increase, as there are always trade-offs between efficiency and resiliency.

3 SUPPLY CHAIN RESILIENCE

The definition for resilience in supply chain management is yet to be agreed upon. However, the literature agrees that the key aspects include readiness, responsiveness and recovery to a disaster. Hence, a node is more resilient than the others if:

- Probabilities of disruptions are low, i.e. Readiness
- Consequences of those disruptions are low, i.e. Response
- Time to recover to normal state is small, i.e. Recovery

Based on the existing qualitative methods and Falasca et al. [5], the node criticality is an important characteristic related to the specific components of supply chain. Given a supply chain network, a node can be considered more critical than others if:

- Relative importance of a given node k, I_k, is high (critical components or large amounts)
- Number of non-redundant inbound flows, $N_{inbound}$, is high
- Number of non-redundant outbound flows, $N_{outbound}$, is high

Our study considers many disturbance factors such as disasters, terrorist attacks, regulations, strikes, traffic and accidents. Each disruption has a consequence with a monetary value due to decrease in throughput (operation level, production, etc.) as well as expenses faced to return to normal state. The idea comes from the resiliency triangle suggested by Tierney et al. [10]. They call this loss of functionality from disruption followed by a gradual recover. According to them, this triangle should be minimized.

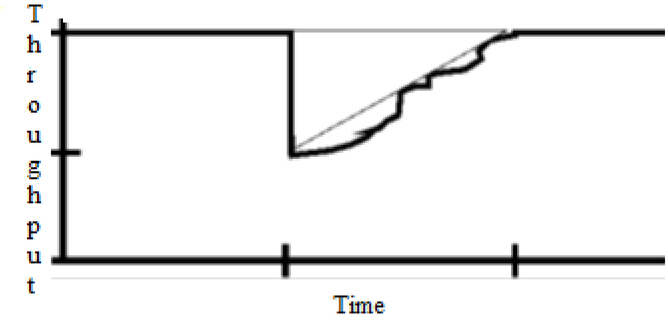

Figure 1: Resiliency triangle, Tierney et al. [10]

In order to achieve a resilient supply chain, the associated components must be evaluated both in terms of their resilience and importance. Based on the concepts mentioned above, we propose the followings to be considered in quantifying resiliency and importance of a node:

- The probability of disturbance at a node, P_{id}, and associated consequences, K_{id}, faced.
- **Lemma 3.1:** The more inbound arcs the node has, it is less likely for its supply to be interrupted. Therefore, expected consequence of a disturbance due to supplier interruption is lower.

  Proof 3.1: Let node *n* be under consideration. With one incoming arc from node 1, the expected consequence from disturbance *d* is $P_{1nd} * K_{1nd}$. Now, assume there is also another incoming arc from node 2. Based on our definitions, expected consequence now is $P_{1nd} * P_{2nd} * \frac{(K_{1nd}+K_{2nd})}{2}$. Assume $K_{1nd} \geq K_{2nd}$, then, based on equation (2), $\bar{K}_{nd} \leq K_{1nd}$. Then, the highest value joint expected consequence can achieve is $P_{1nd} * P_{2nd} * K_{1nd}$. In order to compare the values for node *n* with single incoming arc, and two incoming arcs, we need to compare $P_{1nd} * K_{1nd}$ with $P_{1nd} * P_{2nd} * K_{1nd}$. Since, $0 \leq P_{ind} \leq 1, \forall i \in N$, the expected consequence when there is one incoming arc is higher. By induction and by always taking the highest consequence value for joint consequence as an upper bound, same result can be shown for more than two incoming arcs.
- The more inbound flow the node has, more critical it is, and greater consequences will be faced in case of a disturbance.
- When the outbound flow from the node is greater, it becomes more critical for supplying the rest of the supply chain. Therefore if there is a disturbance at the node, more severe consequences will be faced.

These concepts are going to be the key in designing a supply chain with as resilient nodes as possible. These ideas will be incorporated into the objective function of the mixed integer programming (MIP) model we propose in the following section.

4 MATHEMATICAL FORMULATION

In this paper, we wish to handle transportation of a single product via a supply chain network (SCN), whose weakest link in terms of resiliency is as small as possible. Designing the supply chain for a single product is not a necessity, and the problem can easily be extended to have multiple products flowing. Every candidate node, $i \in N$, is either a supply node, demand node or an intermediate node, based on whether $b_i > 0$, $b_i < 0$, or $b_i = 0$ respectively. The decision to be made is to optimally select which supply nodes should be included in the SCN, and which arcs between nodes will be utilized with the objective to create a SCN as resilient as possible. Assuming that an arc $(i,j) \in A$ has a capacity of H_{ij}, the decision variables for the problem include:

- $f_{ij} = \text{amount of flow between node } i \text{ and } j,\ (i,j) \in A$
- $x_{ij} = \begin{cases} 1, \text{if the link between node } i \text{ and } j \text{ is used} \\ 0, \text{otherwise} \end{cases},\ (i,j) \in A$
- $y_i = \begin{cases} 1, \text{if supply node } i \text{ is used} \\ 0, \text{otherwise} \end{cases},\ i \in N$

$$z_{sgi} = \begin{cases} 1, \text{if } g\text{th element from a possible set of } s \text{ many arcs are chosen incoming to node } i \\ 0, \text{otherwise} \end{cases}$$

We illustrate the binary variable z_{sgi} for a simple case with four nodes as shown in Figure 2. Table 1 is possible combination of incoming arcs and shows the value s and g indices take.

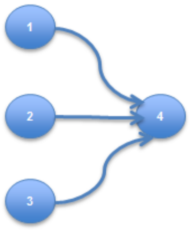

Figure 2: A network with four nodes and three arcs

Table 1: Possible combination of incoming arcs to node 4

***s*=1, i.e. 1 incoming arc**	***g***
x_{14}	1
x_{24}	2
x_{34}	3
***s*=2, i.e. 2 incoming arcs**	***g***
x_{14}, x_{24}	1
x_{14}, x_{34}	2
x_{24}, x_{34}	3
***s*=3, i.e. 3 incoming arcs**	***g***
x_{14}, x_{24}, x_{34}	1

At every node *i*, operations may be disrupted due to a disturbance, *d*, with probability, P_{id}, as well as every transportation on arcs between two nodes *i* and *j* with probability, P_{ijd}. These disturbances are assumed to be independent of each other. So, even if disturbance *d* were to occur on a certain arc or node, the remaining arcs or nodes may not be affected. When a disturbance occurs, there will be a consequence, K_{id} , associated with an interruption at node $i \in N$ or K_{ijd} associated with arc $(i,j) \in A$. Both of these fixed costs (K_{id} and K_{ijd}) are charged only once when a disturbance occurs. In addition, when arc *(i,j)* is interrupted, shipment via the arc will be stalled or partially compromised, which results in a variable cost of C_{ijd} depending on the severity of the interrupted shipment. There is budget limitation on the SCN: B_i is the cost of using a supply node, C_{ij}, is the cost per unit flow between nodes *i* and *j*, and the shipping budget must not exceed *C*. It also must be noted that a total disruption of a node with multiple incoming arcs would only occur if all incoming arcs were interrupted. When such an event occurs, the associated consequence can be calculated as the average of individual K_{ijd} values. Therefore, we define the following two parameters that will be used as input to the optimization model in Section 4:

Definition Expected Supply Disruption Cost (δ_{id})

An expected supply disruption cost is the expected losses to be paid due to disruption *d*, when all of the incoming arcs to node *i* are interrupted.

$$\delta_{id} = \bar{K}_{id} * \prod_j \left(P_{ijd}\right)_{(x_{ji}>0)}, \forall i \in N \qquad \textbf{(1)}$$

Definition Average Disruption Cost ($\bar{K}_{id}$)

An average disruption cost is the value of the consequence to be faced, when all incoming arcs are interrupted. More specifically, $\bar{K}_{id}$ is the average of the individual consequences faced due to disruption *d* for each incoming arc to node *i*.

$$\bar{K}_{id} = \frac{\sum_{j:x_{ji}>0} K_{jid}}{\#\ of\ j|x_{ji}>0}, \forall i \in N \qquad \textbf{(2)}$$

Based on the discussions in Section 3, we propose the following objective function for the MIP model:

- The objective is to find the node with the highest expected consequences, and make it as small as possible.

$$min \max_i \{\sum_d P_{id} * K_{id} * y_i + \sum_d \sum_s \sum_{g \in S} \delta_{id} * z_{sgi} + \sum_d \sum_j P_{jid} * K_{jid} * f_{ji} + \sum_d \sum_j P_{ijd} * C_{ijd} * f_{ij}\} \qquad \textbf{(3)}$$

The four components of this objective function are based on the quantification of node resiliency and importance. The first term is the total expected consequences due to an interruption at node *i*. The second term awards nodes with more incoming arcs, and the overall expected consequence faced is calculated as explained in the previous paragraph. Third and fourth terms are the total expected consequences faced due to interruption at incoming and outgoing arcs, respectively. The constraints are:

- Demand and supply must be satisfied at every node.

$$\sum_{(j:(i,j)\in A)} f_{ij} - \sum_{(j:(j,i)\in A)} f_{ji} = b_i, \ \forall i \in N \qquad \textbf{(4)}$$

- The flow cannot be greater than the arc capacity.

$$f_{ij} \leq H_{ij} x_{ij}, \forall (i,j) \in Arcs \tag{5}$$

- Incoming and outgoing arcs cannot be used unless a node is chosen.

$$\sum_j x_{ij} \leq M * y_i, \forall i \in N \tag{6}$$

$$\sum_i x_{ij} \leq M * y_j, \forall j \in N \tag{7}$$

- Budget limitation.

$$\sum_{(i,j)\in A} C_{ij} f_{ij} + \sum_i B_i y_i \leq C \tag{8}$$

- Set of incoming arcs chosen.

$$x_{ij} \geq \sum_s \sum_g z_{sgj} \quad , \forall (i,j) \in A \tag{9}$$

- To assure that for every demand node i, only one set of arcs are chosen.

$$\sum_s \sum_g z_{sgi} = 1, \forall i \in N_{Demand} \tag{10}$$

The solution of the proposed MIP will give us which supply nodes and arcs will be used in the SCN being built.

5 RESULTS

The MIP formulation was solved using GAMS software package [15]. Once the solution was obtained, i.e. the nodes and arcs chosen and the amount of flow on each arc, the proposed SCN was generated using Arena simulation software [16]. The difference between the two environments is that, the probability of an arc or a node being interrupted was displayed more realistically in Arena, while MIP formulation does not incorporate any interruptions, except in the objective function, thus giving the solver an idea as to what nodes or arcs to avoid. In Arena, it was assumed that every node and arc had varying downtimes and an arc or a node could go down only once during a run. These downtimes caused all of the demand to be not satisfied, but just partially. Arena helped us show that the simplifications used for modelling disruptions in MIP formulation yielded a valid model by evaluating the percentage of the demand satisfied under realistic conditions obtained via simulation. We showed that the proposed SCN using our MIP formulation creates a resilient network and most of the demand is satisfied, even with interruptions to nodes and arcs, thus justifying our MIP formulation. The simulation tool can also be used by the decision makers to explore different supply chain configurations, do what-if analysis and evaluate trade-offs as it should be noted that resilience comes with a price.

Two different sensitivity analyses were performed, one based on change in available budget, C, and the other one with respect to number of nodes, |N|. The solution in GAMS was interrupted after 2 hours. Simulation runs are over after 100 replications, with negligibly small processing time at nodes and transportation time on arcs, for 30 days simulation time.

As can be seen from the results, displayed on Figure 3 as the budget increases, with fixed number of nodes, the percentage of demand satisfied increases. This makes sense because with more budget, but same amount of demand to satisfy, the MIP formulation is inclined to choose more resilient nodes, resulting in fewer interruptions in the supply chain, thus more percentage of the demand is satisfied. However, it is not possible to reach 100% as there are interruptions in the SCN but not in MIP formulation.

On the other hand, Figure 4 shows that with a fixed budget, but increasing number of nodes, i.e. increasing supply and demand, the MIP formulation choses nodes with less resilience, most probably because it is cheaper to operate them, or the consequences associated are not as high. However, due to the drop in the resiliency of the supply chain, percentage of the demand satisfied goes down as well. The asymptotic behaviour verifies that the MIP formulation is able to represent the realistic scenario up to a certain extent.

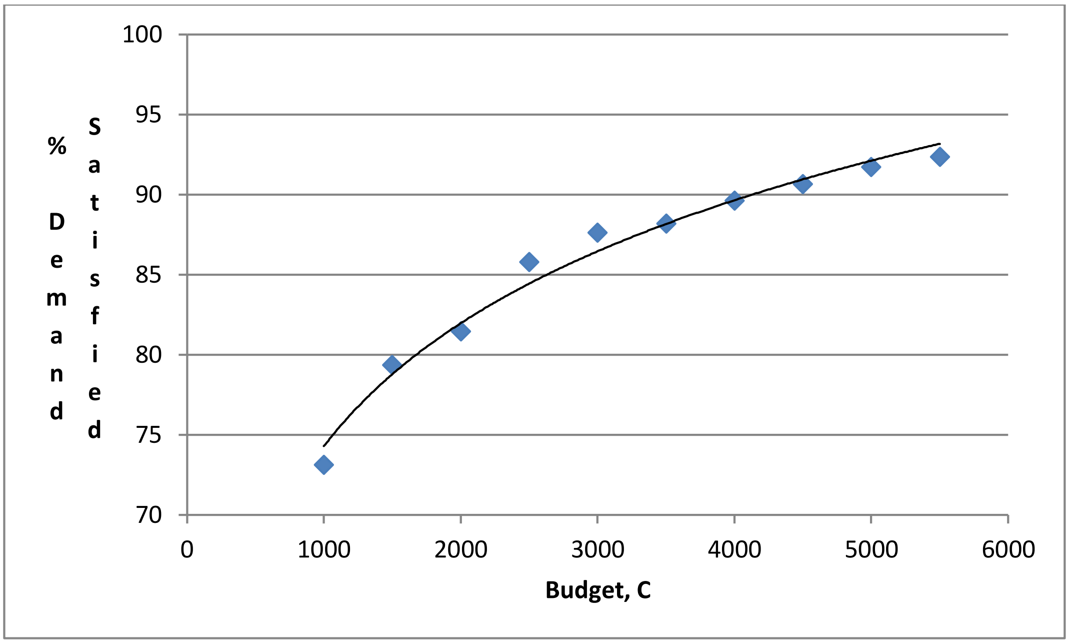

Figure 3: % of Demand Satisfied versus Budget, C, graph

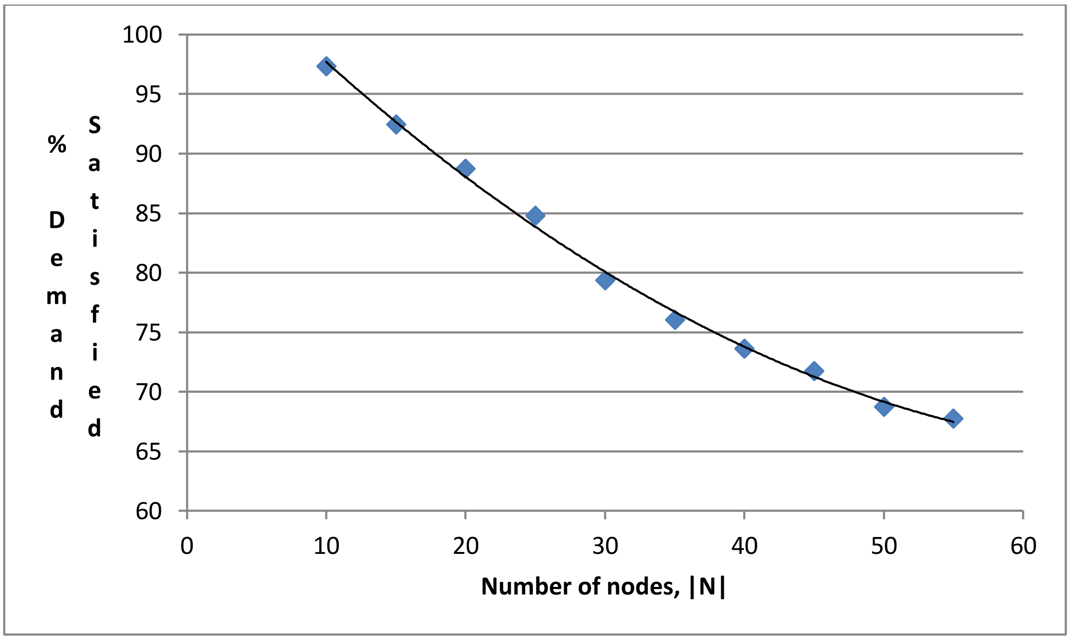

Figure 4: % of Demand Satisfied versus number of nodes, |N|, graph

6 CONCLUSION

This study tackled the problem of quantifying supply chain resilience using mixed integer programming. The ideas on supply chain resilience and node importance were brought together by means of the objective function we propose. Even though the MIP formulation has non-polynomial many decision variables, in application, we do not need to consider all possible combination of incoming arcs to a node, as even the busiest hubs in terms of a particular supply chain, have only limited number of incoming flow different origins.

The formulation proposed tackles two key issues related to quantification of supply chain resilience. First of all, in the existing quantitative literature, if any, the resilience is evaluated for a company or an industry as a whole, but not in terms of components of the supply chain. We provide a decision support tool in making investments to the supply chain to improve the resilience of nodes individually, thus making the whole supply chain more resilient. Also, previous quantitative attempts are heavily based on judgment of individuals, whereas this study uses empirical data that can be collected from companies via studies.

The results by Arena show that the SCN proposed by MIP formulation, creates a resilient supply chain, which is able to satisfy most of the demand when there are interruptions in the flow, and Arena verifies it. NCI value we propose considers both node resiliency and node importance, and gives meaningful insights to decision makers for managing the supply chain network. NCI shows how viable a node is compared to another based on its preparedness, response and recovery, as well as its importance for maintenance of the existing supply chain operations. NCI will not only help in evaluating different options in creating a network, but will also help in comparing the nodes within a supply chain. With this setup, it is possible to do quantitative evaluations on the resiliency of a supply chain for a company or set of companies as it has been done in previous studies, but it will also be possible to evaluate the performance of buildings blocks of a supply chain.

The results by Arena show that the SCN proposed by MIP formulation, creates a resilient supply chain, which is able to satisfy most of the demand when there are interruptions in the flow. As a future work, we are working on solving MIP formulation via heuristics. Our next goal is to obtain a meaningful resiliency and criticality index for nodes, and the supply chain, to provide a decision-making tool in terms of both designing the supply chain, as well as making improvements to its current operations. Also, extending the MIP formulation to incorporate changes over time would yield a better decision support tool. Another challenge is the representation of MIP formulation in a simulation environment, as the current MIP formulation does not incorporate time and interruptions are only represented as expected consequences that could be faced.

Acknowledgments

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