An Interdependent Layered Network Model for a Resilient Supply Chain

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***Abstract*—This paper addresses the design of a resilient supply chain by proposing efficient restoration strategies to help the supply chain quickly recover from a disruption and limit the effect on their customers. This paper on supply chain management is unique in that it considers infrastructures and their influences on the supply chain. The supply chain network is modeled not in isolation, but is dependent on infrastructures, and these dependencies are explicitly represented. We propose a framework for generating efficient restoration strategies that involve not only redesigning the network and decision making regarding production, inventory, and distribution, but also cooperation between the supply chain and infrastructure system to mitigate the impact of a disruption.**

***Index Terms*—Supply Chain Management, Interdependent Layered Networks, Resilience, Network Flows, Mixed Integer Programming.**

I. INTRODUCTION

THIS paper addresses the design of a resilient supply chain by proposing efficient restoration strategies to cope with supply chain disruptions. A supply chain comprises different entities that are connected by the physical flow of materials or products. Disruptions could occur at any section of the network, in any of the processes, for a wide variety of reasons such as transportation delays, power outages, or natural or man-made disasters. A resilient supply chain is a system that has the ability to recover quickly from disruptions and ensure customers are minimally affected.

Craighead and colleagues [1] studied the severity of the disruption and related it to three supply chain design characteristics: density, complexity, and node criticality; and to the two supply chain mitigation capabilities: recovery and warning. They pointed out that, as recovery capacity increases within a supply chain, the quicker the supply chain returns to the normal level and the less severe the disruption will likely be. They conclude that "*an unplanned event that disrupts a supply chain with the capability to respond quickly and effectively is less likely to be severe than the same supply chain disruption affecting a supply chain with little or no capability to recover*". It can be illustrated by the respective responses of Nokia and Ericsson to the loss of a supply of radio-frequency chips (RFC) in early 2000 [2],[3]. Although facing the same situation, two companies responded differently and thus ended up with two endings: one survived from the disruption while the other ultimately exited from the business.

We approach the question of efficient restoration strategies raised by a resilient supply chain from the perspective of infrastructure systems and their logical relationship with the supply chain. Since the functioning of society heavily depends on energy, transportation, telecommunication, financial, and other infrastructures, infrastructure systems play an important role in operations of a supply chain. Ignoring these fundamental systems will make the study of supply chain management unrealistic and impractical, especially for supply chain restoration. In the example of 3J's Trucking Company (3J's) [4], we can see that in order to restore its destroyed distribution system, its logistical scheduling system had to work effectively. However, the disruption to the telecommunication service caused 3J's to be unaware of road information and thus unable to devise alternate routes. Telecommunication restoration is critical to 3J's. It would bring back timely and accurate transportation information, which leads to efficient logistical schedules. Ignoring telecommunication restoration, as well as its influence, would eventually make the company pay more money and time for its distribution system. In the example of the Northeast Blackout of 2003 [5], the loss of the power supply caused the loss of production capacity of the factories in the affected area. Those factories couldn't restore their production until the power grid was stabilized. They were dependent on restoration of the power grid. If this dependency was taken into account—in other words, power restoration information was considered by supply chain managers during their restoration planning—they would make better decisions on supply, inventory, and distribution. For example, they could arrange the supply on an accurate basis, arriving just as the area comes back online to avoid paying too much for storing materials before machines are able to run, or lacking supply in the first few days of restoration.

Consideration of infrastructure systems in supply chain restoration will raise the following questions: How can we represent relationships between infrastructure systems and the supply chain? How can supply chain managers utilize information from infrastructure managers to make efficient restoration plans? And how can their plans benefit infrastructure managers? Our approach in addressing those questions seeks to achieve two goals: 1) develop a mathematical representation of logical dependencies between the supply chain and infrastructure systems, and 2) provide the best

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restoration strategy that helps the cooperation of supply chain managers and infrastructure managers to mitigate the impact of a disruption.

II. Literature Review

Supply chain restoration involves determining the supply chain configuration and distribution of resources over the resulting supply chain network. Basically, it is a two-stage network design problem [6]. First, managers decide on locations where facilities will be established and on the capacity to be assigned to each facility. Second, they assign current demand to the available facility and identify lanes along which products will be transported. How do they design a supply chain network to make maximum profits? Different companies gave their own answers. Warner-Lambert Company (now Pfizer, Inc.) [7] modeled its distribution system as a two-echelon network which included its two large distribution centers, over 35 third-party pool distribution locations, and its customers' receiving locations. Its optimization models supported decisions in areas of distribution and supply chain. Kellogg Company [8] developed an operational planning system to help determine where products are produced and how finished products and in-process products are shipped between plants and distribution centers, which reduced production, inventory, and distribution costs by an estimated $4.5 million in 1995. Procter & Gamble (P&G) [9] conducted a study of product supply to reexamine and reengineer P&G's product sourcing and distribution system for its North American operations. As a result of this study, P&G saved over $200 million in pretax costs per year. There are many companies using optimization techniques to optimize their supply chain, such as Deere's Commercial and Consumer Equipment (C&CE) Division's inventory management system [10], Hewlett-Packard's supply chain [11], and so on.

Recent literature points out the need for the design of a resilient supply chain [3],[2],[12]. The research on supply chains dealing with disruptions can be divided into two trends. Some researchers viewed disruptions as one type of supply chain risk and discussed them from the perspective of risk management. Harland and colleagues [13] provided a review of risk in supply network and discussed a theoretical tool that helps in the assessment and management of the risk. Sinha and colleagues [14] presented a generic prescriptive methodology for mitigating disruption risk in an aerospace supply chain based on the methodologies from risk management and supply chain management. Chopra and Sodhi [15] classified supply chain risks into different categories, identified drivers of these different risk categories, and discussed risk mitigation strategies. They defined disruptions as disruptions to material flows anywhere in the supply chain and classified them into one risk category. Kleindorfer and Saad [16] developed a conceptual framework for risk assessment and risk mitigation. They identified three categories of supply chain strategies available to address disruption risk based on application areas. Restoration strategies proposed in this paper belong to the third category, the operational control of the supply chain, including emergency (or crisis) response.

Some researchers discussed disruption issues from the perspective of supply chain uncertainty. In Moinzadeh and Aggarwal [17] disruptions refer to process unreliability, the effect of unreliability on production systems, including machine failure, labor strikes, and other breakdowns in production. The authors modeled those process disruptions as randomly distributed events and the production inventory system as a stochastic process. Tomlin [18] developed a supply chain model to investigate mitigation and contingency strategies based on a single-product setting with two supplier options: one is unreliable and another is reliable but more expensive. The author focused on supply-side tactics for managing disruption risks caused by supply uncertainty. Some papers discussed increasing flexibility to cope with those disruptions. Beach and colleagues [19] reviewed the theory and methodology of manufacturing flexibility and examined issues related to it, specifically, its relationship with environmental uncertainty. They developed a conceptual framework of manufacturing flexibility. Jordan and Graves [20] analytically compared different scenarios based on a planning model for assigning production to plants and developed several principles of manufacturing flexibility. Snyder and colleagues [21] gave an overview of designing supply chain networks against uncertainty of supply or demand and facility failures. The risk of uncertainty of disruptions is measured by two methods: expected cost and worst-case cost. The models identified optimal strategies for allocating limited resources among possible investments. Snyder and colleagues [22] surveyed recent developments in supply chain disruption research.

This paper addresses the design of a resilient supply chain by proposing efficient restoration strategies to help the supply chain quickly recover from a disruption and limit the effect on their customers. We argue that supply chain restoration is a function of the infrastructure systems that support the supply chain. Therefore, civil infrastructures must be taken into account. In addition, restoration needs to consider all phases of the supply chain operation, including production, inventory, transportation, and distribution. This research on supply chain management is unique in that it considers infrastructures and their influences on the supply chain. The supply chain network is modeled not in isolation, but is dependent on infrastructures, and these dependencies are explicitly represented. We propose a framework for generating efficient restoration strategies, which involve not only redesigning the network and decision making on production, inventory, and distribution, but also cooperation between the supply chain and infrastructure system to mitigate the impact of a disruption.

III. Interdependent Layered Network Model

Generally, the graphical representation of a supply chain consists of a single-layer network. Nodes could be production facilities, warehouses, or demand zones. Arcs in the network represent connectivity between different nodes. Flows on the individual arcs represent the movement of materials or products between nodes connected by arcs. One limitation of the single-layer network structure is the inability to represent relationships between supply chains and other support infrastructure networks that influence supply chain operations, such as power, communication, and transportation. To model these dependencies, a different structure, Interdependent Layered Networks (ILN), is employed in this paper. The concept of ILN was proposed by Lee and colleagues and was implemented into the restoration of interdependent infrastructure systems [23],[24].

ILN is composed of multiple networks, with each network identified as a layer. There exist logical relationships that connect layers. ILN is designed to capture and highlight such logical relationships. Based on the framework of ILN, the supply chain and its support infrastructure networks are modeled as individual network layers, and their interdependent relationships are explicitly taken into account. The subsequent subsections discuss the characteristics of each layer and their interdependencies.

A. Supply chain network layer

The supply chain is modeled as a graph G^{sc}, where $G^{sc} = G(V^{sc}, E^{sc})$. The set of nodes V^{sc} include plants, V_P^{sc}, warehouses, V_W^{sc}, and customer demand zones, V_D^{sc}. Arcs in E^{sc} denote connectivities between different locations. The manufactured products could be stored either at the plant or a warehouse, or directly sent to the demand zones to satisfy customer requirements. Basically, the supply chain model is an arc-based, multi-commodity, flow network layer. It is assumed that shipping lead times are much longer than the manufacturing lead time, so the time gap between releasing a production order and its availability at a demand zone is dominated by the shipping lead times.

Let T denote the number of periods in the planning horizon and $d_{j,k,t}$ denote the demand for product k in demand zone j during a particular time period t. Let $pro_{i,k,t}/inv_{i,k,t}$ denote the production/inventory at node i for commodity k during time period t and $x_{(j,l)k,t}$ denote movement of product k on arc (j,l) during time period t. The following are the constraints associated with the operations of the supply chain network layer:

For each product produced at a plant, the sum of production during a period and the beginning inventory must equal the sum of the inventory at the end of this period and the total units shipped to warehouses and demand zones during this period:

$$pro_{p,k,t} + inv_{p,k,t-1} = \sum_{l \in V_W^{sc} \cup V_D^{sc}} x_{(p,l),k,t} + inv_{p,k,t}, \quad \forall p \in V_P^{sc}, \forall k \in K \ \texttt{and} \ t \in T \quad (1)$$

For each product at a warehouse, the sum of beginning inventory and the units received from the plants during a period must equal the sum of the inventory at the end of this period and the total units shipped out during this period:

$$\sum_{p \in V_P^{sc}} x_{(p,w),k,t-LT(p,w)} = \sum_{l \in V_D^{sc}} x_{(w,l),k,t} + inv_{w,k,t} - inv_{w,k,t-1}, \quad \forall w \in V_W^{sc}, k \in K \ \texttt{and} \ t \in T \quad (2)$$

At each customer zone, products available at a warehouse (or a plant) during a time period are used to meet that period's demand. If the demand cannot be met from available inventory, the unmet demand for product k at demand zone j at time t is modeled by a non-negative slack variable $s_{j,k,t}^{sc}$ that will be lost and result in a penalty in the objective function.

$$\sum_{w \in V_W^{sc}} x_{(w,l),k,t-tl(w,l)} + \sum_{p \in V_p^{sc}} x_{(p,l),k,t-tl(p,l)} + s_{l,k,t} = d_{l,k,t}, \forall l \in V_D^{sc}, \forall k \in K \ \texttt{and} \ t \in T \quad (3)$$

Flow capacity constraints:

$$\sum_{k \in K} x_{(j,l),k,t} \leq v_{(j,l)}, \quad \forall (j,l) \in E^{sc} \ \texttt{and} \ t \in T \quad (4)$$

Production capacity constraints:

$$\sum_{k \in \phi(p)} pro_{p,k,t} \leq w_p, \quad \forall p \in V_P^{sc} \ \texttt{and} \ t \in T \quad (5)$$

Inventory capacity or storage space constraints:

$$\sum_{k \in K} inv_{l,k,t} \leq q_l, \quad \forall l \in V_P^{sc} \cup V_W^{sc} \ \texttt{and} \ t \in T \quad (6)$$

The products shipped out from a plant must be produced at this plant:

$$\sum_{l \in V_W^{sc} \cup V_D^{sc}} x_{(p,l),k,t} = 0, \forall p \in V_P^{sc}, k \in K/\ \phi(p), \text{ and } t \in T \quad (7)$$

B. Power system network layer

The power system network layer is modeled as a graph G^{pr}, where $G^{pr} = G(V^{pr}, E^{pr})$. Power is produced at generating stations and then is raised to the needed high voltages and transmitted on the transmission lines. It is stepped down at substations to the voltage on the distribution lines, and eventually it is lowered by transformers to the level required by the users' equipment. A modern electric power system [23] consists of six main components: 1) the power station, 2) a set of transformers to raise the generated power to the high voltages used on the transmission lines, 3) transmission lines, 4) substations at which the power is stepped down to the voltage on the distribution lines, 5) the distribution lines, and 6) the transformers that lower the distribution voltage to the level used by the consumer's equipment. In this paper, the power system layer consists of power stations, transformers, substations, and transmission lines, not including low voltage distribution. Power stations are modeled as supply nodes, transformers as transshipment nodes, and substations as demand nodes in V^{pr}. Arcs in E^{pr} represent transmission lines connecting the different locations. Power is assumed to be delivered through transmission lines to substations and each substation serves an area.

The power system is a single commodity network. Equations (8)–(12) are single commodity flow conservation and capacity constraints. Equation (8) is the power node capacity constraint. Equation (9) is the power demand constraint with consideration of unmet demand, $s_{j,t}$. Binary variable $z_{j,t}^{pr}$ indicates if an unmet demand exists and will be used later in modeling interdependencies. Equation (10) sets an upper bound of unmet demand $s_{j,t}$. Equation (11) sets the flow balance for the transshipment nodes. Equation (12) ensures that a damaged transmission line cannot work until it is repaired. Binary parameter $y_{(i,j),t}$ indicates the decision on repairing a transmission line. The set of y reflects a restoration plan.

$$\sum_{(i,j)\in E^{pr}} x_{(i,j),t} \leq b_i \quad \forall i \in V^{pr} \text{ and } t \in T \tag{8}$$

$$\sum_{i\in V^{pr}} x_{(i,j),t} + s_{j,t} = d_j \quad \forall j \in V^{pr} \text{ and } t \in T \tag{9}$$

$$s_{j,t} \leq d_j * z^{pr}_{j,t}, \quad \forall j \in V^{pr}_D, t \in T \tag{10}$$

$$\sum_{(i,j)\in E^{pr}} x_{(i,j),t} - \sum_{(j,l)\in E^{pr}} x_{(j,l),t} = 0 \quad \forall j \in V^{pr} \text{ and } t \in T \tag{11}$$

$$x_{(i,j),t} \leq v_{(i,j)} * y_{(i,j),t}, \quad \forall (i,j) \in E^{pr} \text{ and } t \in T \tag{12}$$

C. Telecommunication system layer

The communication network layer is modeled as a graph G^{ph}, where $G^{ph} = G(V^{ph}, E^{ph})$. A typical communication system network consists of fiber spans [27]. A span is a fundamental physical component in the network connecting two terminals. A span may fail because of various causes, including cable cuts and natural disasters. Data traffic is routed on the network through a sequence of spans. In this paper, spans are modeled as arcs and terminals as nodes. The telecommunication system is modeled as a multi-commodity network. A phone call is specified by an origin node and a destination node. For each pair of terminals (nodes), referred to as an OD (Origin and Destination) pair, several routes (or paths) may exist to deliver telecommunication service. Those with the same OD pair are modeled as one commodity. Different commodities mean phone calls have different origins and/or different destinations.

Equations (13)–(16) are basic multi-commodity flow conservation and capacity constraints with consideration of unmet communication demand, $s_{jl,t}$. Equation (13) defines the unmet demand for each OD pair. Equation (14) sets the upper bound of the unmet demand. Equation (15) links path flows to arc flows. The flow on each arc is calculated by summing all flows along paths that contain this arc. Equation (16) is the node capacity constraint. Equation (17) ensures that a damaged span cannot work until it is repaired. Binary variable $z^{ph}_{j,t}$ indicates if there are unmet communication demands. Parameter $y_{(i,k),t}$ indicates the decision on repairing a span. The set of y reflects a restoration plan.

$$\sum_{n\in 1..N} f_{jl,n,t} + s_{jl,t} = m_{jl}, \quad \forall jl \in OD^{ph} \text{ and } t \in T \tag{13}$$

$$s_{jl,t} \leq m_{jl} * z^{ph}_{jl,t}, \quad \forall jl \in OD^{ph} \text{ and } t \in T \tag{14}$$

$$\sum_{(jl,n) contains (i,k)} f_{jl,n,t} = x_{(i,k),t}, \quad \forall (i,k) \in E^{ph} \text{ and } t \in T \tag{15}$$

$$\sum_{(i,j)\in E^{ph}} x_{(i,j),t} \leq b_j, \quad \forall j \in V^{ph} \text{ and } t \in T \tag{16}$$

$$x_{(i,j),t} \leq v_{(i,j)} * y_{(i,j),t}, \quad \forall (i,j) \in E^{ph} \text{ and } t \in T \tag{17}$$

D. Transportation system layer

The nodes in the supply chain network correspond to the nodes in the transportation network, and the arcs in the supply chain network represent transportation connectivity. An arc in the supply chain network denotes a path connecting two locations. In practice, this path could be the shortest path, the least-time path, or any other suitably defined path. Therefore, the transportation system can be viewed as part of the supply chain.

When a disruption event occurs, connectivity in the transportation network could be affected and thus decision makers have to consider alternative paths to move products. This necessitates an update of the supply chain network with new parameters, such as transshipment cost, capacity limit, and even the network structure if, for example, due to transportation disruption there is no way to move products between two locations. As a result, the arc between two corresponding nodes in the network will be eliminated. Decision makers will require flow distribution to be re-optimized through the updated network.

E. Modeling interdependencies

Dependencies are represented as follows: Let $D(sc, i)$ be the set of ordered pairs (p, l), where p is a node (or an arc) of the supply chain network that is dependent on a demand node (or demand pair) l of infrastructure i. For example, a plant is modeled as a node p of the supply chain network and its need for electricity supply is modeled as a demand node l of the power network. As another example, transportation from warehouse w to demand zone d is modeled as an arc e in the supply chain network and its need for telecommunication service between these two locations is modeled as an OD demand pair wd in the telecommunication network since the transportation network needs telecommunication services to communicate instructions. A disruption will drop capacities of affected nodes and arcs to zero. As a result, commodities, such as products, electrical power, and phone calls, will not be allowed to move across the networks, which will cause insufficient flow into demand nodes or demand pairs, and eventually unmet demands.

The slack variable, s, represents the unmet demand. The constraints for all demand nodes in infrastructure network i become:

$$s^i_{l,t} + \sum_{(m,l)\in E^i} x^i_{l,l,t} = b^i_l, \forall l \in V^i_D \text{ and } t \in T \tag{18}$$

Let the binary dependency variable z indicate whether or not demand is met. It takes a value of zero when demand is met, but otherwise, one. The slack variable s and the dependency variable z are related by the following constraint:

$$s^i_{l,t} \leq b^i_l * z^i_{l,t}, \forall l \in V^i_D \text{ and } t \in T \tag{19}$$

If the slack variable is positive then the corresponding dependency variable will be forced to one. By adding the dependency variable z to supply chain capacity constraints, the flow capacity v, the production capacity w, and the inventory capacity q become $v*(1-z), w*(1-z), q*(1-z)$, respectively. Occurrence of unmet demand, that is, $z = 1$, will drop the supply chain capacity to zero. In this way, the status of infrastructures influence supply chain operations. We detail this influence in constraints (20)–(23) below.

1) Dependency on power: Both plants and distribution centers need electricity to operate. If the power supply is disrupted, production capacity of a plant will drop to zero until power is restored. Likewise, throughput capacity of a warehouse will drop to zero without power supply. Then the company might adjust its production strategy and those plants with power supply may need to produce more products in order to cover the loss of plants caused by the power outage.

Power outage causes the unmet demand indicated by variable $z^{pr}_{l,t}, l \in V^{pr}_D$. It takes a value of zero if node l's demand is met during time t, but otherwise, one. Occurrence of unmet power demand will drop production capacity of the plant to zero. Such a dependency can be formulated as:

$$\sum_{k\in\phi(p)} pro_{p,k,t} \le w_p(1 - z^{pr}_{l,t}),$$
$$\forall (p,l) \in Dep(sc,pr) \;\; \texttt{and} \;\; t \in T \tag{20}$$

where $Dep(sc,pr)$ is the set of ordered pairs (p,l), p is the plant and l is the demand node of the power network serving plant p. If plant p loses power supply completely, that is, $z^{pr}_{l,t}$=1, the right-hand side of constraint (20) will equal zero, which drives the total production to zero.

For warehouses, their throughput capacities will drop to zero without power supply, too. Therefore, these warehouses w cannot receive (21) or ship (22) products:

$$\sum_{k}\sum_{j} x_{(j,w),k,t-tl(j,w)} \le q_w(1 - z^{pr}_{l,t}),$$
$$\forall (w,l) \in Dep(sc,pr) \;\; \texttt{and} \;\; t \in T \tag{21}$$

$$\sum_{k}\sum_{j} x_{(w,j),k,t} \le q_w(1 - z^{pr}_{l,t}),$$
$$\forall (w,l) \in Dep(sc,pr) \;\; \texttt{and} \;\; t \in T \tag{22}$$

The above discussion is for the case of the complete loss of power supply. More complicated dependencies can be modeled based on equations (20)–(22). For example, the power supply could be reduced to a certain amount instead of a complete loss, which doesn't destroy the capability of the plant, but does reduce its production capacity. Representing the reduced capacity by a function of the dependency variable z would be an option.

2) Dependency on telecommunication: Sometimes the transportation between plants and distribution centers is affected by telecommunications. Once the telecommunication service fails for any reason, products might not be transported because instructions for supply chain operations are conveyed by telecommunications and shippers will not transport products without instructions. The variable $z^{ph}_{jl,t}, jl \in OD^{ph}$ takes a value of one if communication between j and l is not operational during time t, otherwise it is equal to zero. The dependency of transportation capacity on communication is formulated as:

$$\sum_{k\in K} x^{sc}_{(j,l),k,t} \le v^{sc}_{(j,l)}(1 - z^{ph}_{jl,t}),$$
$$\forall ((j,l),jl) \in Dep(sc,ph) \;\; \texttt{and} \;\; \forall t \in T \tag{23}$$

where $Dep(sc,ph)$ is the set of ordered pairs $((j,l),jl)$, arc (j,l) is transportation from plant j to warehouse l, and jl is the demand pair in the telecommunication network that represents the telecommunication service between these two locations. If telecommunication between plant j and distribution center l fails, that is, $z^{ph}_{jl,t} = 1$, the right-hand side of constraint (23) will equal zero, which drives the total flows on the arc (j,l) in the supply chain to zero.

3) Dependency within infrastructures: Dependency between telecommunication and power should also be taken into account. Some telecommunication terminals need electric power supply to operate. Without power supply, telecommunication service can't be conveyed through these terminals. Just like the case of plants affected by power outage, power outage causes the unmet demand indicated by variable $z^{pr}_{l,t}, l \in V^{pr}_D$. It takes a value of zero if node l's demand is met during time t, but otherwise, one. Occurrence of unmet power demand will drop terminal capacity to zero. Such a dependency can be formulated as:

$$\sum_{(i,m)\in E^{ph}} x_{(i,m),t} \le b_m(1 - z^{pr}_{l,t}),$$
$$\forall (m,l) \in Dep(ph,pr) \;\; \texttt{and} \;\; t \in T \tag{24}$$

where $Dep(ph,pr)$ is the set of ordered pairs (j,k), k is the telecommunication terminal, and j is the demand node of the power network serving terminal k. If terminal k loses power supply completely, that is, $z^{pr}_{l,t}$=1, the right-hand side of constraint (24) will equal zero, which drives the total capacity to zero.

IV. Solution Approach

We investigate a potential scenario where a disaster disrupts the power supply, telecommunications, and the transportation network in a given area. Production facilities and warehouses in this area are affected by the disaster. To address the loss of production and distribution capabilities, managers of the supply chain have the following options: (i) adjust the production at the other plants to cover the loss, (ii) procure products from sources external to the supply chain (sub-contract or outsource), and (iii) re-examine distribution related to the affected zone. All these decisions will be influenced by the condition of infrastructure systems. Because of these influences, decisions on the infrastructure will have an impact on restoration of service for the supply chain. We explicitly study this dependency in this research.

Power and telecommunication infrastructure managers need to develop restoration plans after a disaster. They typically have contractual obligations to restore service in a timely manner, and they need to address the (possibly conflicting)

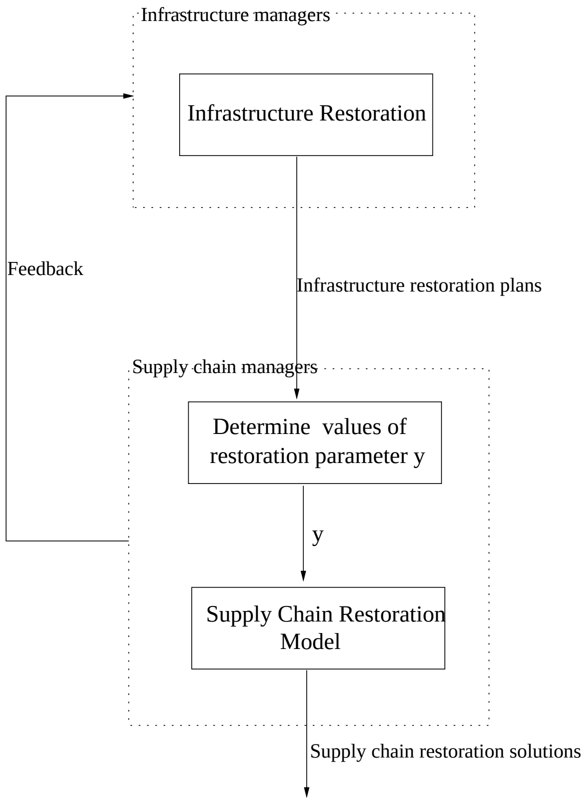

Fig. 1. Problem-solving process

demands of multiple stakeholders. The supply chain manager is one of these stakeholders. We have previously proposed that the infrastructure managers should develop an efficient frontier of solutions to their multi-objective optimization problem [26], and we envision a situation in which the supply chain manager can influence the final selection of a restoration plan from this efficient frontier.

The problem-solving process for the supply chain restoration problem is depicted in Figure 1. Infrastructure managers work out the infrastructure restoration plans and provide them to supply chain managers. Based on what infrastructure managers provide, the value of the restoration parameter y is determined and then enters the supply chain restoration model as input. The model is solved for the best restoration plan.

On the other side, supply chain managers give some feedback about infrastructure plans to infrastructure managers. For each infrastructure plan, there will be an optimal supply chain plan obtained by our proposed model. Infrastructure managers might have several plans that are equally good for restoration. Based on the above problem-solving process, supply chain managers, from their own points of view, can judge which plan is best, that is, the one which most benefits the supply chain. The feedback might help infrastructure managers to choose their best plan, perhaps with financial help from the supply chain manager. The whole problem-solving process turns out to be a closed loop. This closed loop is our proposal for an efficient cooperation between supply chain managers and infrastructure managers.

A. The supply chain manager's restoration problem

In a normal situation, decision makers seek a set of optimal strategies involving production, inventory, and distribution for a given time horizon T. The supply chain performance could be measured by the total cost, delivery time, quality, flexibility, or revenue. In general, the model seeks the minimum cost or the maximum net revenue with consideration of delivery time, quality, and flexibility. In this paper, the objective for restoration will be to minimize the total cost and unmet demands subject to the limited resources available for restoration as follows:

$$\texttt{minimize} \sum_{t\in T}\sum_{(j,l)\in E^{sc}}\sum_{k\in K} c\_flow_{(j,l)}x_{(j,l),k,t}$$

$$+\sum_{t\in T}\sum_{p\in V_P^{sc}}\sum_{k\in K} c\_pro_{p,k}pro_{p,k,t}+\sum_{t\in T}\sum_{l\in V_W^{sc}\cup V_P^{sc}}\sum_{k\in K} c\_inv_{l,k}inv_{l,k,t}$$

$$+\sum_{t\in T}\sum_{l\in V_D^{sc}}\sum_{k\in K} c\_sl_k^1 s_{l,k,t}+\sum_{t\in T}\sum_{l\in V_W^{sc}\cup V_P^{sc}}\sum_{k\in K} c\_sl_k^2 s\_inv_{l,k,t} \quad (25)$$

The first three items in the objective function are the total costs including transportation, production, and inventory cost, and the remaining two items comprise the total slacks including the unmet demand and unmet safety stock. Parameters c_sl^1 and c_sl^2 transfer the unit of the slack from the quantity of the product into dollars to make the two parts of the objective function comparable. The decision makers are able to trade off between the cost and the slack by using different weights. Constraints of the supply chain restoration model are those discussed in Section III, including each individual layer flow constraints and interdependency constraints. A complete supply chain restoration model is presented in Appendix B.

B. The infrastructure managers' restoration problem

The infrastructure managers have to construct a restoration plan that meets their contractual obligations, and represents a compromise between multiple objectives including restoring service quickly, minimizing the cost of restoration, and respecting the interests of various stakeholders. They have to develop a schedule for restoring various elements of the infrastructures. We give a summary of this problem in this section; for more details see our earlier papers [26],[24].

A Pareto optimal solution to this problem can be obtained by solving a two-stage network design model that restores disrupted elements of interdependent, multiple layered infrastructure networks [24], and a planning and scheduling model that implements restoring elements [26]. It enters the supply chain restoration model as inputs, specifically, the values of parameter y.

The infrastructure managers' problem is inherently a multi-objective one. This opens the possibility of cooperation between these managers and the supply chain manager, with the supply chain manager suggesting alternative Pareto optimal solutions that are more favorable for the supply chain.

V. Computational Results

In order to demonstrate our research on supply chain restoration, we designed a supply chain, based on the following rules, that includes plants, distribution centers, and demand zones all over the United States, as well as a rough national power grid (Figure 2) and a rough national telecommunication network (Figure 3).

- Location of plant: There are ten plants which together make 400 products, including bottled water, food, medicines, tents, and so on. Each plant produces approximately 100 products. Production strategies are designed in such a way that the same product can be made by at least two different plants. These two plants are located in different parts of the country to avoid the risk that both of them are affected by the same event.
- Location of distribution center: There are 12 distribution centers across the country and they are located where transportation is convenient.
- Location of demand zone: Demand zones are determined based on geographical location. Generally, they are located near urban areas. Each state has at least one demand zone. Each zone's demand is proportional to the population of the zone it serves.
- Potential connectivity of the network: Theoretically, a distribution center is able to supply all demand zones and a plant is able to supply all distribution centers and demand zones. Taking transportation into consideration, we assigned distribution centers to the nearest demand zones and assigned a plant to the nearest distribution centers and demand zones, as we show in Figure 5.
- Planning horizon: Restoration requires timely and accurate information and decision making. In this example, the planning horizon is set to ten days and the data such as demands and capacities are based upon one day.

A scenario of the major disruption in the eastern United States is developed as Figure 4. Communication towers in the Boston area are down and the part of the telecommunication network connecting Boston to other locations (New York City, Buffalo, and Hartford) fails, which causes the telecommunication service around the Boston area to be disrupted. Transportation to the distribution center, dc12, relies on communication between Boston and New York City and thus no products can be shipped to or from dc12. The power supply in the shadow area is disrupted, which causes a plant, p9, and a distribution center, dc12, to shut down because of the power shortage.

We assume all data associated with disruptions and restoration are available to decision makers (including emergency managers and supply chain managers), and are known with certainty.

A. Infrastructure Restoration

In order to restore the plant in area2, p9, and the distribution center in area3, dc12, infrastructures delivering services in these areas need to be restored first, particularly power restoration in area2 and area3, and communication restoration between Boston and New York City. They are shown in the shadowed areas in Figure 4 as well as dotted lines representing disrupted telecommunication spans from Boston to New York City, Buffalo, NY, and Hartford, CT. For the power system, the restoration option could be repairing destroyed transmission lines or installing temporary shunts to get power supply from Hartford. As three power demand nodes (161, 109, 121 in Figure 6) get sufficient supply, power services in area1, area2, and area3 will be restored, respectively. For the telecommunication system, the restoration mission is relatively straightforward, that is, the repair of three destroyed spans. We use methods mentioned in Section IV.B to obtain the Pareto-optimal restoration plans for infrastructures as follows:

- **Case 1 (money is the top priority)**: Repair highlighted transmission lines as in Figure 6 such that area1 is restored on the seventh day, area2 on the eighth day, and area3 on the twelfth day; repairing three disrupted spans from Boston such that communication to New York is restored on the third day, Buffalo on the fifth day, and Hartford on the sixth day.
- **Case 2 (time is the top priority)**: Repair highlighted transmission lines as in Figure 6 such that area2 and area3 are restored on the seventh day and area1 on the sixth day ; repairing three disrupted spans from Boston such that communication to New York is restored on the sixth day, Buffalo on the second day, and Hartford on the third day.
- **Case 3 (both time and money are equally prioritized)**: Repair highlighted transmission lines as in Figure 6 such that area1 is restored on the sixth day, area2 on the eighth day, and area3 on the forth day; repairing three disrupted spans from Boston such that communication to New York is restored on the fifth day, Buffalo on the second day, and Hartford on the sixth day.

For infrastructure managers, they have to trade off between time and money. As illustrated by above plans, an earlier restoration would cost a larger amount of money, while a tight budget would sacrifice the pace of restoration. Different sets of priorities give managers multiple options that will enter the supply chain restoration model as inputs.

B. Supply Chain Network Restoration

Figure 5 shows the movement of commodities in the supply chain in the normal situation. For clarity, the figure presents only one type of product although our model works for 400 types of products, and each flow in the figure represents a sum of flows over ten days (therefore, it's not a state of the supply chain on a certain day, but accumulated flows of the supply chain over ten days). There are two plants, p6 and p9, which produce this type of product. Plant p6 is responsible for the demand from the western region while plant p9 is for the eastern region. After the disruptions occurred, plant p9 and distribution center dc12 were shut down because of failures of power supply and telecommunication service. According to the power and telecommunication companies, it would take around ten days to restore services in this area. The problem is to arrange production, distribution, and inventory during the ten-day period to meet customers' demands. The company could adjust its production strategy. For example, plant p6, making similar products as plant p9, might increase its production at a certain cost to cover the loss of plant p9, or outsource work to another manufacturer.

The supply chain network optimization model gives a solution, that is, let plant p6 produce more products and outsource part of production to the manufacturer represented as plant p11. This "outsource" plant is treated the same as other plants except an additional cost with this plant occurs when outsourcing. In this solution, we didn't consider the infrastructures and so the supply chain was treated as an isolated network. As we discussed in previous sections, decisions on the supply chain restoration should be based on infrastructure restoration. Based on three different restoration plans for power and telecommunication services in the affected area, our proposed model gives three optimal supply chain restoration strategies as follows.

- **Case 1**: Plant p9 is restored on the eighth day. For the first seven days, the company outsources most of its products to plant p11. From the eighth day on, plant p9 restores its production and plant p6 adjusts its production correspondingly. Since distribution center dc12 is down during the ten-day period, demand zones surrounding dc12 are served by dc11. Therefore, dc12 is isolated from the network.
- **Case 2**: Both plant p9 and distribution center dc12 are restored on the seventh day. For the first six days, the company outsources most production to plant p11. From the seventh day, plant p9 restores its production and plant p6 adjusts its production. For the first six days, demand zones surrounding dc12 are served by dc11. From the seventh day, dc12 restores function and begins to serve those demand zones.
- **Case 3**: Plant p9 is restored on the eighth day while distribution center dc12 is restored on the sixth day. For the first seven days, the company outsources most production to plant p11. From the eighth day, plant p9 restores its production and plant p6 adjusts its production to a low level correspondingly. For the first four days, demand zones surrounding dc12 are served by dc11. From the fifth day, dc12 restores function and begins to serve those demand zones.

Table I presents the supply chain restoration in different scenarios. The first row is the solution of the supply chain operating in the normal situation. The second row is the solution using the existing method, that is, the isolation of the supply chain from its supporting infrastructures. The remaining rows are the solutions obtained by our proposed restoration model. From Table I we find that when the disruption occurs the extra money to restore the supply chain will be $4,219,751 (the difference of costs between the normal situation and disruption) by the existing method. Our proposed method will save us as much as $1,153,443 (the difference of costs between isolated restoration and case2), almost thirty percent of the restoration cost. The reduction can be explained by the fact that the more we know about the operational environment of the supply chain, the more accurate decisions we can make. This significant reduction in the restoration cost demonstrates that taking infrastructures into account is not trivial in supply chain restoration. We also find that the earlier the plant is restored, the less the supply chain pays. Case2 costs the least money compared to the other cases, because it restores the disrupted plant and stops higher outsource cost at the earliest time.

TABLE I
SUPPLY CHAIN RESTORATION SOLUTION COMPARISON

Scenario	**Supply Chain Cost ($)**	**Infrastructure Restoration Plan and Schedule**
Normal Situation	64,243,975	Supply chain is operating in the normal situation
Isolated Restoration	68,463,726	Restoration without consideration of infrastructure, i.e., everything is restored after the 10th day
Case1	68,018,470	Area1 is restored on the 7th day, area2 on the 8th day, area3 on the 12th day; Telecommunication service to New York City is restored on the 3rd day, Buffalo on the 5th day, and Hartford on the 6th day
Case2	67,310,283	Area2 and area3 are restored on the 7th day, area1 on the 6th day; Telecommunication service to New York City is restored on 6th day, Buffalo on the 2nd day, and Hartford on the 3rd day
Case3	67,774,830	Area1 is restored on the 6th day, area2 on the 8th day, area3 on the 4th day; Telecommunication service to New York City is restored on 5th day, Buffalo on the 2nd day, and Hartford on the 6th day.

When multiple restoration plans are generated, it might be difficult for infrastructure managers to tell which of them is best. By using our approach, supply chain managers are able to measure these plans in terms of supply chain restoration cost and then give suggestions from their points of view. Infrastructure managers would find this feedback helpful for decision making.

As pointed out in the previous section, the solving process we proposed is a closed loop, which works in two directions. Infrastructure managers provide their plans to supply chain managers. With infrastructure information and our restoration model, supply chain managers have the ability to obtain more accurate supply chain restoration plans and then make a good preparation for restoration. At the same time, supply chain managers give feedback to infrastructure managers in terms of benefits to supply chain restoration. As a result, it is possible for infrastructure managers to consider the influence of their plan on the supply chain as they make their restoration plan. The closed loop of the solving process and two-direction information flows between managers reflect our approach for the cooperation between the supply chain and infrastructure systems.

VI. Conclusions

We present a framework of supply chain restoration with consideration of infrastructure, study interdependencies between supply chain network and infrastructures, and apply them to supply chain restoration to improve the company's resilience to disasters. Our goal is an efficient restoration strategy by providing supply chain managers with the ability to work with infrastructure managers. However, this is only our first step to taking infrastructures into supply chain restoration. There exist the following limitations to our research and they are also directions of our future research:

1) Models discussed in this paper are deterministic and we assume that everything is known with certainty. Issues of uncertainty and non-anticipativity will be discussed in our future work.
2) We discuss infrastructure restoration and supply chain restoration as two individual problems. The optimal solution is only optimal to one of them. Our current approach doesn't address the issue of global optimality, that is, a solution that is optimal for both of them.

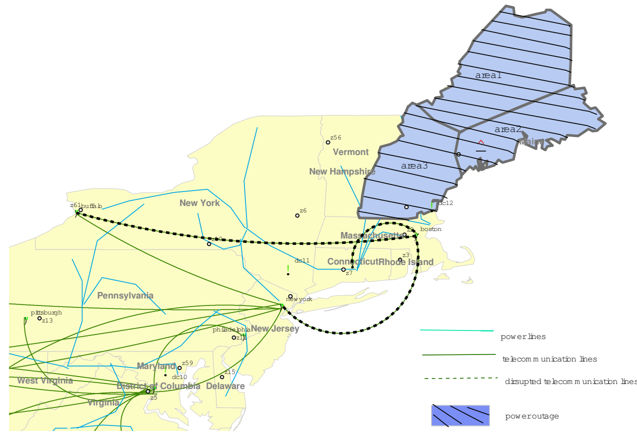

Fig. 4. Disruptions

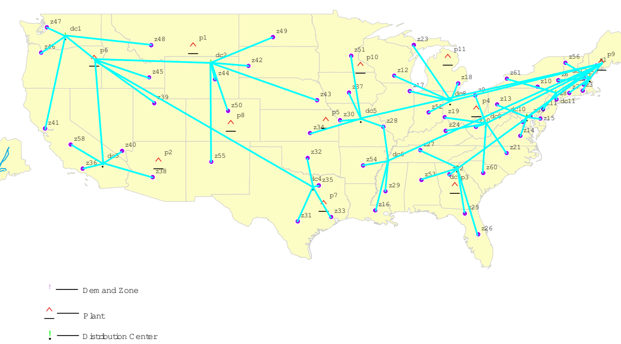

Fig. 5. Solution In the Normal Situation

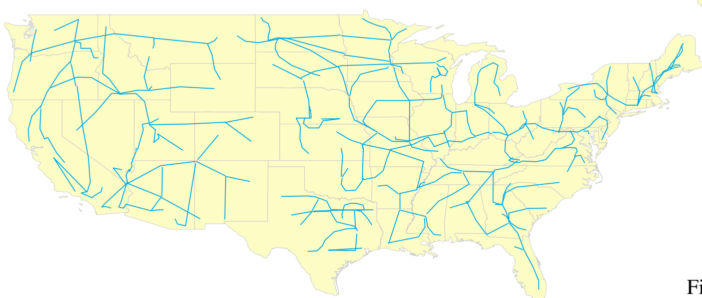

Fig. 2. An Approximation to National Power Grid

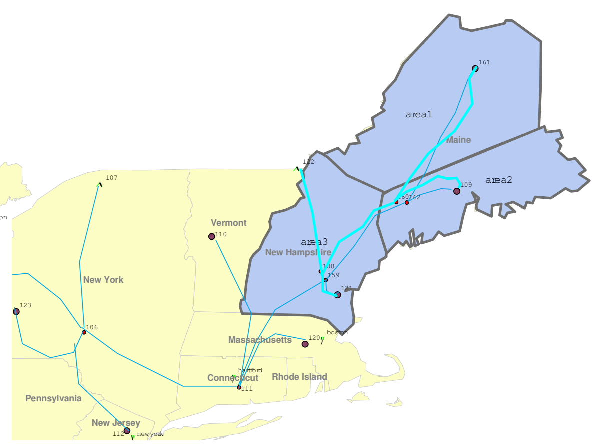

Fig. 6. Power Restoration Plan

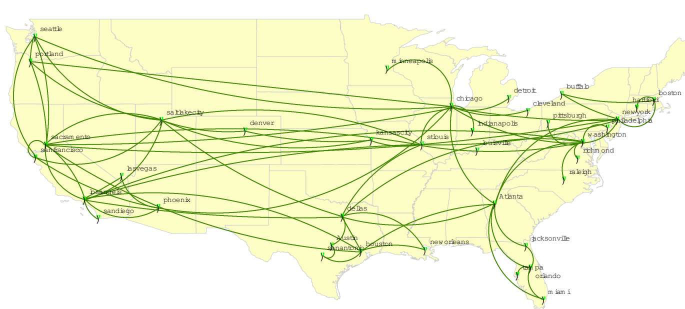

Fig. 3. An Approximation to National Telecommunication Network

Appendix A
Notations

Sets

I: the set of networks including power(pr), telecommunication(ph) and supply chain(sc).
V^i: the set of nodes in network i.
E^i: the set of arcs in network i.
$\phi(p), p \in V^{sc}$: the set of products produced at plant p.
$\delta(l), l \in V^{sc}$: the set of demand zones supplied by plant (or dc) l.
V^{pr}: the set of nodes in the power network.
E^{pr}: the set of arcs in the power network.
V^{ph}: the set of nodes in the communications network.
E^{ph}: the set of arcs in the communications network.
OD^{ph}: the set of Origin-Destination pairs in the communications network.

Parameters

$v_{(j,l)}, (j,l) \in E^i$: the capacity of arc (j,l).
T: the time horizon.
$d_{j,k,t}, j \in V^{sc}$: the amount of product k required by demand zone j at time t.
$w_p, p \in V^{sc}$: the production capacity at plant p.
$q_l, l \in V^{sc}$: the inventory capacity at location l.
$\alpha_{j,k}, j \in V^{sc}, k \in K$: the weight of demand on product k at demand zone j.
$LT(j,l), (j,l) \in E^{sc}$: the shipping lead time of arc (j,l).
$c\_flow_{(j,l)}, (j,l) \in E^{sc}$: the transportation cost of arc (j,l).
$c\_inv_{l,k}, l \in V^{sc}$: the inventory cost of product k at location l.
$c\_pro_{p,k}, p \in V^{sc}$: the production cost of product k at plant p.
$c\_sl^1_k, k \in K$: the cost of unmet demand of product k.
$\pi_k, k \in V^{sc}$: a multiplier.
$b_j, j \in V^{pr}$: the power production capacity of node j.
$d_j, j \in V^{pr}$: the demand for power of node j.
$v_(i,j), (i,j) \in E^{pr}$: the transmission capacity of arc (i,j).
$b_j, j \in V^{ph}$: the capacity of node j.
$m_{jl}, jl \in OD^{ph}$: the demand of OD pair jl.
$v_(i,j), (i,j) \in E^{ph}$: the transmission capacity of arc (i,j).
$y_{(j,l),t}, (j,l) \in E^i$: the parameter indicating whether arc (j,l) in network i is repaired or installed at time t.

Variables

$x_{(j,l),k,t}, (j,l) \in E^{sc}$: the amount of commodity k moving on arc (j,l) at time t.
$pro_{p,k,t}, p \in V^{sc}$: the amount of product k produced at plant p at time t.
$inv_{l,k,t}, l \in V^{sc}$: the amount of product k stored at location l at time t.
$s_{j,k,t}, j \in V^{sc}$: the slack of product k at demand zone j at time t.
$x_{(i,j),t}, (i,j) \in E^i$: the flow on arc (i,j).
$z^{pr}_{l,t}, l \in V^{pr}$: the variable indicating whether the demand of node l in power system is met.
$s_{j,t}, j \in V^{pr}$: the unmet demand at node j.
$f_{jl,n,t}, jl \in OD^{ph}, n \in N$: the flow on the nth path for OD pair jl, i.e., from node j to node l.
$z^2_{jl,t}, jl \in OD^{ph}$: the variable indicating whether the demand of OD pair jl in telecommunication system is met.
$s_{jl,t}, jl \in OD^{ph}$: the unmet demand at OD pair jl, be restricted to non-negative.

Appendix B
A complete supply chain restoration model

$$\texttt{minimize} \sum_{t\in T}\sum_{(j,l)\in E^{sc}}\sum_{k\in K} c\_flow_{(j,l)} x_{(j,l),k,t} + \sum_{t\in T}\sum_{p\in V^{sc}_P}\sum_{k\in K} c\_pro_{p,k} pro_{p,k,t} + \sum_{t\in T}\sum_{l\in V^{sc}_W \cup V^{sc}_P}\sum_{k\in K} c\_inv_{l,k} inv_{l,k,t} + \sum_{t\in T}\sum_{l\in V^{sc}_D}\sum_{k\in K} c\_sl^1_k s_{l,k,t} + \sum_{t\in T}\sum_{l\in V^{sc}_W \cup V^{sc}_P}\sum_{k\in K} c\_sl^2_k s\_inv_{l,k,t} \tag{26}$$

$$pro_{p,k,t} + inv_{p,k,t-1} = \sum_{l\in V^{sc}_W \cup V^{sc}_D} x_{(p,l),k,t} + inv_{p,k,t}, \quad \forall p \in V^{sc}_P, k \in K, t \in T \tag{27}$$

$$\sum_{p\in V^{sc}_P} x_{(p,w),k,t-LT(p,w)} = \sum_{l\in V^{sc}_D} x_{(w,l),k,t} + inv_{w,k,t} - inv_{w,k,t-1}, \forall w \in V^{sc}_W, k \in K, t \in T \tag{28}$$

$$\sum_{w\in V^{sc}_W} x_{(w,l),k,t-tl(w,l)} + \sum_{p\in V^{sc}_p} x_{(p,l),k,t-tl(p,l)} + s_{l,k,t} = d_{l,k,t}, \forall l \in V^{sc}_D, k \in K, t \in T \tag{29}$$

$$\sum_{k\in K} x_{(j,l),k,t} \le v_{(j,l)}, \quad \forall (j,l) \in E^{sc}, t \in T \tag{30}$$

$$\sum_{k\in\phi(p)} pro_{p,k,t} \le w_p, \quad \forall p \in V^{sc}_P, t \in T \tag{31}$$

$$\sum_{k\in K} inv_{l,k,t} \le q_l, \quad \forall l \in V^{sc}_P \cup V^{sc}_W, t \in T \tag{32}$$

$$\sum_{l\in V^{sc}_W \cup V^{sc}_D} x_{(p,l),k,t} = 0, \quad \forall p \in V^{sc}_P, k \in K/\ \phi(p), t \in T \tag{33}$$

$$\sum_{(i,j)\in E^{pr}} x_{(i,j),t} \le b_i \quad \forall i \in V^{pr}, t \in T \tag{34}$$

$$\sum_{i\in V^{pr}} x_{(i,j),t} + s_{j,t} = d_j \quad \forall j \in V^{pr}, t \in T \tag{35}$$

$$s_{j,t} \le d_j * z^{pr}_{j,t}, \quad \forall j \in V^{pr}_D, t \in T \tag{36}$$

$$\sum_{(i,j)\in E^{pr}} x_{(i,j),t} - \sum_{(j,l)\in E^{pr}} x_{(j,l),t} = 0, \quad \forall j \in V^{pr}, t \in T \tag{37}$$

$$x_{(i,j),t} \le v_{(i,j)} * y_{(i,j),t}, \quad \forall (i,j) \in E^{pr}, t \in T \tag{38}$$

$$\sum_{n\in 1..N} f_{jl,n,t} + s_{jl,t} = m_{jl}, \quad \forall jl \in OD^{ph}, t \in T \tag{39}$$

$$s_{jl,t} \le m_{jl} * z^{ph}_{jl,t}, \quad \forall jl \in OD^{ph}, t \in T \tag{40}$$

$$\sum_{(jl,n) contains (i,k)} f_{jl,n,t} = x_{(i,k),t}, \quad \forall (i,k) \in E^{ph}, t \in T \tag{41}$$

$$\sum_{(i,j) \in E^{ph}} x_{(i,j),t} \le b_j, \quad \forall j \in V^{ph}, t \in T \tag{42}$$

$$x_{(i,j),t} \le v_{(i,j)} * y_{(i,j),t}, \quad \forall (i,j) \in E^{ph}, t \in T \tag{43}$$

$$\sum_{k \in \phi(p)} pro_{p,k,t} \le w_p (1 - z^{pr}_{l,t}), \quad \forall (p,l) \in Dep(sc,pr), t \in T \tag{44}$$

$$\sum_k \sum_j x_{(j,w),k,t-tl(j,w)} \le q_w (1 - z^{pr}_{l,t}), \quad \forall (w,l) \in Dep(sc,pr), t \in T \tag{45}$$

$$\sum_k \sum_j x_{(w,j),k,t} \le q_w (1 - z^{pr}_{l,t}), \quad \forall (w,l) \in Dep(sc,pr), t \in T \tag{46}$$

$$\sum_{k \in K} x^{sc}_{(j,l),k,t} \le v^{sc}_{(j,l)} (1 - z^{ph}_{jl,t}), \quad \forall ((j,l),jl) \in Dep(sc,ph), t \in T \tag{47}$$

$$\sum_{(i,m) \in E^{ph}} x_{(i,m),t} \le b_m (1 - z^{pr}_{l,t}), \quad \forall (m,l) \in Dep(ph,pr), t \in T \tag{48}$$

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