THE STUDY OF SUPPLY CHAIN FACILITIES AND THEIR INTERCONNECTION WITH CRITICAL CIVIL INFRASTRUCTURE SYSTEMS

by

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ABSTRACT

Many events in recent years regarding natural disasters and terrorism have highlighted the consideration of disruptions when designing supply chain networks and allocating the critical facilities. There is usually less flexibility regarding supply chain infrastructure since the strategic decisions cannot be changed quickly and the physical constructions can’t be modified without raising more issues. Based on reviews of modeling the supply chain, describing the network of critical civil infrastructure systems, and researches on interdependencies of systems and the idea of the system of systems, we chose the network flow models to depict each system as single or multi commodity network, and used the concept of binary variables to represent the switching effect of the interconnections with a weighted supply chain cost analysis model that generalized the normal cost and optimization of operating a supply chain and illustrated the weight penalty for disruptions from power and communication systems. The model included most transportation modes and all steps in supply chain and provided a base to analyze the resilience and sustainability of a supply chain once getting designed or empirical data.
Supply chain facility location problem are always considered as the most critical and most complex of the issues to run an efficient supply chain. Usually, changes of other components in the supply chain such as the transportation, inventory and information systems’ can be made with less hassle due to relatively bigger amount of choices. In other words, these types of decisions can be readily re-optimized in response to changes in the underlying conditions of the supply chain[1]. There are terms harder to change in short period such as the capacity of facilities, such as the production rate and the production quantity. Also the lead time in ordering makes many changes happen in relatively longer time. But facility locations are often fixed and difficult to change once they have been built. It has involved many issues such as finance, coordination, government planning, and the most important, the market.

It is common knowledge that inefficient locations for producing and assembling plants and distribution centers will result in excessive costs throughout long term. Also we may notice if not considerately planned, one or many of the constructed facilities may be vulnerable when facing disruptions caused by natural disasters, terrorist attacks or labor actions.

The major reasons and results of supply chain disruptions are not only concerned by theoretical researches, but also highly emphasized in practices of logistics operation, since risk in the context of supply chains may appear in different
steps such as the material procurement, the production, the coordination, the business strategy and alliances, and the demand markets.

From past examples we notice that disruptions affect the supply chain in the following aspects: water and sewer, electricity, communication may be cut out temporarily. There are direct damages of factories. The materials suppliers are also damaged. People can’t work. Rerouting different modes of transportation around the shattered infrastructure is demanding task.

Most of the effects mentioned above emphasized the supply chain’s reliance on civil infrastructure systems. Sheffi[2] said that the structure of supply chain create vulnerability.

It has been argued that supply chain disruptions and the associated operational and financial risks are the most pressing issue faced by firms in today’s competitive global environment. We present a network flow model that not only minimizes the transportation costs among facilities and markets, but also illustrate the interdependencies between supply chain facilities and other civil infrastructure systems that help analyzing the reliance of the facilities’ locations.
Chapter 2

LETTERATURE REVIEW

The literature review covers two major areas. The first area is past work regarding supply chains, particularly work discussing risk and uncertainties in supply chains and modeling of supply chains. The second portion of the literature review covers modeling of infrastructure systems.

Supply Chain

A common definition of a supply chain is “a network of facilities that functions to procure material, transform that material into intermediate and finished products, and distribute finished products to customers” [3]. A supply chain usually includes all of the companies and their associated business activities that are needed for the design, manufacture, and distribution of a product or set of products. In other words, a supply chain is the system of organizations, people, technology, activities, information and resources involved in moving a product or service from the supplier to the customer.

Supply chains vary in level of detail, but in their most general form they could include the extraction of raw material, several production processes (e.g., raw material processing, component construction, and assembly) before moving on to storage facilities and finally reaching the consumer.
**Modeling of Supply Chain Network and Location Problem**

A large amount of work has been done in recent years regarding modeling supply chain networks and in locating facilities. The most established models of the facility location problem are found in many sources. They include the P-Median model, with the hypothesis that there are no fixed cost and no capacity limits for warehouses. Its alternative is the single source model which is used in the circumstance that the number of warehouses is not fixed and that there are fixed costs and capacity constraints for the warehouses [4].

If the limitations and descriptions of facilities are well known, then there exist general models which represent the supply chain network. These facility location problems can be formulated and solved in many ways including mixed integer, unified and descriptive models as well as decision support models. [5].

Current research tends to treat the supply chain as a network with goods flowing in it. This approach captures the main functions and summarizes the main character of a supply chain system. It can also provide a dynamic view of the complex relationships among the elements of a supply chain. However, these models fail to implicitly capture the element that the performance of a supply chain relies on the civil infrastructure systems. Power is needed to operate the production line and other facilities; roads are needed roads to transport materials and products; communication lines are needed to receive orders and provide management and supervision. In the trend of seeking a way to improve resilience of modern supply chains, a better way is needed to include other critical infrastructure systems that these supply chains rely on. The purpose of this research is to provide a framework for modeling the system of systems, that is, the relationship not only within the supply chain system, but also among the supply chain system and other critical civil infrastructure systems.
Modeling of Individual Civil Infrastructure Systems

Many efforts over the years have focused on disruptions affecting single infrastructure systems. Hasse [6] and Amin[7] have discussed the Complex Interactive Network Systems Initiative (CIN/SI). CIN/SI is a joint endeavor between the Department of Defense, academia and the Electric Power Research Institute (EPRI), with the objective create revolutionary self-stabilizing, self-optimizing, and self-healing capabilities for the electric power grid. Salmeron [8] discussed analytic techniques to mitigate disruptions in electric power grids caused by terrorist attack, but only considered components in the power system and not systems they rely on. Haimes [9] looked at the issue of reducing vulnerability of water systems to willful acts and identified the need for further research in identifying critical points and quantitative methods focused on attack consequences, not likelihood of the disruptive event. Both of these needs are addressed in this research. The National Petroleum Council [10] pointed out the increased reliance of petroleum and gas systems on information technology and telecommunications. Kuhn [11] provided a quantitative analysis of outages in the phone system including power system failure as a cause. Klincewicz [12] looked at the integrated design of computer networks, but made no mention of considerations for the components reliance on power. Chamberland [13] discussed design of multi-technology data networks, but failed to consider interconnectedness to other systems. Cremer [14] looked at issues relating to the physical construction of the Internet, focusing on issues of connectivity and degradation of service, but focused completely on only its system’s components. While not exhaustive, these papers and reports show the quantity and breadth of past and on-going work.
Each of these systems mentioned above has evolved independently, however as technology has advanced, has become highly interconnected to others. Failures within the communications network or in the power system, by whatever cause, may have far reaching effects across many systems. Some of these works also mentioned that interdependency and interconnection of the systems, but since it is one of the most difficult areas to understand this issue has hardly been modeled.

**Modeling the System of Systems**

The interconnectedness of infrastructure systems has been an important issue of past research but not in the context of supply chain resilience. Haimes and Jiang [15] presented a Leotief-based input-output model called the interoperability input-output model (IIM) which provided a method for representing the interconnectedness among infrastructure systems. However this approach worked at a macroscopic level and while useful for vulnerability assessments, it would be difficult to extend this approach to systems such as supply chains. In a more recent work Haimes [16] continued the development of the IIM and its ability to measure economic impact among various sectors in the economy by analyzing both the initial disruption and the ripple effects. Carullo [17] presented experimental studies in electrical power systems with an embedded communication system for transmission of network conditions. However, this work only looks at control issues due to communication system delay issues. Holmgren [18] also presented issues in power control systems and the associated communication systems.

Additionally, there is a body of work in what could be labeled “hybrid systems”. Nagurney’s work in supernetworks would be an example [19-21]. These hybrid systems are new networks formed from portions of the underlying civil
systems. A supernetwork might consist of one set of arcs between an origin and destination representing traditional purchasing and goods delivery systems and a parallel set of arcs representing e-business transactions. A supply chain could also classify as a supernetwork, but the formulations used by Nagurney result in an abstract representations of the networks under consideration. Similarly, Cetin [22] did work integrating physical flow layers of transportation system models with the data layers they rely on for control systems by extracting portions of information and transportation systems.

Peeta, Zhang and Friesz [23] presented a preliminary model of dynamic multilayer infrastructure networks in the context of telecommuting where three coupled network layers – automobiles, urban freight and data – were modeled as dynamic agents. The work looked at “switchable flows”. Commuters could choose to either commute to work based on existing efficiency within the telecommunications subsystem. This work did assume the presence of a super authority responsible for providing information to commuters and freight operators. This super authority would also be a controlling entity for improvements in both the transportation and information networks. In Zhang, Peeta and Friesz [24], this work was presented in a game theoretic formulation where investments in the three infrastructure systems were controlled by the super authority.

In Lee [25] a mixed integer formulation was developed which modeled the system of interconnected civil infrastructures. This work was developed for managing disruptions and detecting vulnerability but focused only on this set of civil systems. It was not extended to service systems such as supply chains. All of these
efforts are noteworthy and work to improve understanding. However, no work has been done which integrates the set of civil infrastructure systems to a supply chain. The importance of any of these civil infrastructure systems with respect to supply chains has been recognized in past studies to some degree. In Yossi Sheffi’s book, ‘The Resilient Enterprise’, (citation here), he discussed the possibility of disruptions, and the difficulty to measure its effect on a supply chain. Also, the author states that effective crisis control could be a competitive advantage for companies. In a corporate world focused in lean inventory management, consideration of systematic flexibility might become the critical surviving ability for an enterprise when facing any kind of disaster.

Another example of a discussion of the interconnectedness of supply chains and infrastructure, Lau and W. B. Lee [26] concluded that information systems have extended the scope and efficiency of an enterprise’s supply chain providing an infrastructure which facilitates the efficient exchange of data among various value chain components. However, he did not discuss how disruptions in this communication system might disrupt operations.

**Risks and Uncertainties in Supply Chains**

Sheffi [2] has stated there exists the high-possibility of the occurrence of disruptions within a supply chain and has discussed the effect these disruptions may have on the associated supply chain. According to Sheffi, the solutions to various kinds of risks rely not only on the strategic management of the enterprise, but also on the prediction of the probability of the disaster.

Cui and Ouyang and Shen [27] discussed the method of choosing reliable facility locations taking into account the risk of disruptions. The type of disruption
risks were not specified in the paper, but the probability of the risks were assumed to be known and formed the key point of finding a solution to the facility location problem. Redmond [28] thinks that human factors play a more and more important role in not only man-made disasters but also natural disasters, so there will always be some unrecognized disaster that is not only unpredictable but also hard to recover from. Within the supply chain itself, the fluctuations of normal demands, needs also to be considered when solving network problem. This analysis excludes the unpredictable incidents that may happen and disrupt the supply chain, [29].

Qiang and Nagurney [30] have developed a supply chain network model with the demand being random and the supply-side risks modeled as uncertain parameters in the underlying cost functions to study the demand-side as well as the supply-side risks. By using cost to represent the result brought by disruptions in supply chain it created a way easier yet effective to model the risks.
Chapter 3

NETWORK FLOW MODELS OF CIVIL INFRASTRUCTURE SYSTEMS

General Network Flow Problem

An infrastructure system can be treated as a network flow model, which consists of a collection of nodes and arcs. All activities are represented as the movements into and out of the nodes or along paths, including management activities and regular commodity movement. All arcs have limited capacities. Nodes can be divided into three types. A supply node is a source for producing commodity, having only out going flow in a certain infrastructure system; a demand node consumes commodities, having only incoming flow and a transshipment node which can have commodities pass by without amount changing.

In a single commodity network, material moves from one or more supply points, through the set of arcs and nodes, subject to constraints on capacity and reaches one of more demand points, in a system-optimal fashion, which means demand is satisfied with the available supplies and total shipping costs are minimized.

Usual constraints on capacity includes that the flow on each arc not exceeding its capacity, the flow coming into a demand node meeting its demand, the flowing going out from a supply node not exceeding its production capacity and the the same amount flow which enters a transshipment node also leaves.

In a multi commodity network, each type of commodity does not move independent of each other. There still exists a network where each link has a certain capacity for each commodity and for all commodities. There are many types
of commodities with their own source and demand. The objective is to find an assignment of flow which satisfies the constraints of capacity on the link and nodes, the flow conservation, that is, each type of commodity comes out from a certain node and only goes to one destination, and at last but not least, the demand satisfaction.

In the minimum cost multi commodity flow problem, the cost for satisfying all the demands is minimized. In the maximum multi commodity flow problem, there are no hard demands on each commodity, but the total throughput is maximized. In the maximum concurrent flow problem, the task is to maximize the minimal fraction of the flow of each commodity to its demand.

In our model of this paper, since the disruptions bring abnormally high cost, we are looking for a minimum cost solution for the systems which can be considered as multi commodity, such as the telecommunications and transportation networks.

**Power Network**

A power network is commonly consist of the power plants with their Step-up transformer to raise the voltage level, the transmission lines with their customers, and the distribution network, that is, the final stage in the delivery (before retail) of electricity to end users.

**Figure 1: Simple Diagram of Electricity Grids in North America[31]**
The Figure 1 above shows the basic electricity grids in North America. Electric distribution substations transform power from transmission voltage to the lower voltage used for local distribution to homes and businesses. So basically the power is generated from the factory and transformed to higher voltage to reduce loss due to the resistance, goes on the routes to local substations, gets transformed there to a lower voltage, then goes into the distribution system. A distribution system's network carries electricity from the transmission system and delivers it to consumers. Typically, the network would include medium-voltage (less than 50 kV) power lines, electrical substations and pole-mounted transformers, low-voltage (less than 1000 V) distribution wiring and sometimes electricity meters [32].

Usually the hierarchy type of structure of network exhibits unavoidable disturbances of all sizes, up to the size of the entire system. This has brought many times of large blackouts in the last century. However, in recent decades, power system has been improving with more and more backup power producing facilities and one customer may be connected to more than one delivery system so that even one has had some problem in functioning, the other would take the responsibility temporarily until the problem is fixed.
Mathematically we assume that all the power plants, substations and customers in the power system are nodes in a network flow problem. There are nodes N and associated with each node \( j \in N \) is a scalar \( b_j \) representing its supply or demand. There are also directed arcs A representing the links between each pair of node facilities. Depending on the type of the node \( j \in N \) is a demand node, a supply node or a transshipment node, it would be \( b_j < 0, b_j > 0 \) and \( b_j = 0 \) respectively. If \( j \in N \) is a supply node, then \( b_j \) is the maximum capacity of electricity production of that node. A nonnegative vector of variables \( f_a \) represents the flow on each arc \( e \) of the infrastructure. Associated with each arc \( a \) in \( A \) are non-negative scalars of costs \( q_a \) and capacities \( c_a \), where \( 0 \leq f_a \leq c_a \).

Arcs are represented using either the endpoints of the arc or the index of the arc. For a node \( l \in N \), let \( R^+(l) \) and \( R^-(l) \) denote the set of arcs in \( N \) that enter or leave node \( l \) respectively, and \( R(l) = R^+(l) \cup R^-(l) \) denote all arcs incident to node \( l \). A transshipment node has a capacity limit \( \omega_j \).

Since we are not seeking the optimization of the cost of the electricity network, what fall into our concern is the interrelation of the electricity flow and their relation with the other systems, which are the demanding nodes in this system but might be producing or transshipment nodes in other systems. Listed below are the flow conservation constraints:

\[
\sum_{a \in R^+(j)} f_a = -b_j \quad \forall j \in N^+
\]

This ensures the demand node having the incoming flow meeting its demand.

\[
\sum_{a \in R^-(j)} f_a \leq b_j \quad \forall j \in N^-
\]
This ensures that the supply node having the outgoing flow within its capacity.

\[ \sum_{a \in R^+(j)} f_a - \sum_{a \in R^-(j)} f_a = 0 \quad \forall j \in N^x \]

\[ \sum_{a \in R^+(j)} f_a \leq w_j \quad \forall j \in N^x \]

This ensures that the transshipment node having the equal incoming and outgoing flow and the flow through it won’t exceed its capacity.

\[ f_a \leq c_a \quad \forall a \in A \]

\[ f_a \geq 0 \quad \forall a \in A \]

This makes sure that each arc having its flow within its capacity range and each arc’s flow is a nonnegative vector.

**Phone Network**

Nowadays there is more than one way to communicate in business. Phone system is not the only infrastructure ordering and communication can rely on. But typically, the hub-spoke structure of the public switched telephone network is the main scheme that all other important connections use. We will take one way of telecommunication for our model, which is enough to represent the structure and major relation inside and outside of the system.

The telephone network formed by the end systems (telephones, faxes, modems etc.) and the hierarchic switching and transmission systems is called Public Switched Telephone Network.
Like showed in the figure above, each telephone is connected to a local exchange. Each village or small town will have a local exchange with a few hundred telephones connected into it. A call between p1 and p2 is switched in the local exchange v1. For a call between p1 and p3 the call must go from local exchange v1 to v2 through the next level exchange t2, normally located in a large town. Most of the telephones in the town will also be connected into t2, so that it serves as a local exchange also for its own area. There will be one or two exchanges at this level in most counties. A call from p1 to p4 must go from t2 to t3 through c1, which is a
secondary trunk exchange. This is normally in a large city. Finally a call from \( p_1 \) to \( p_5 \) must go through \( M_1 \), a tertiary trunk exchange in a large metropolitan area. This is effectively the centre of the network. There is a higher level exchange, a quaternary trunk exchange. In most countries this is normally used for connection to the international network.

Same as the power network, in reality, the introduction of digital switching and transmission techniques in recent decades has allowed more flexibility into the network, and the requirements of the mobile network and other services have introduced some extra complexity as well as extra resilience.

The fundamental task in phone network design consists in transporting different services in order to connect different customers. In order to achieve this task, multi-commodity network flow models will be used to describing the system.

**Transportation Network**

A transportation network is a type of directed, weighted graph or network. Transportation networks are used to model the flow of commodity, information, or traffic. In logistic operation, this layer of network can include links of physical transportation routes in different modes, such as highway, sailing route and air route. It also includes the nodes where the freight can be processed, such as assembled, grouped and loaded, or even not physically changed but virtually going through a step that may change the freight's status, for example, change the owner and change from the product of one stage to the material of the other stage.

The transportation network is somehow similar to the phone network in our aspect to look at the system, for both are comprised of nodes and arcs and the flow
within the network has pre-assigned origins and destination. So we will model the transportation with multi-commodity network flow models also.

The phone system or the transportation system can be represented by a set of nodes $N$ and a set of directed arcs connecting the nodes $A$. Set $O$ represents the origin-destination pairs, and each pair associated with the amount of commodity demand flow $k_o$. Also for each O-D pair there’s a set of possible paths $P_o$, each path $p$ in $P$ consists a subset of arcs in $A$. The flow on one path is $x$ and the total flows through all the paths in O-D pair $P_o$ must equal $k_o$. On each arc $a$, there is a flow amount $f$, equaling to the sum of the flow on all paths which contain $a$ and is constrained by its capacity, $u$. For a node $l \in V$, let $R^+(j)$ denotes the set of arcs in $V$ that enter node $j$, and it has a capacity limit $w_j$, so the total flow across the arcs $R^+(j)$ has an upper bound. Then the multi-commodity network flow problem’s constrains are as follows:

$$\sum_{p \in P_o} x_{o,p} = k_o \quad \forall o \in O, \forall p \in P$$

This makes sure that the demands between any O-D pairs are met.

$$f_a \leq u_a \quad \forall a \in A$$

This ensures the arc’s load doesn’t exceed its capacity.

$$\sum_{a \in R^+(j)} f_a \leq w_j \quad \forall j \in N$$

This controls the node’s load within its capacity.

$$x_a = \sum_{p \in P_o \text{ containing } a} x_{o,p} \quad \forall o \in O, \forall p \in P$$
This means that the load on an arc equals to the sum of the flow on all paths which contain the arc.

\[ x_{o,p} \geq 0 \quad \forall o \in O, \forall p \in P \]

\[ f_{a} \geq 0 \quad \forall a \in A \]

These two constrains limit the flow on the arc and path are nonnegative values.

Though we consider the two systems work in a similar fashion, there are different values of each parameter in them. We can add superscript to differentiate the systems.

**Supply Chain Network**

Supply Chain Network is the integration of the power and phone system to the basic transportation system. Service of these two systems the infrastructure of the systems for use and consumption. Electricity is provided in order to meet the need of producing, used by another infrastructure. Provision of a service requires a set of activities to materials, such as collection, movement, transformation or storage. These activities may be initiated at one or many locations and may be terminated at one or many locations. For example, management activities are necessary when provision of the service requires cooperation of more than one entity. In this case, product of the communication system serves to meet the perceived need of management.

Materials, intermediate products, and final products get created or converted with the assistance of the product of the power system - electricity, flow on the links in the transportation system, and get coordinated by the communication lines. In simple words, the key connections in the whole process among the systems are as follows: Order only possible if the communication system works; producing only
possible if the power system works; shipment and delivery only possible if the transportation system works.

Since the supply chain network’s links and nodes are based on the transportation network, we build the network flow model with the same way as the transportation network, and by adding binary variables to control the function of interrelated nodes and links.
Chapter 4
NETWORK FLOW MODELS FOR SUPPLYCHAIN AND THE INTERCONNECTION

The Network We Use

Figure 3 The printer supply chain, [3]

We use the supply chain model of the HP DeskJet printer which has been studied by Hau L. Lee and Corey Billington. Lee and Billington’s research that has brought up this network has been done more in 1990s’, although now the DeskJet developed into HP’s current DeskJet, DesignJet, PhotoSmart and Professional Series
printer lines. What we are trying to focus on is the mode of the supply chain, the suitable definition of the scope as well as the level of aggregation of the supply chain.

In the manufacturing stage there are two main components, the division that manufactures ASICs (application-specific integrated circuits) which serve as an input to the board assembly manufacturing stage and the other division that manufactures print-heads that also goes into the final assembly stage. The board assembly manufacturing stage (PCAT) and the final assembly stage (FAT) are the two main processes in Vancouver. As Lee and Billington explained, every manufacturing stage is actually a complex supply chain itself, just for the purpose of analyzing the supply chain in Vancouver these were marked as single nodes. But for our research, since we are going to discuss the relation between supply chain and other civil infrastructure systems, we treat these processes as single nodes to control the aggregation of the network. Also in our research, we don’t emphasize all the components at the same city. Actually we distribute the components in the way to associate them with different civil infrastructure service zones, which might cause them in different cities at all.

There are four groups of suppliers in the network that represent the different level of all suppliers, as well as the different level of the materials they supply. One group of the materials goes directly into the final assemble stage, but the material for the print head needs one more stage of processing before reaching the final assembly while the suppliers of the ASIC needs to go through two. Since as mentioned above the components of the manufacturing process are dispersed in different civil infrastructure service zones, these suppliers are also located in different service zones.
The Interconnection

A supply chain may be seen as a set of facilities interconnected by the power, telecommunications and transportation networks. Power must be available at production facilities or else they cannot produce products. Depending on the specifics of distribution centers (transshipment nodes), they also may not function with a loss of power.

Orders passing between facilities require telecommunications and deliveries require transportation. Failures in one telecommunication mode may require a facility to shift to manual order taking system, increasing the cost (time) for that good or service. Similarly, failures within the transportation system will require use of alternative and higher cost systems.

The following equations describe the operation of the supply chain and its interdependence on civil infrastructure systems. Supply chains are time dependent networks in that events in one period affect the ability of the network to operate in the next. An order placed in period \( t \) may not be filled until \( t+n \) where \( n \) is the production and shipment time.

This model framework will consider that all suppliers produce at rates equal to or higher than the consumption rate at downstream facilities. A supplier, \( S \), has a production rate \( PR_s \). The available inventory at a supplier in time period \( t \), \( I_{sup}(t) \), is given by:

\[
I_{sup}(t) = PR_s(t) + I_{sup}(t-1) - \text{Shipments}(t)
\]

In words, the available inventory at time \( t \) is the production rate during the interval added to the inventory at (t-1) minus any shipments leaving in period \( t \).

The demand for power at a production facility is given by \( b_{elec}^{sup} \). If the flow \( f \) to a facility does not equal \( b_{elec}^{sup} \), there will be unmet demand, \( UD_{elec}^{sup} \). For
simplicity, we will assume that the facility cannot operate if the power demand isn’t met so we will introduce a binary variable, $Y$, to reflect its operation condition.

$$UD_{sup}^{elec} \leq (1 - Y_{elec})b_{sup}^{elec}$$

This equation causes $Y_{elec} = 0$ when $UD_{sup}^{elec} > 0$. This variable, $Y_{elec}$, can be combined with the production rate of facility to reflect its reliance on power to produce.

$$PR_{ACT} = PR * Y_{elec}$$

When inventory drops below some minimum limit then the facility would place an order to its supplier. This order requires an operation path.

As discussed earlier in the telecommunication system there exists some market for calls. We will assume that the market between the production center and supplier is 1. So if this one call can flow through the telecommunication system from origin to destination by any path, then the order is placed.

$$k_0^{phone} = 1$$

$$\sum_{p \in P_o} f_{o,p}^{phone} + UD_{order}^{phone} = k_0^{phone} \quad \forall o \in O, \forall p \in P$$

$$UD_{order}^{phone} \leq (1 - Y_{phone})k_o$$

Since telecommunication and transportation are similar. Deliveries can be considered in an identical manner. So this new model would select the cheapest available delivery method. If a supplier is affected, the system could include alternative suppliers whose products would be available at higher costs.

$$\sum_{p \in P_o} f_{o,p}^{trans} + UD_{order}^{trans} = k_0^{trans} \quad \forall o \in O, \forall p \in P$$

$$UD_{order}^{trans} \leq (1 - Y_{trans})k_o^{trans}$$
Consider the simplified case showed above. One supplier send production to an inventory stockpile A, the production facility uses material from this stockpile and provides finished products to its inventory stockpile B. The distribution center requests inventory for B to sell to customers. A and B are co-located to PF and do not require telecommunication or transportation.

Inventory at j at period t:
\[ I_j(t) = Orders(t - d) + I_j(t - 1) - Deliveries to PF(t), d \text{ is delivery time.} \]

If \( I_j < L_{min} \) then an order is placed.
\[ S = I_j - L_{min} \]
\[ S \leq (1 - Y_{order})L_{min} \]

The shipment from the supplier occurs if the order is generated and placed and it can be delivered. \( D = Order \text{ amount} \), which we assume is a constant.
\[ D(t) = Y_{order} \times Y_{phone} \times Y_{trans} \times D \]

**The Objective Function and Constrains of the Network Flow Model**

Integrating the systems mentioned above together. The cost we consider from the aspect of supply chain manager is not related to the cost on the communication network nor the power network directly, but since transportation is a very major part of the logistics, its cost would be considered as the main component of
the system of systems. The effect of the other two networks, as we mentioned above, will be considered as constrains. We got our objective functions and constrains as following:

\[
\sum_{a \in \mathcal{A}_{\text{trans}}} q^\text{trans}_a x^\text{trans}_a + \sum z_{\text{prod}} (1 - Y_{\text{elec}}) b_{\text{sup}}^\text{elec} + \sum z_{\text{order}} (1 - Y_{\text{phone}}) k_o
\]

\[
+ \sum z_{\text{trans}} (1 - Y_{\text{trans}}) k_o^{\text{trans}}
\]

The first part of the function is the cost of transportation fee. It represents the biggest part of the cost regularly occurred in the system. \(q^\text{trans}_a\) is the price of each flow unit on the specific arc \(a\), and \(x^\text{trans}_a\) is the actual flow on the arc. In reality, we can add more frequently considered cost to this part according to the need to describe the network.

\[\sum z_{\text{prod}} (1 - Y_{\text{elec}}) b_{\text{sup}}^\text{elec}\] is the penalty cost of having not enough electricity for factories, and \(z_{\text{prod}}\) is the weighed lost of electricity failure. It includes the direct lost of the unmet demand and also the bad customer satisfaction and its future reputational defect. The same situation is with the other two parts, which represents the penalty cost of failure in communication and transportation.

The penalty cost parts can also be adjusted according to the situation of the systems in reality, and the weighing factor \(z\) needs to be evaluated for each system.
Chapter 5
SUMMARIES AND CONCLUSIONS

As the importance of the supply chain concept sinks into every corner of the industrial world and our daily life, civil infrastructures work every day to support facilities that are critical to the efficient and effective operation of a supply chain. Factories and warehouses planned lack of rounded consideration can result in degraded services or even collapse of the system no matter how high production rate is or how well transportation routes are planned or information technology are updated.

We have reviewed a number of methods to model the supply chain as well as to describe the other civil infrastructure systems. We also studied the researches on interdependencies of systems and the idea of the system of systems. We chose the network flow models to depict each system as single or multi commodity network, and used the concept of binary variables to represent the switching effect of the interconnections.

We also proposed a weighted supply chain cost analysis model that generalized the normal cost and optimization of operating a supply chain and illustrated the weight penalty for disruptions from power and communication systems.

The model can generally include most transportation modes and all steps in supply chain from materials supply to different levels of production, from the distribution centers to retailers and from the retailers to customer markets. For future research, we plan to expand the model to describe more in detail the effect of
disruption to each type of facilities, evaluate the model’s feasibility, and analyze the resilience of a supply chain based on designed and empirical data.
REFERENCES


