Design of Sustainable Supply Chains for Sustainable Cities

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Abstract: Supply chains provide the critical infrastructure for the production and distribution of goods and services in our Network Economy and serve as the conduits for the manufacturing, transportation, and consumption of products ranging from food, clothing, automobiles, and high technology products, to even healthcare products. Cities as major population centers serve not only as the principal demand points but also as the locations of many of the distribution and storage facilities, transportation providers, and even manufacturers. In this paper, we develop a new model for the design of sustainable supply chains with a focus on cities that captures the frequency of network link operations, which is especially relevant to cities due to frequent freight deliveries. The model is also related to recent literature on this subject. Our goal is to demonstrate how, through the proper design (and operation) of these complex networks, waste can be reduced, along with the environmental impacts, while minimizing operational and frequency costs, and meeting demand.

Keywords: sustainable cities, supply chains, sustainability, network design, multicriteria decision-making, optimization

1. Introduction

Cities, as dynamic complex networks, are the systems in which more people now live than don't and which represent the economic engines for commerce, research and development, education, healthcare, and even culture. They have evolved over space and time on built infrastructure from transportation networks to telecommunication and electric power networks. At the same time, cities are the centers of resource usage from electricity and other forms of energy and fuel, to food, water, and a plethora of other products. Hence, they also are the repositories and generators of waste output and other environmental pollutants, such as carbon and other emissions, sewage, noise, etc. The term *Sustainable Cities* has come into increasing use in the past two decades, with a focus of making cities more livable, with an eye not only on the present generation but towards future ones, as well (cf. Nijkamp and Perrels, 1994; Capello, Nijkamp, and Pepping, 1999; Knickerbocker, 2007; Grant Thornton, 2011).

A recent World Bank report (see Suzuki et al., 2009) noted that the world is shrinking with cheaper air travel, large-scale commercial shipping, and expanding road networks. Today, only 10% of the globe's land area is considered to be remote, that is, more than 48 hours from a large city. Hence, our world is becoming a network of interconnected cities or a supernetwork of cities. According to Alusi et al. (2011), urbanization is one of the most pressing and complex challenges of the 21st century, with the citizenry characterized by a growing awareness of a threat to the sustainability of the earth's natural environment, coupled with the increase in the number of people moving into and living in cities.

Supply chains consisting of suppliers, manufacturers, transportation service providers, storage facilities and distributors, as well as retailers, and consumers, serve as the backbones for the provision of goods as well as services on our modern global economy (cf. Nagurney, 2006). Supply chains have revolutionized the way in which products are sourced, produced, distributed, and consumed around the globe. They may involve thousands of stakeholders from suppliers and manufacturers to hundreds of thousands of consumer demand points around the globe. Cities are supplied by a complex array of supply chains servicing an immense spectrum of economic activities from food stores and restaurants, office supplies and high tech equipment, apparel, construction materials, as well as raw materials, to name just a few. The sustainability of supply chains is, hence, a precursor to the sustainability of our cities. Indeed, according to a Business for Social Responsibility (2009) paper, it is now widely acknowledged that making significant progress on mitigating the impact of climate change depends on reducing the negative environmental impacts of supply chains through their redesign and enhanced management (see also McKinsey Quarterly, 2008). Furthermore, as noted by Capgemini in its 2008 report: *2016: Future Supply Chain*, "Preserving energy and raw materials and other resources like water will become a crucial aspect in future supply chains, as costs will likely remain volatile and supplies will continue to dwindle." These conditions may well create substantial pressure on current supply chain models.

Although the importance of sustainable supply chains to the sustainability of cities is being increasingly recognized (cf. Grant Thornton, 2011), in terms of not only the enhancement of business processes in terms of efficiency and cost reduction but also the reduction of negative environmental externalities as well as waste, there have been only limited modeling efforts that capture supply chains within a cities framework. Models of sustainable supply chains are important since they enable the evaluation (before expensive investments are actually made) as to alternative network designs, technologies, as well as sensitivities to cost and demand structures. In addition, Batty and Cheshire (2011) have eloquently argued for the need for new theories of flows and networks for cities and have stated that "we might use our knowledge to produce cities that are more equitable, efficient, sustainable, more beautiful, and more socially caring." Moreover, they have argued for the need to capture the dynamics of flows in a city context.

The edited volume of Taniguchi and Thompson (2004), which focuses on logistics systems for sustainable cities, emphasizes the unique features of urban logistical systems, which may include more frequent freight shipments and deliveries, with the concomitant negative externalities. Geroliminis and Daganzo (2005) further emphasize that the environmental impacts of logistical activities are most severe where population densities are highest, that is, in cities. They have identified innovative practices of cities around the globe in terms of their logistics systems and sustainability, including the use of alternative modes of transportation, such as, for example, even bicycles for deliveries in Amsterdam.

In this paper, we focus on the design of sustainable supply chains for sustainable cities.

Our goal is to capture the system-wide network structure of supply chains and to include the frequency of the various supply chain network economic activities, along with the environmental impact costs, as well as the waste management costs. We first construct a model that emphasizes the operational aspects and then demonstrate how, as a special case, it can also handle design of a sustainable supply chain network from scratch. In order to distinguish between the various operational costs associated with manufacturing, storage, and distribution, and the environmental impact costs as well as the decision-maker's willingness (or not) to address the environmental impacts, we introduce an associated weight for the minimization of environmental impact costs and waste costs.

The management and design of supply chains, with a focus on sustainability, has been a topic of growing research activity. Many authors (cf. Beamon, 1999; Sarkis, 2003; Corbett and Kleindorfer, 2003; Nagurney and Toyasaki, 2005; Sheu, Chou, and Hu, 2005; Kleindorfer, Singhal, and van Wassenhove, 2005; Nagurney, Liu, and Woolley, 2007; Linton, Klassen, and Jayaraman, 2007; and Nagurney and Woolley, 2010) have emphasized that sustainable supply chains are critical for the examination of operations and the environment. Moreover, according to Nagurney (2006), firms are being held accountable not only for their own environmental performance, but also for that of their suppliers, distributors, and even, ultimately, for the environmental consequences of the disposal of their products. Poor environmental performance at any link of the supply chain network may, thus, damage what is considered a firm's premier asset – its reputation (see Fabian, 2000).

Nagurney and Nagurney (2010), more recently, developed a rigorous model, along with numerical examples, for a sustainable supply chain network design problem in which a firm is assumed to be a multicriteria decision-maker who seeks to not only minimize the total costs associated with design/construction and operation, but also to minimize the emissions generated, with an appropriate weight, which reflects the price of the emissions, associated with its various supply chain network activities. Nagurney and Yu (2012) considered competitive supply chains and the sustainability of a specific industry (fashion) and noted that other sustainable supply chain frameworks have arisen as a focus for special issues (see Piplani, Pujawan, and Ray, 2008). Nagurney and Masoumi (2011) formulated a sustainable supply chain network model for a healthcare application – that of blood supply chains. Policies to reduce emissions have also been explored in rigorous frameworks (see Dhanda, Nagurney, and Ramanujam, 1999; Nagurney, 2000; Wu et al., 2006, and Chaabane, Ramudhin, and Paquet, 2010). For a thorough survey of sustainable supply chain management until 2008, see Seuring and Muller (2008). The edited volume by Boone, Jayaraman, and Ganeshan (2012) contains an innovative collection of state-of-the-art papers on the subject. We also emphasize that in this paper we focus on dynamics of supply chains in terms of frequencies of economic activities of production, transportation, etc. A multilevel approach to supply chain network dynamics was proposed earlier in Nagurney et al. (2002), also using a supernetwork perspective. Additional background on supernetworks and complexity can be found in Nagurney (2011).

This paper is organized as follows. In Section 2, we develop the sustainable supply chain network model. The firm is a multicriteria decision-maker and seeks to minimize the total operational costs and to minimize the total environmental impact costs and waste costs, with an associated weight for the latter criterion. We establish that the optimization problem is equivalent to a variational inequality problem, with nice features for computations. The solution of the sustainable supply chain network model yields the optimal product flows, and the optimal frequencies of operating the various links of the supply chain network, so that the total cost, which includes the weighted environmental costs, is minimized and the demands are satisfied. We then prove that the model, as a special case, can also handle not only the operation of an existing supply chain for sustainability, but also a design of such a network from scratch.

The model introduces the novel feature of the frequency of operation of the various links into sustainable supply chain networks, which was inspired by Beckmann (2010), who proposed a transportation model with the frequency of operation for buses (and planes), assuming capacities. In addition, we don't limit the decision-maker to assess only the emissions generated, but, rather, also allow for the inclusion of any relevant environmental impacts, as well as waste costs. Waste costs were described earlier in Nagurney, Masoumi, and Yu (2012) in the context of a distinct supply chain network model and application, in which perishability was the primary feature of the product of concern. Moreover, unlike the model of Nagurney and Nagurney (2010), here, for the purpose of flexibility in decision-making, we allow for the option of direct shipments from the manufacturing plants to the demand points.

We propose an algorithm, in Section 2, which exploits the underlying network structure of the problem, and which computes the optimal product flows and frequencies, and also the relevant Lagrange multipliers. In addition, we establish convergence of the algorithm for the solution of our model.

In Section 3 we apply the algorithm to several numerical sustainable supply chain network examples. In Section 4, we summarize the results in this paper and present our conclusions.

2. The Sustainable Supply Chain Network Model with Frequency of Activities

In this Section, we present the model for sustainable supply chain networks with a focus of the frequency of the various supply chain activities. As noted in the Introduction, logistics in cities are often characterized by more frequent shipments, especially using primarily freight vehicles such as trucks. However, the scope of our model is broader and we also capture the optimal frequencies of the other activities, that is, those of manufacturing, storage, etc.

We consider the supply chain network topology depicted in Figure 1 but note that this network is simply representative and more disaggregation can be included, depending on the application. The top level (origin) node 0 corresponds to the firm and the bottom level (destination) nodes correspond to the demand sites, which can denote, for example, retailers or consumers, that the firm wishes to supply. The paths joining the origin node to the destination nodes depict sequences of supply chain network activities that guarantee that the product is produced and is delivered to the demand sites.

For feasibility, we assume that there is at least one path joining node 0 with each destination node so that the demand at each demand point will be met. The solution of the model will yield the optimal product flows and the optimal frequency of operation (or replenishment) of each of the activity links at the minimum total cost and the minimum total environmental impact costs and waste costs (with an appropriate firm-imposed weight). It is important to emphasize that by optimizing the supply chain network operations through production/manufacturing, transportation, storage, and distribution, subject to the demand being satisfied and the total costs being minimized, which will also include the costs of frequency operations, one is also enhancing the network's sustainability and that of the city or cities that it impacts. Indeed, we expect that the majority of the demand point nodes will be located in urban locations since that is where the greatest population densities are, as noted in the Introduction. In addition, the solution of the model will determine which manufacturing plants should be used and the same for which storage facilities / distribution centers and whether or not these are located in a city or outside.

We assume that the firm is considering n_M manufacturing facilities/plants; n_D distribution centers, and is to serve the n demand locations with the respective demands given by: d_1, d_2, …, d_n. The links from the top-tiered node 0 are connected to the manufacturing nodes of the firm, which are denoted, respectively, by: $M_1, \ldots, M_{n_M}$ These links represent the manufacturing links. There may be multiple alternative links joining node 0 to each of the manufacturing nodes in order to depict different possible technologies associated with a given manufacturing plant, which, in turn, can be associated with different levels of environmental impacts and associated costs as well as waste production.

The links from the manufacturing nodes are connected to the distribution center nodes of the firm, and are denoted by $D_{1,1}, \ldots, D_{n_D,1}$. These links correspond to the possible transportation/shipment links between the manufacturing plants and the distribution centers where the product will be stored. In addition, we allow for the possibility, if relevant and feasible, of direct links from the manufacturing nodes to the demand points. For example, a firm may decide that, rather than having the product shipped and stored and then distributed to the retailers and consumers that it may be beneficial (cost-wise and/or environmentally) to ship the product directly. There may be multiple such links joining a manufacturing node to a demand node to denote alternatives.

We also emphasize that our model can allow for outsourcing of production, transportation, etc., with appropriate changes in the cost functions (see below) so that contracts can also be captured. In that case, the firm may agree on a fixed unit price or cost for a particular link activity.

The links joining nodes $D_{1,1}, \ldots, D_{n_D,1}$ with nodes $D_{1,2}, \ldots, D_{n_D,2}$ represent the possible storage links, and here, for flexibility, and an eye towards sustainability, we allow for multiple possible storage links to represent different levels of environmental impacts. For example, a particular storage facility / distribution center may be "greener" than another in terms of LEED certification, energy consumption, etc. Finally, there are, for the sake of generality, multiple possible transportation/shipment links joining the nodes $D_{1,2}, \ldots, D_{n_D,2}$ with the demand nodes: $1, \ldots, n$ since there may exist multiple modes of transportation for distribution purposes and the firm may wish to select one with its degree of desired environmental impact. Note that in Figure 1 such alternatives are depicted as distinct links joining a pair of nodes.

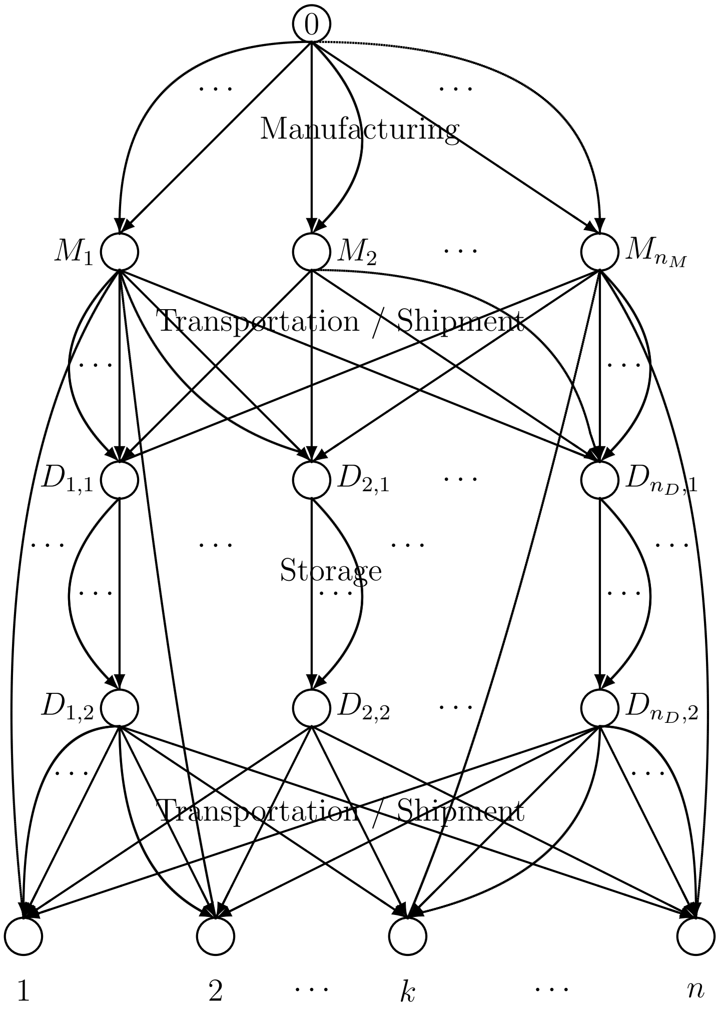

Figure 1: The Supply Chain Network Topology

Implicit in our framework is a time horizon, as, for example, a week, over which the relevant decisions are made and the activities conducted. Hence, the solution of the model(s) will provide the optimal values for both the product flows (and the levels of their production, storage, and transportation), along with the frequencies of operation of the links, so that the demands are satisfied.

The supply chain network consisting of the graph $G = [N, L]$, with N denoting the set of nodes and L the set of directed links. We assume that the firm seeks to minimize the total costs associated with its production, storage, and transportation/distribution activities, along with the total cost of link operation frequencies, plus the total cost of environmental impact and waste, which we elaborate upon below, subject to the demand being satisfied at the demand sites.

Associated with each link (cf. Figure 1) of the network is a total cost that reflects the total cost of operating the particular supply chain activity, that is, the manufacturing of the product, the shipment of the product, the storage of the product, etc., over the time horizon underlying the problem. We denote the links by a, b, etc., and the total cost on a link a by $\hat{c}_a$. For the sake of generality, we note that the total costs are generalized costs and may include, for example, risk, time, etc. (see also Nagurney, 2010).

A path p in the network (see, e.g., Figure 1) joining node 0, which is the origin node, to a demand node, which is a destination node, represents the activities and their sequence associated with producing the product and having it, ultimately, delivered. Let w_k denote the pair of origin/destination (O/D) nodes $(0, k)$ and let P_{w_k} denote the set of paths, which represent alternative associated possible supply chain network processes, joining $(0, k)$. P is the set of all paths joining node 0 to the demand nodes. n_P denotes the number of paths from the organization to the demand markets.

Let x_p represent the nonnegative flow of the product on path p joining (origin) node 0 with a (destination) demand node. Let d_k denote the demand, which is assumed to be known and fixed, for the product at demand location k. Then, the following conservation of flow equation must hold:

$$d_k \equiv \sum_{p \in P_{w_k}} x_p, \quad k = 1, \ldots, n, \tag{1}$$

that is, the demand must be satisfied at each demand site.

In addition, let f_a denote the flow of the product on link a. The following conservation of flow equations must be satisfied:

$$f_a = \sum_{p \in P} x_p \delta_{ap}, \quad \forall a \in L, \tag{2}$$

where $\delta_{ap} = 1$, if link a is contained in path p, and $\delta_{ap} = 0$, otherwise; that is, the total amount of a product on a link is equal to the sum of the flows of the product on all paths that utilize that link.

The path flows must be nonnegative, that is,

$$x_p \geq 0, \quad \forall p \in P, \tag{3}$$

since the product will be produced in nonnegative quantities.

The total operational cost on a link, be it a manufacturing/production link, a transportation/shipment link, or a storage link is assumed to be a function of the flow of the product on the link; see, for example, Nagurney and Nagurney (2010) and Nagurney (2006) and the references therein. We have, thus, that

$$\hat{c}_a = \hat{c}_a(f_a), \quad \forall a \in L. \tag{4}$$

We assume that the total cost on each link is convex and continuously differentiable, and has bounded second order partial derivatives.

We denote the total cost of operating link a at a frequency γ_a by $\hat{\pi}_a$, $\forall a \in L$, and assume that

$$\hat{\pi}_a = \hat{\pi}_a(\gamma_a), \quad \forall a \in L. \tag{5}$$

These frequency operational cost functions are assumed to be convex and continuously differentiable and to have bounded second order partial derivatives.

The sustainable supply chain network design optimization problem faced by the firm can be expressed as follows. The firm seeks to determine the optimal levels of product processed on each supply chain network link coupled with the optimal levels of frequency link operation subject to the minimization of the total cost. Hence, the firm is faced with the following objective function:

$$\text{Minimize} \quad \sum_{a \in L} \hat{c}_a(f_a) + \hat{\pi}_a(\gamma_a). \tag{6}$$

In addition, it is assumed that the firm is concerned with the environmental impact of its activities, which can include not only the emissions generated but also noise pollution, as well as other types of pollution and infrastructure deterioration. Let $\hat{e}_a(f_a, \gamma_a)$, $\forall a \in L$, denote the environmental impact function associated with link a. Also, let $\hat{z}_a(f_a)$, $a \in L$, denote the waste management cost associated with link a, $a \in L$. These functions are also assumed to be convex and continuously differentiable and to have bounded second order partial derivatives, as are the above functions in our model. Such assumptions are not unreasonable and are needed to establish convergence of the algorithm. For definiteness, one may assume that the environmental impact function captures carbon emissions but we emphasize that other negative environmental externalities should also be included in such functions. Examples of functional forms and references can be found in Nagurney, Qiang, and Nagurney (2010); see also Dhanda, Nagurney, and Ramanujam (1999).

The second objective of the firm is then given by:

$$\text{Minimize} \quad \sum_{a \in L} \hat{e}_a(f_a, \gamma_a) + \hat{z}_a(f_a). \tag{7}$$

The Multicriteria Optimization Problem for Sustainable Supply Chain Network Design with Frequency of Activities

A nonnegative constant ω is now assigned to the environmental criterion (7). The constant ω is a weight that the firm assigns. Of course, ω can also be interpreted as a "tax" imposed by the governmental/environmental authority (see, e.g., Wu et al., 2006).

We assume, as given a parameter $\bar{u}_a$, $\forall a \in L$. These parameters denote the existing capacities of the links. For example, for a manufacturing link $\bar{u}_a$ would denote the capacity of production, that is, the volume of the product that could be produced on the link; for a storage link a, the capacity would denote how much of the product could be stored there, and, similarly, for a transportation/shipment link, $\bar{u}_a$ would represent the amount that could be shipped (could denote a truckload, for example).

Using results from multicriteria optimization (see, e.g., Nagurney and Dong, 2002), one can then construct the following objective function which combines both criteria of the firm:

$$\text{Minimize} \quad \sum_{a \in L} \hat{c}_a(f_a) + \hat{\pi}_a(\gamma_a) + \omega(\sum_{a \in L} \hat{e}_a(f_a, \gamma_a) + \hat{z}_a(f_a)). \tag{8}$$

The firm, hence, seeks to solve (8), subject to the constraints: (1), (2), (3), and

$$f_a \leq \bar{u}_a \gamma_a, \quad \forall a \in L. \tag{9}$$

$$0 \leq \gamma_a, \quad \forall a \in L. \tag{10}$$

Constraint (9) guarantees that the product flow on a link does not exceed that link's capacity times the frequency of replenishing that link. Constraint (10) states that the frequencies must be nonnegative. Note that the frequencies take on continuous, rather than discrete values since, for example, truckloads may not need to be be filled to capacity in order to satisfy the demand.

We now provide the variational inequality formulation of the above multicriteria sustainable supply chain network design optimization problem. For background on variational inequalities, see Nagurney (1999). A variational inequality formulation will enable the solution of our problem in an elegant and effective manner. Moreover, it enables the development of competitive supply chain network models to capture, for example, oligopolistic behavior (cf. Masoumi, Yu, and Nagurney, 2011; Nagurney and Yu, 2012) as well as to capture uncertainties (see Nagurney, Yu, and Qiang, 2011). Observe that the above optimization problem is characterized, under our assumptions, by a convex objective function and the feasible set defined by the above constraints is convex.

We associate the Lagrange multiplier μ_a with constraint (9) for each link $a \in L$ and we denote the associated optimal Lagrange multiplier by μ_a^*. These terms may also be interpreted as the price or value of an additional unit of "capacity" on link a. We group these Lagrange multipliers into the respective vectors μ and μ^*.

We now state the following result in which we provide variational inequality formulations of the problem in link flows.

Theorem 1

The optimization problem (8), subject to the constraints (1) – (3), (9), and (10), is equivalent to the variational inequality problem: determine the vectors of link flows, link operation frequencies, and Lagrange multipliers $(f^*, \gamma^*, \mu^*) \in K$*, such that:*

$$\sum_{a \in L} \left[\frac{\partial \hat{c}_a(f_a^*)}{\partial f_a} + \omega \frac{\partial \hat{e}_a(f_a^*, \gamma_a^*)}{\partial f_a} + \omega \frac{\partial \hat{z}_a(f_a^*)}{\partial f_a} + \mu_a^* \right] \times [f_a - f_a^*]$$

$$+ \sum_{a \in L} \left[\frac{\partial \hat{\pi}_a(\gamma_a^*)}{\partial \gamma_a} + \omega \frac{\partial \hat{e}_a(f_a^*, \gamma_a^*)}{\partial \gamma_a} - \bar{u}_a \mu_a^* \right] \times [\gamma_a - \gamma_a^*]$$

$$+ \sum_{a \in L} [\bar{u}_a \gamma_a^* - f_a^*] \times [\mu_a - \mu_a^*] \geq 0, \quad \forall (f, \gamma, \mu) \in K, \tag{11}$$

where $K \equiv \{(f, \gamma, \mu) | \exists x \geq 0, \text{ and } (1), (2), \text{ and } (10) \text{ hold, and } \mu \geq 0\}$*, where* f *is the vector of link flows,* γ *is the vector of link operation frequencies, and* μ *is the vector of Lagrange multipliers.*

Proof: See Bertsekas and Tsitsiklis (1989) page 287 and Nagurney (2010). □

Variational inequality (11) can be put into standard form (see Nagurney (1999)): determine $X^* \in \mathcal{K}$ such that:

$$\langle F(X^*)^T, X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K}, \tag{12}$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product in $\mathcal{N}$-dimensional Euclidean space. If we define the column vectors: $X \equiv (f, \gamma, \mu)$ and $F(X) \equiv (F_1(X), F_2(X), F_3(X))$, such that

$$F_1(X) \equiv [\frac{\partial \hat{c}_a(f_a)}{\partial f_a} + \omega \frac{\partial \hat{e}_a(f_a, \gamma_a)}{\partial f_a} + \omega \frac{\partial \hat{z}_a(f_a)}{\partial f_a} + \mu_a; \quad a \in L], \tag{13}$$

$$F_2(X) \equiv \left[\frac{\partial \hat{\pi}_a(\gamma_a)}{\partial \gamma_a} + \omega \frac{\partial \hat{e}_a(f_a, \gamma_a)}{\partial \gamma_a} - \bar{u}_a \mu_a; a \in L \right], \tag{14}$$

$$F_3(X) \equiv [\bar{u}_a \gamma_a - f_a; \quad a \in L], \tag{15}$$

and define $\mathcal{K} \equiv K$, then (11) can be re-expressed as (12).

We now consider the following special case of the above model, which captures the optimal design of a sustainable supply chain network from scratch (whereas the above model focused on optimizing the existing operations for sustainability).

Let $\bar{u}_a = 1$, for all links $a \in L$. Moreover, let $\hat{\pi}_a$ now denote the total cost associated with investment to a level of operation γ_a on link a, for each link $a \in L$. Then we have the following, the proof of which is immediate:

Corollary 1

Under the preceding assumptions, the optimality conditions for the sustainable supply chain network model take on the following variational inequality form: determine the vectors of link flows, link capacity investments, and Lagrange multipliers $(f^*, \gamma^*, \mu^*) \in K^1$, *such that:*

$$\sum_{a \in L} \left[\frac{\partial \hat{c}_a(f_a^*)}{\partial f_a} + \omega \frac{\partial \hat{e}_a(f_a^*, \gamma_a^*)}{\partial f_a} + \omega \frac{\partial \hat{z}_a(f_a^*)}{\partial f_a} + \mu_a^* \right] \times [f_a - f_a^*]$$

$$+ \sum_{a \in L} \left[\frac{\partial \hat{\pi}_a(\gamma_a^*)}{\partial \gamma_a} + \omega \frac{\partial \hat{e}_a(f_a^*, \gamma_a^*)}{\partial \gamma_a} - \mu_a^* \right] \times [\gamma_a - \gamma_a^*]$$

$$+ \sum_{a \in L} [\gamma_a^* - f_a^*] \times [\mu_a - \mu_a^*] \geq 0, \quad \forall (f, \gamma, \mu) \in K^1, \tag{16}$$

where $K^1 \equiv \{(f, \gamma, \mu) | \exists x \geq 0, (1), (2),$ *and* (10) *hold with* $\bar{u}_a = 1, \forall a,$ *and* $\mu \geq 0\}$.

Interestingly, the resulting special case model, governed by variational inequality (16), provides us with an extension of the sustainable supply chain network design model of Nagurney and Nagurney (2010) in which not only are optimal link investments γ^* determined (and, hence, the optimal network design) but also the emissions generated (which are included in our environmental impact functions). For the design from scratch model, Figure 1 acts as a template and represents the topology (and associated links) that the firm is considering. The solution of the model determines which link capacities are zero (and, hence, can be removed from Figure 1). We present numerical examples in the next Section that illustrate the models. Note also that, unlike the model in Nagurney and Nagurney (2010), here we also include waste costs and the environmental impact functions, which can include the associated environmental damage, and which are a function of both the frequency/capacity and the link flow.

Variational inequality (11) and, clearly, variational inequality (16), can be solved using the modified projection method (also sometimes referred to as the extragradient method), which was also used in Nagurney and Nagurney (2010) and other supply chain network models (cf. Nagurney, 2006 and the references therein). The elegance of this computational procedure in the context of the above variational inequalities lies in that it allows one to can apply algorithms for the solution of the *uncapacitated* system-optimization problem (for which numerous algorithms exist in the transportation science literature) with straightforward update procedures at each iteration to obtain the link frequencies/capacities and the Lagrange multipliers explicitly and in closed form. To solve the former problem we utilize in Section 3 the well-known equilibration algorithm (system-optimization version) of Dafermos and Sparrow (1969) (see also Nagurney, 1999). The modified projection method (cf. Korpelevich, 1977) is guaranteed to converge to a solution of a variational inequality problem, provided that the function that enters the variational inequality problem is monotone and Lipschitz continuous (conditions that are satisfied under the above imposed assumptions on the cost and emission functions) and that a solution exists.

Once we have solved problem (11) we have the solution (f^*, γ^*) that minimizes the objective function (8) associated with the operation/design of a sustainable supply chain network.

We now establish both monotonicity of $F(X)$ above as well as Lipschitz continuity.

Theorem 2

The function $F(X)$ as defined following (12) (see (13) – (15)), under the assumptions above, is monotone, that is,

$$\langle (F(X^1) - F(X^2))^T, X^1 - X^2 \rangle \geq 0, \quad \forall X^1, X^2 \in \mathcal{K}. \tag{17}$$

Proof: Expanding (17), we obtain:

$$\langle (F(X^1) - F(X^2))^T, X^1 - X^2 \rangle$$

$$= \sum_{a \in L} \left[(\frac{\partial \hat{c}_a(f_a^1)}{\partial f_a} + \omega \frac{\partial \hat{e}_a(f_a^1, \gamma_a^1)}{\partial f_a} + \omega \frac{\partial \hat{z}_a(f_a^1)}{\partial f_a} + \mu_a^1) - (\frac{\partial \hat{c}_a(f_a^2)}{\partial f_a} + \omega \frac{\partial \hat{e}_a(f_a^2, \gamma_a^2)}{\partial f_a} + \omega \frac{\partial \hat{z}_a(f_a^2)}{\partial f_a} + \mu_a^2) \right]$$

$$\times \left[f_a^1 - f_a^2 \right]$$

$$+ \sum_{a \in L} \left[(\frac{\partial \hat{\pi}_a(\gamma_a^1)}{\partial \gamma_a} + \omega \frac{\partial \hat{e}_a(f_a^1, \gamma_a^1)}{\partial \gamma_a} - \bar{u}_a \mu_a^1) - (\frac{\partial \hat{\pi}_a(\gamma_a^2)}{\partial \gamma_a} + \omega \frac{\partial \hat{e}_a(f_a^2, \gamma_a^2)}{\partial \gamma_a} - \bar{u}_a \mu_a^2) \right] \times \left[\gamma_a^1 - \gamma_a^2 \right]$$

$$+\sum_{a\in L}\left[(\bar{u}_a\gamma_a^1 - f_a^1) - (\bar{u}_a\gamma_a^2 - f_a^2)\right] \times \left[\mu_a^1 - \mu_a^2\right]$$

$$= \sum_{a\in L}\left[\frac{\partial \hat{c}_a(f_a^1)}{\partial f_a} - \frac{\partial \hat{c}_a(f_a^2)}{\partial f_a}\right] \times \left[f_a^1 - f_a^2\right] + \omega \sum_{a\in L}\left[\frac{\partial \hat{e}_a(f_a^1,\gamma_a^1)}{\partial f_a} - \frac{\partial \hat{e}_a(f_a^2,\gamma_a^2)}{\partial f_a}\right] \times \left[f_a^1 - f_a^2\right]$$

$$+\omega \sum_{a\in L}\left[\frac{\partial \hat{z}_a(f_a^1)}{\partial f_a} - \frac{\partial \hat{z}_a(f_a^2)}{\partial f_a}\right] \times \left[f_a^1 - f_a^2\right]$$

$$+\sum_{a\in L}\left[\frac{\partial \hat{\pi}_a(\gamma_a^1)}{\partial \gamma_a} - \frac{\partial \hat{\pi}_a(\gamma_a^2)}{\partial \gamma_a}\right] \times \left[\gamma_a^1 - \gamma_a^2\right] + \omega \sum_{a\in L}\left[\frac{\partial \hat{e}_a(f_a^1,\gamma_a^1)}{\partial \gamma_a} - \frac{\partial \hat{e}_a(f_a^2,\gamma_a^2)}{\partial \gamma_a}\right] \times \left[\gamma_a^1 - \gamma_a^2\right]. \quad (18)$$

But the expression in (18) is greater than or equal to zero, since we have assumed that the total cost, the environmental impact cost functions, and the waste cost functions are convex and continuously differentiable and that the weight ω is nonnegative. Hence, the result has been established. □

Theorem 3

The function $F(X)$ as defined following (12) is Lipschitz continuous, that is,

$$\|F(X^1) - F(X^2)\| \leq \|X^1 - X^2\|, \quad \forall X^1, X^2 \in \mathcal{K}. \quad (19)$$

Proof: Since we have assumed that the $\hat{c}_a(f_a)$ functions, the $\hat{\pi}_a(\gamma_a)$, the $\hat{e}_a(f_a,\gamma_a)$ and the $\hat{z}_a(f_a)$ functions all have bounded second-order derivatives for all links $a \in L$, the result is direct by applying a mid-value theorem from calculus to the function F that enters the above variational inequality. □

It is important to realize that linear functions are convex and continuously differentiable. Hence, our model can be applied (and solved) under many different not unreasonable cost settings.

We now state the convergence result for the modified projection method for this model.

Theorem 4: Convergence

Assume that the function that enters the variational inequality (11) (or (12)) has at least one solution and satisfies the conditions in Theorem 2 and in Theorem 3. Then the modified projection method converges to the solution of variational inequality (11) (or (12)) and, similarly, due to Corollary 1, to the solution of (16).

Proof: According to Korpelevich (1977), the modified projection method converges to the solution of the variational inequality problem of the form (12), provided that a solution exists and that the function F that enters the variational inequality is monotone and Lipschitz continuous and that a solution exists. Monotonicity follows from Theorem 2. Lipschitz continuity, in turn, follows from Theorem 3. □

3. Numerical Examples

The modified projected method was implemented in FORTRAN and a Unix system at the University of Massachusetts Amherst was used for all the computations. We initialized the algorithm by equally distributing the demand at each demand site among all the paths joining the firm node 0 to the demand node. All other variables, that is, the link frequencies and the Lagrange multipliers, were initialized to zero. We used the equilibration algorithm for the solution of the embedded quadratic programming network optimization problems. The numerical examples were solved to a high degree of accuracy since the imposed convergence criterion guaranteed that the absolute value of successive iterates differed by no more than 10^{-5}.

We computed solutions to three numerical supply chain network examples.

The first two examples had link capacities as reported in Table 1. The third numerical example (since it was a supply chain network design example) had $\bar{u}_a = 1$ for all links a, with the interpretation that the optimal values for the γ_a^*, for all links $a \in L$, would reflect the effective optimal capacities of the corresponding links (see, e.g., Nagurney, 2010).

The supply chain network topology for Examples 1 and 2 is as depicted in Figure 2 with the links defined by numbers as in Figure 2.

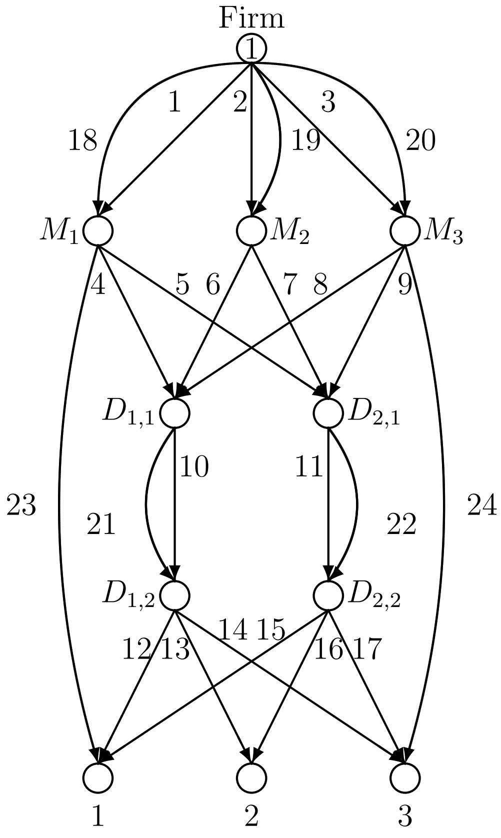

Figure 2: The Supply Chain Network Topology $G = [N, L]$ for the Examples

Example 3 also had the topology given in Figure 2 but since it is a design from scratch example, this topology serves as a template (see also Nagurney, 2010).

The numerical examples consisted of a firm faced with 3 possible manufacturing plants, each of which had 2 possible technologies, 2 distribution centers, each of which also had 2 distinct technologies, and the firm had to supply the 3 demand points. There was only a single mode of transportation/shipment available between each manufacturing plant and each distribution center and between each distribution center at a given demand point.

Demand points 1 and 3 had direct shipments from the respective manufacturing plants permitted, as depicted in Figure 2.

The common input data for the first two examples are reported in Table 1.

Table 1: Total Operating and Frequency Cost Functions, Environmental Impact Cost and Waste Cost Functions, and Link Capacities for Numerical Examples 1 and 2

Link a	$\hat{c}_a(f_a)$	$\hat{\pi}_a(\gamma_a)$	$\hat{e}_a(f_a, \gamma_a)$	$\hat{z}_a(f_a)$	$\bar{u}_a$
1	$.5f_1^2 + 2f_1$	$.5\gamma_1^2 + \gamma_1$	$.05f_1^2 + f_1 + 1.5\gamma_1^2 + 2\gamma_1$	$.05f_1^2 + f_1$	100.
2	$.5f_2^2 + f_2$	$2.5\gamma_2^2 + \gamma_2$	$.1f_2^2 + f_2 + 2\gamma_2^2 + 2\gamma_2$	$.1f_2^2 + 2f_2$	100.
3	$.5f_3^2 + f_3$	$\gamma_3^2 + 2\gamma_3$	$.15f_3^2 + 2f_3 + 2.5\gamma_3^2 + \gamma_3$	$.25f_3^2 + 5f_3$	200.
4	$1.5f_4^2 + 2f_4$	$\gamma_4^2 + \gamma_4$	$.05f_4^2 + .1f_4 + .1\gamma_4^2 + .2\gamma_4$	$.05f_4^2 + 2f_4$	20.
5	$f_5^2 + 3f_5$	$2.5\gamma_5^2 + 2\gamma_5$	$.05f_5^2 + .1f_5 + .05\gamma_5^2 + .1\gamma_5$	$.1f_5^2 + 3f_5$	20.
6	$f_6^2 + 2f_6$	$.5\gamma_6^2 + \gamma_6$	$.1f_6^2 + .1f_6 + .05\gamma_6^2 + .1\gamma_6$	$.05f_6^2 + f_6$	20.
7	$.5f_7^2 + 2f_7$	$.5\gamma_7^2 + \gamma_7$	$.05f_7^2 + .2f_7 + .1\gamma_7^2 + .2\gamma_7$	$.25f_7^2 + f_7$	20.
8	$.5f_8^2 + 2f_8$	$1.5\gamma_8^2 + \gamma_8$	$.05f_8^2 + .1f_8 + .1\gamma_8^2 + .3\gamma_8$	$.2f_8^2 + 2f_8$	10.
9	$f_9^2 + 5f_9$	$2\gamma_9^2 + 3\gamma_9$	$.05f_9^2 + .1f_9 + .1\gamma_9^2 + .2\gamma_9$	$.1f_9^2 + 5f_9$	10.
10	$.5f_{10}^2 + 2f_{10}$	$\gamma_{10}^2 + 5\gamma_{10}$	$.2f_{10}^2 + f_{10} + 1.5\gamma_{10}^2 + 3\gamma_{10}$	$.05f_{10}^2 + 5f_{10}$	50.
11	$f_{11}^2 + f_{11}$	$.5\gamma_{11}^2 + 3\gamma_{11}$	$.25f_{11}^2 + 3f_{11} + 2\gamma_{11}^2 + 3\gamma_{11}$	$.1f_{11}^2 + 2f_{11}$	50.
12	$.5f_{12}^2 + 2f_{12}$	$.5\gamma_{12}^2 + \gamma_{12}$	$.05f_{12}^2 + .1f_{12} + .1_{12}^2 + .2\gamma_{12}$	$.05f_{12}^2 + 3f_{12}$	15.
13	$.5f_{13}^2 + 5f_{13}$	$.5\gamma_{13}^2 + \gamma_{13}$	$.1f_{13}^2 + .1f_{13} + .05\gamma_{13}^2 + .1\gamma_{13}$	$.05f_{13}^2 + 5f_{13}$	15.
14	$f_{14}^2 + 7f_{14}$	$2\gamma_{14}^2 + 5\gamma_{14}$	$.15f_{14}^2 + .2f_{14} + .1\gamma_{14}^2 + .1\gamma_{14}$	$.05f_{14}^2 + 3f_{14}$	15.
15	$f_{15}^2 + 2f_{15}$	$.5\gamma_{15}^2 + \gamma_{15}$	$.05f_{15}^2 + .3f_{15} + .1\gamma_{15}^2 + .2\gamma_{15}$	$.1f_{15}^2 + 5f_{15}$	20.
16	$.5f_{16}^2 + 3f_{16}$	$\gamma_{16}^2 + \gamma_{16}$	$.05f_{16}^2 + .1f_{16} + .1\gamma_{16}^2 + .1\gamma_{16}$	$.15f_{16}^2 + 3f_{16}$	20.
17	$.5f_{17}^2 + 2f_{17}$	$.5\gamma_{17}^2 + \gamma_{17}$	$.15f_{17}^2 + .3f_{17} + .05\gamma_{17}^2 + .1\gamma_{17}$	$.1f_{17}^2 + 5f_{17}$	20.
18	$.5f_{18}^2 + f_{18}$	$\gamma_{18}^2 + 2\gamma_{18}$	$.2f_{18}^2 + 2f_{18} + 2\gamma_{18}^2 + 3\gamma_{18}$	$.05f_{18}^2 + f_{18}$	100.
19	$.5f_{19}^2 + 2f_{19}$	$\gamma_{19}^2 + \gamma_{19}$	$.25f_{19}^2 + 3f_{19} + 3\gamma_{19}^2 + 4\gamma_{19}$	$.1f_{19}^2 + 2f_{19}$	200.
20	$1.5f_{20}^2 + f_{20}$	$\gamma_{20}^2 + \gamma_{20}$	$.3f_{20}^2 + 3f_{20} + 2.5\gamma_{20}^2 + 5\gamma_{20}$	$.15f_{20}^2 + f_{20}$	100.
21	$.5f_{21}^2 + 2f_{21}$	$\gamma_{21}^2 + 3\gamma_{21}$	$.1f_{21}^2 + 3f_{21} + 1.5\gamma_{21}^2 + 4\gamma_{21}$	$.15f_{21}^2 + 3f_{21}$	100.
22	$f_{22}^2 + 3f_{22}$	$.5\gamma_{22}^2 + 2\gamma_{22}$	$.05f_{22}^2 + 4f_{22} + 2.5\gamma_{22}^2 + 4\gamma_{22}$	$.25f_{22}^2 + 5f_{22}$	100.
23	$.5f_{23}^2 + f_{23}$	$.25\gamma_{23}^2 + \gamma_{23}$	$.2f_{23}^2 + f_{23} + \gamma_{23}^2 + 2\gamma_{23}$	$.2f_{23}^2 + 4f_{23}$	150.
24	$f_{24}^2 + f_{24}$	$.25\gamma_{24}^2 + \gamma_{24}$	$.1f_{24}^2 + 3f_{24} + .05\gamma_{24}^2 + 2\gamma_{24}$	$.1f_{24}^2 + 2f_{24}$	150.

Example 1

In Example 1 the demands were:

$$d_1 = 100, \quad d_2 = 200, \quad d_3 = 100.$$

The total operating and frequency cost, the environmental impact, and the waste cost functions were as reported in Table 1. In Example 1 we assumed that the firm did not care about the environmental impact and the waste generated generated in its supply chain and, hence, $\omega = 0$. The computed solution is reported in Table 2. The total cost (see objective function (6)) was: 55,920.97. The total environmental impact cost(see objective function (7)) was: 11,966.57, and the total waste costs were: 15,551.25. The value of the objective function (8) was, hence, 55.920.97.

It is interesting that all the demand for demand market 1 is fulfilled through link 23 since links 12 and 15 have zero product flow on them. Of course, the corresponding frequencies of operating these links is also zero.

Also, note that, since, in this example, the firm is not at all concerned about its environmental impact and wastes generated, the value of the objective function corresponds to the total operational and frequency costs.

Table 2: Example 1 Optimal Solution

Link a	f_a^*	γ_a^*	μ_a^*
1	74.61	.7461	.0175
2	58.08	.5808	.0390
3	100.71	.5035	.0150
4	25.30	1.2651	.1765
5	24.89	1.2443	.4111
6	46.75	2.3373	.1669
7	68.45	3.4228	.2211
8	49.52	4.9520	1.5856
9	11.20	1.1202	.7481
10	60.73	1.2146	.1486
11	52.76	1.0551	.0811
12	0.00	.0000	.0000
13	108.47	7.2307	.5481
14	13.10	.83733	.5662
15	0.00	.0000	.0000
16	91.53	4.5766	.5076
17	13.01	.6506	.0826
18	75.58	.7558	.0351
19	57.12	.2856	.0079
20	33.90	.3390	.0168
21	60.84	.6084	.0422
22	51.79	.5179	.0252
23	100.00	.6667	.0089
24	73.89	.4926	.0083

Example 2

Example 2 had the identical data as in Example 1 except that the firm was now concerned about the environment with $\omega = 1$. The new computed solution is given in Table 3. The total cost (see objective function (6)) was now: 56,632.07. The environmental impact cost (see objective function (7)) was now: 11,468.64. The waste cost was: 14,326.37. The value of the objective function (8) was, hence, 82,427.09. Due to the higher weight on the environmental and waste costs, the impact on the environment was reduced. However, as a consequence, the total cost is now higher than in Example 1 although not substantially so.

Links 12 and 15, which are transportation/shipment links, are not used/operated, as was also the case in Example 1.

As expected, there is a transfer of production to the more environmentally-friendly manufacturing plants, with the associated technologies of production.

Table 3: Example 2 Optimal Solution

Link a	f_a^*	γ_a^*	μ_a^*
1	90.32	.9032	.0661
2	62.87	.6287	.0866
3	84.87	.4223	.0298
4	31.83	1.5913	.2351
5	30.93	1.5471	.4994
6	53.64	2.6821	.2026
7	59.35	2.9677	.2381
8	35.89	3.5892	1.2784
9	8.70	.8703	.6857
10	60.29	1.2057	.2806
11	52.30	1.0461	.2246
12	0.00	.0000	.0000
13	109.41	7.2947	.6089
14	11.95	.7966	.5630
15	0.00	.0000	.0000
16	90.59	4.5294	.5533
17	8.41	.4204	.0781
18	72.45	.7245	.0935
19	50.13	.2506	.0350
20	39.77	.3977	.0878
21	61.07	.6107	.1005
22	46.69	.4669	.0880
23	100.00	.6667	.0311
24	79.64	.5310	.0085

Example 3

Example 3 had the same data as Example 2 except that the $\bar{u}_1 = 1$ for all links $a = 1, \ldots, 24$. hence, the firm, in Example 1, was interested in designing a sustainable supply chain network for the product, with concern for the environment.

The computed solution is reported in Table 4.

The total cost was: 122,625.56. The environmental impact was now: 102,133.26. The waste cost was: 13,464.07. The value of the objective function (8) was 238,222.89.

Since, as reported in Table 4, links 12, 14, 15, and 17, have zero flows and zero effective capacities on those links, the optimal sustainable supply chain network design topology is given by the topology in Figure 3. Observe that demand points 1 and 3 are now served exclusively through direct shipments following the manufacture of the product.

We kept the cost data for Example 3 as in Example 2 for comparison purposes. For actual design purposes one would need to increase the values of the $\hat{\pi}_a$ functions for all links $a \in L$, since these would then reflect actual construction/investment costs in the links (cf. Nagurney, 2010).

Here our goal was to demonstrate the flexibility of the modeling and computational framework.

One can conduct additional sensitivity analysis exercises to evaluate, for example, the effects of increases in population and, hence, the demand for the product. Indeed, when we doubled the demands at each of the three demand points in Examples 1 through 3, the same links had zero flows as under the original demands. This kind of information is useful for a firm. One can also explore increases in the weight ω and improvements in environmental technologies.

The above examples, although stylized, illustrate the practicality and flexibility of the sustainable supply chain network modeling approach and algorithm.

Table 4: Example 3 Optimal Solution

Link a	f_a^*	γ_a^*	μ_a^*
1	97.25	97.25	391.9421
2	52.05	52.05	471.3385
3	70.95	70.95	499.5281
4	39.78	39.78	88.7147
5	24.65	24.65	127.7666
6	53.33	53.33	59.7681
7	54.01	4.01	66.0133
8	19.80	19.80	64.6667
9	8.43	8.43	38.5899
10	56.30	56.30	289.4470
11	47.05	47.05	241.1960
12	0.00	.0000	.0000
13	112.92	112.92	125.3066
14	0.00	.0000	5.1009
15	0.00	.0000	.3203
16	87.08	87.08	192.6962
17	0.00	.0000	.0000
18	67.18	67.18	407.9846
19	55.29	55.29	447.2140
20	57.28	57.28	406.8561
21	56.61	56.61	289.9844
22	40.04	40.04	246.2007
23	100.00	100.00	252.9854
24	100.00	100.00	51.0052

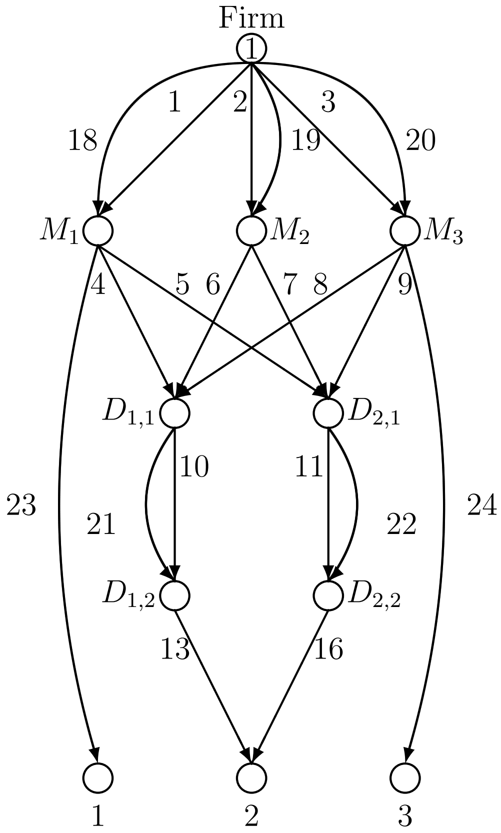

Figure 3: The Optimal Supply Chain Network Topology for Example 3

4. Summary and Conclusions

In this paper, we developed a rigorous mathematical modeling and computational framework for sustainable supply chains with a focus on sustainable cities. Cities, as centers of population, represent not only demand points for numerous products for their residents as well as workers and even tourists, but also as supply points or sources of environmental emissions as well as wastes. Hence, a holistic, system-wide approach to capturing the complexity of supply chains with the associated activities of manufacturing, transportation/shipment, as well as storage, coupled with the reality of the frequency of such supply chain activities and the associated environmental impacts, in order to satisfy the demands has been needed.

The sustainable supply chain network model developed in this paper allows for the optimization of supply chain network activities and frequencies of link operations so that the total costs are minimized as well as the environmental impacts and wastes with a weight imposed by the cognizant firm decision-maker for the environmentally-based criterion. The weight may also be interpreted as a tax that the government can assess and impose, if appropriate. Moreover, as we establish in this paper, the model can also be utilized to design a sustainable supply chain network from scratch.

Theoretical as well as numerical results are provided in this paper to demonstrate the modeling and computational framework.

This work is a contribution to the growing literature on sustainable supply chain networks and provides extensions to the existing literature by including frequencies and additional relevant environmental cost functions.

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