Multiproduct Humanitarian Healthcare Supply Chains: A Network Modeling and Computational Framework

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Abstract: In this paper, we develop a model for supply chain network design in the case of multiple products, with particular relevance to humanitarian healthcare. The model allows for the determination of the optimal capacities of supply chain network activities in the form of manufacturing, storage, and distribution, as well as the optimal multiple product flows, and identifies at what minimal total cost the demands for the products at the various points are achievable. The model may be utilized for the determination of the optimal allocation of resources for multiple vaccine and medicine production, storage, and distribution to points of need in the case of disasters, epidemics, or pandemics. The model is sufficiently general to handle supply chain network design, as well as redesign, and can be used by organizations to quantify the humanitarian healthcare supply chain costs in a transparent way to stakeholders, including governments and funding agencies.

Key words: humanitarian supply chains, multiproduct supply chains, network design / redesign, healthcare, vaccine production, medicine production, pharmaceuticals

1. Introduction

Supply chains, in today's complex, networked economy, provide a plethora of products throughout the globe. With the emphasis on efficiency and cost-cutting, firms that realize optimal supply chain network designs may have significant competitive advantage in providing their customers with the demanded products. Moreover, when it comes to healthcare supply chains, appropriate supply chain designs may positively affect the health and well-being of citizens, with broader impacts on the economy and even national security (see, e.g., Raja and Heinen (2009)). Never are healthcare supply chains more needed than in the case of disasters, whether natural or man-made, and it has been identified that the number of disasters as well as the number affected by them has been growing (see Nagurney and Qiang (2009)).

Despite significant advances in supply chain management in terms of both methodology and application, healthcare supply chains, and, in particular, humanitarian healthcare supply chains have not received the needed attention. In particular, humanitarian healthcare supply chains have many unique characteristics. For example, as pointed out in the introduction section of the handbook published by the Pan American Health Organization and World Health Organization (2001), "The various stages in the flow of supplies from their point of origin to the moment they reach their recipients – whether they be the organizations managing the emergency or the actual beneficiaries of the assistance – are a chain made up of very close links. How any one of these links is managed invariably affects the others. Supply management must therefore be the focus of an integral approach that looks at all the links in the sequence and never loses sight of their interdependence ..." Hence, an appropriate framework for humanitarian healthcare supply chains must capture the entire relevant network.

Moreover, Van Wassenhove and Pedraza Martinez (2010) have argued that "The key for logistics restructuring is better network design" and noted that logistics restructuring is a supply chain management best practice that could be used in humanitarian logistics restructuring, singling out the restructuring of the International Federation of Red Cross and Red Crescent Societies (IFRC). Each IFRC office has a distinct geographical responsibility and designs its operations based on the particular needs of the area in terms of the transportation providers, the suppliers, as well as product specifications. The ultimate goals of restructuring, according to these authors, is assistance in making better decisions, improved supply chain efficiency, and the achievement of sustainability.

In this paper, we develop a multiproduct supply chain network framework that allows for both network design and redesign by taking into consideration the reality of issues surrounding humanitarian healthcare, which differ from commerical supply chains. Such a framework is relevant since, in practice, there have been numerous dramatic examples of humanitarian healthcare supply chains that failed to deliver the necessary medicines and vaccines. For example, there were severe shortages of medicine post Hurricane Andrew in 1992, and, as noted by Jones (2006), lessons were not learned so that when Hurricane Katrina struck in 2005, there were again severe shortages of medicine. Indeed, as noted by Cefalu et al. (2006), the aftermath of Katrina and its effects on those dislocated with chronic medical illnesses, such as diabetes, demonstrated the lack in medical emergency preparedness. More recently, during ongoing strife in Africa, vaccines and their dissemination have become essential components of humanitarian operations, as in Sudan (cf. United Nations Office for the Coordination of Humanitarian Affairs (2011a), as well as in drought and famine-ravaged Somalia (see United Nations Office for the Coordination of Humanitarian Affairs (2011)).

In addition, in 2008-2009, there were flu vaccine shortages (both seasonal and H1N1 (swine) ones). Flu medicines were also in short supply in parts of the world in 2009, demonstrating serious shortfalls in proper supply chain network design with appropriate demand satisfaction (cf. Belluck (2009)) and with increasing evidence of the prevalence of the H1N1 pandemic (cf. Reed et al. (2009)).

Furthermore, documentation suggests that, among the few firms that are presently involved in flu vaccine production, there was a switching from the production of seasonal flu vaccines in 2009 to the production of the H1N1 vaccine, with increased shortages of the former, as a consequence, and delayed deliveries of the latter (cf. McNeil Jr. (2009)). As reported in the latter reference, the five corporations that are licensed to make seasonal flu vaccine shots for the US (see also Dooren (2009)): GlaxoSmithKline, Novartis, Sanofi-Aventis, CSL, and Medimmune, originally planned on producing only slightly more than 118 million units of the seasonal flu vaccine that they produced the year before. However, GlaxoSmithKline, because of production problems, cut its run by half, whereas Novartis's yield was reduced by 10 percent. Subsequently, all five producers had to switch their vaccine production from the seasonal flu to the H1N1 (swine) flu vaccine. Shortages of seasonal flu vaccine were chronic in the US in nursing homes in late 2009 with federal officials beginning to intervene since the elderly are the most vulnerable to seasonal flu. As of February 2010, it was estimated that 57 million people in the US, alone, had contracted H1N1, with about 257,000 cases resulting in hospitalizations, with the number of deaths due to H1N1 estimated at 17,000 (Falco (2010)).

In the past year, the US experienced shortages, due to manufacturer production problems associated with crystallization, of the critical drug, cytarabine, which is used in the chemotherapy treatment of leukemia, with shortages adversely affecting cancer patients' treatments and, hence, chances of survival. The Food and Drug Administration, due to the severity of this medical crisis for leukemia patients, is exploring the possibility of importing this medical product (Larkin (2011)). In addition, Hospira, one of the companies that manufactures this medicine, re-entered the market in March 2011, after fixing the crystallization problem, and has made the manufacture of cytarabine a priority ahead of other products.

Unfortunately, in 2011, more than 251 drug shortages were reported, including 20 chemotherapy agents, according to the American Society of Health-System Pharmacists. The drug shortage crisis has not only forced patients to switch to more expensive alternatives, but also posed potential hazards of medical errors (Rabin (2011)). Although the causes of drug shortages are complicated, it has been noted that production disruption at one manufacturing facility can lead to widespread drug shortages.

Everard (2001) identified concerns about the 'broken' healthcare supply chain, due to serious fragmentation in the chain (see also Burns (2002)), where instead of the overall efficiency of the chain, the outcome of each activity is mistaken to be optimized in healthcare supply chain operations. According to Keen, Moore, and West (2006), there have been few studies that integrate systems and network approaches to assist in the understanding of healthcare processes. In this paper, we attempt to overcome this shortcoming in the context of multiproduct supply chain network design with applications to healthcare and, specifically, to humanitarian healthcare supply chains where cost minimization, rather than profit maximization, subject to the demand being met, is the appropriate objective function. Humanitarian supply chains are supposed to provide necessities against time, in order to minimize avoidable injuries and death (see, e.g., Van Wassenhove (2006), Balcik and Beamon (2008), and Christopher and Tatham (2011)). Thus, the use of a profit maximization criterion is not appropriate in times of crises (see, e.g., Tomasini and Van Wassenhove (2009a, 2009b), and Vitoriano et al. (2010)).

We now overview the existing literature on the topic of concern in order to emphasize both the scope and the methodologies used to-date. We emphasize that the topic of humanitarian healthcare multiproduct supply chain network design is relatively new. Altay and Green III (2006) in their review of the disaster operations management literature argued for the need for effective and cost-efficient solutions. Tetteh (2009) claimed that drug supply chains should receive a high priority status in that they affect the availability and the affordability dimensions of access to medicine. Sinha and Kohnke (2009) proposed a conceptual framework for the design of healthcare supply chains. Shah et al. (2008) used a case study approach to study the coordination and collaboration of decentralized organizations in the healthcare industry and noted that high performance of a specific healthcare supply chain may be due to the application of lean principles.

After reviewing the healthcare supply chain literature, Chahed et al. (2009) proposed a mixed integer model dealing with an anti-cancer drug supply chain in the French context. The authors divided the drug supply chain process into production, storage, distribution, and home administration. Papageorgiou, Rotstein, and Shah (2001) earlier formulated a commercial pharmaceutical supply chain optimization problem as a mixed-integer linear programming model in order to maximize the net present value over a fairly long horizon of interest, thereby, capturing the product development and introduction strategy and a capacity planning and investment strategy. Pacheco and Casado (2005) studied a real health resources case by solving two location models (p-center problem and maximum set covering problem) with few facilities. Tsang, Samsatli, and Shah (2006) considered medium-term planning and scheduling in a flu vaccine manufacturing facility. Reimann and Schiltknecht (2009), in turn, discussed the manufacturing capacity allocation problem for a given portfolio of products, focusing on the market of specialty chemicals with applications to pharmaceuticals. Banerjee (2009) studied the multiproduct distribution problem in order to align the production schedule of multiple products in a manufacturing facility with a periodic full truckload shipping plan. For a survey of vaccine distribution and delivery issues in the United States, see Jacobson, Sewell, and Jokela (2007).

Inspired by the humanitarian relief operations in south Sudan, Beamon and Kotleba (2006a, 2006b) discussed single-item inventory management quantitatively for humanitarian organizations subject to total cost minimization. Balcik and Beamon (2008) studied facility location problems in favor of disaster preparedness via a mixed integer programming model in order to maximize the total expected coverage. Salmerón and Apte (2010) developed a two-stage stochastic optimization model and provided insights in the strategic planning and resource allocation ahead of cyclic disasters. Mete and Zabinsky (2010) considered disaster preparedness and response jointly in terms of the storage and distribution problem of medical supplies within a stochastic optimization framework. Nagurney, Masoumi, and Yu (2011) developed a network optimization model for the management of the procurement, testing and processing, and distribution of a special healthcare product – human blood. The model captured the perishability of blood. Qiang and Nagurney (2011) modeled critical needs supply chain networks under capacity and demand disruptions and proposed a bi-criteria supply chain network performance indicator for the evaluation of supply chain network performance under multiple scenarios.

The majority of previous articles have adopted mixed integer programming formulations in order to model supply chain network design problems, with production and distribution (see, e.g., Mula et al. (2010)). With exclusively linear cost functions, however, such models may not capture possible congestion and risk associated with supply chain activities (see, e.g., Nagurney et al. (2005) and Qiang, Nagurney, and Dong (2009)), of specific relevance in disaster operations (cf. Van Wassenhove and Pedraza Martinex (2010)). For example, Jayaraman and Pirkul (2001) provided a mixed integer programming formulation of an integrated logistics system with multiple products. The model aimed to address two essential decisions, with one being strategic (location choices) and the other, operational (the distribution strategy). A large-scale integer linear programming model was developed by Eskigun et al. (2005) in order to design the outbound supply chain network, with the consideration of lead time, the location of distribution facilities, and the selection of transportation mode. Haghani and Oh (1996) further noted the importance of including nonlinearities in relief operations modeling, due to the reality of congestion. More recently, Zhang, Berman, and Verter (2009) incorporated congestion in their model for preventive healthcare facility design.

Keskin and Üster (2007), in turn, presented a mixed integer problem formulation with the objective of minimizing the total costs, in the case of a multiple product, two-stage production/distribution system design problem. In earlier proposed models, unlike the one that we develop in this paper, capacities were treated as given parameters, rather than as decision variables. Indeed, according to the recent review by Melo, Nickel, and Saldanha da Gama (2009), there are only a limited number of articles that combine both capacity expansion with locational decisions. For instance, Pirkul and Jayaraman (1998) developed a mixed integer programming model for a multi-commodity and multi-plant facility location problem to minimize the total operational costs, subject to limited facility capacities. Melo, Nickel and Saldanha da Gama (2005) proposed dynamic programming for strategic supply chain planning. In their model, a capacity transfer is allowed amongst the facilities with fixed total capacity.

In this paper, we develop a multiproduct supply chain network design model that, when solved, yields the optimal investment capacities associated with supply chain network activities of manufacturing, storage, and transportation/shipment of multiple products that an organization is involved in producing/procuring. The model allows for the optimal supply chain network design in the case that there are, at present, no available capacities on any of the supply chain network links that the firm is considering, or, in the case of some existing links, both the enhancement of such link capacities as well as the determination of the optimal capacities of new links. Hence, the model can handle either the design or the redesign problem and can handle nonlinear total cost functions, which capture congestion. Of course, if the existing supply chain has sufficient capacity to meet the demands for the healthcare products, then the model collapses to a humanitarian healthcare operations model with the criterion of total generalized cost minimization.

Jahre et al. (2010), in their paper, with authors including practitioners from UNICEF and the Global Emergency Group, have argued for the need for drug supply chain process redesign as an issue of great importance in most developing countries, and an essential part of any health system, and provided further empirical evidence that the authors note is much needed in humanitarian logistics.

Our model has the feature that enables the organization (which could be a firm) to evaluate alternative technologies associated with its manufacturing facilities, alternative modes of transportation/shipment of the products from the manufacturing facilities to the storage/distribution centers, and, finally, to the demand points. Including transportation alternatives is especially relevant in disaster operations since the critical infrastructure, including roads, may be severely damaged. We also allow, for the sake of flexibility, alternative modes of storage that may reflect, for example, different energy requirements, or different requirements to minimize perishability, an issue in the case of both certain vaccines and medicines. We utilize continuous decision variables, rather than discrete variables, with a resulting formulation that enables large-scale problem solution, and efficient recomputation, which is relevant as more information may become available during the response and recovery phases. Finally, our modeling framework integrates both systems and network perspectives and does not focus exclusively on an individual component or set of components of the supply chain network but, rather, on the full supply chain network and its associated spectrum of activities.

The potential applications of the rigorous modeling framework constructed in this paper are numerous. For example, the model developed here can be utilized by a pharmaceutical firm to evaluate how much it will cost to manufacture, store, and have distributed its portfolio of products, which can include vaccines and medicines, at minimal total cost, given the demands for its various products. Note that, in the case of humanitarian healthcare, cost minimization is the appropriate and most relevant criterion or objective function, coupled with the need to ensure that the demands for the healthcare products are met. We do not consider elastic demands in the model in this paper, since meeting the healthcare needs of the population, whether in a natural disaster or in pandemics or epidemics, should be achieved first. By quantifiably determining what the minimal total costs are, the firm or organization can then plan accordingly and also contract wisely with the cognizant governments or other authorities, including humanitarian ones. In addition, we explicitly allow for alternative technologies since, as is well-known, vaccine production may be achievable in distinct ways, with some technologies, nevertheless, dating back decades.

We note that Nagurney (2010) formulated a supply chain network design model, but in the case of profit maximization and oligopolistic competition. Furthermore, the production of only one product was considered by the multiple firms in that paper. Here, in contrast, we focus on the production of multiple products at minimal total cost. We allow, as described in Section 2 of this paper, for the total cost function associated with a given product and a given supply chain link to be distinct for each product and each supply chain network link. Nagurney, Woolley, and Qiang (2010) also focused on multiproduct supply chains, but in the context of mergers and acquisitions, and constructed an appropriate measure for synergy evaluation under total cost minimization. In their models, however, the capacities associated with the supply chain links were assumed fixed. In this paper, link capacities are explicit decision variables. The flexibility of the model in this paper allows a firm/organization to evaluate the redesign of its supply chain network in the case of increased demands, for example, as might occur during a pending health crisis, including a flu pandemic. For some background material on recent approaches to multitiered supply chain network models and applications, but not in the healthcare arena, we refer the reader to Nagurney et al. (2005), Nagurney (2006), Liu and Nagurney (2009), Wu and Blackhurst (2009), Cruz (2009), Qiang, Nagurney, and Dong (2009), and the references therein. Also, we recognize the contributions of Operations Research in healthcare (see Brandeau, Sainfort, and Pierskalla (2004) and Denton and Verter (2010)).

The paper is organized as follows. In Section 2, we introduce the multiproduct supply chain network design model and also present several numerical examples, for definiteness and insights. In Section 3, we present a case study in which we further illustrate the breadth and depth of the modeling framework. In Section 4, we summarize the results and present our conclusions.

2. The Multiproduct Supply Chain Network Design Model

This Section develops the multiproduct supply chain network design model with the incorporation of explicit capacities on the various links as the design decision variables and the different product flows as additional decision variables. We also provide a variational inequality formulation of the optimal multiproduct supply chain network design.

We assume that the organization (which may be a firm) is involved in the production, storage, and transportation / distribution of J products, with a typical product denoted by j and is represented as a network of its possible supply chain activities, as depicted in Figure 1. In the network there are n_M possible manufacturing facilities, n_D possible distribution centers, and the firm must serve n_R demand points. The network in Figure 1 represents the topology over which the final optimal design will be determined. The initial network topology, as in Figure 1, is an abstraction to enable the evaluation of the possible alternatives. The model can handle any appropriate network configuration, including one in which the organization may wish to consider direct shipments to the demand points from its manufacturing plants. We emphasize that outsourcing, for example, as in procurement, could also be captured via specific links that would originate in the top-most node and terminate at the relevant demand point (bottom) node or set of nodes. Similarly, a link could represent outsourcing of the manufacturing and first level of distribution with storage done at the organization's storage facility (or set of facilities) and use of its own transportation providers to deliver to the demand points. Such a link (or set of links) would originate at the top-most node and would terminate at a third-tier node (or set of such nodes). Numerous variations are possible in our general, flexible supply chain network framework.

The links In Figure 1 from the top-tiered node are connected to the manufacturing facility nodes of the firm, which are denoted, respectively, by: $M_1, \ldots, M_{n_M}$. Note that we allow for the possibility of multiple possible links connecting the top tier node with each manufacturing facility in order to represent different possible technologies associated with manufacturing associated with a given facility. These links represent the possible manufacturing links. The links from the manufacturing facility nodes, in turn, are connected to the distribution/storage center nodes of the firm, which are denoted by $D_{1,1}, \ldots, D_{n_D,1}$. We allow, thus, for the possibility of multiple links joining each such pair of nodes to reflect possible alternative modes of transportation/shipment between the manufacturing facilities and the distribution centers where the products are stored. The links joining nodes $D_{1,1}, \ldots, D_{n_D,1}$ with nodes $D_{1,2}, \ldots, D_{n_D,2}$ correspond to the possible storage links for the products. Here we also allow for multiple links since there may be different storage technologies for the products requiring, for example, different amounts of energy, etc. Finally, there are multiple transportation/shipment links joining the nodes $D_{1,2}, \ldots, D_{n_D,2}$ with the demand nodes: $R_1, \ldots, R_{n_R}$, which represent possible alternatives that the firm wishes to evaluate for the supply chain network design. Distinct such links correspond to different modes of transportation/shipment.

Let $G = [N, L]$ denote the graph consisting of nodes $[N]$ and directed links $[L]$ representing the possible supply chain activities associated with the organization as depicted in Figure 1. The optimal supply chain network design will provide the final supply chain network topology with the links that have optimal positive capacities.

As claimed by Klein and Myers (2006), the demand market for vaccines is relatively fixed (see also Zoon (2002)). The demands for the healthcare products, notably, vaccines and medicines, are, hence, assumed as given and are associated with each product and demand point. Note that, in the case of disasters, as well as epidemics and pandemics, there will be information available as to the expected spread of diseases and, hence, as to the needs for vaccines and medicines. Let d_k^j denote the demand for product j; $j = 1, \ldots, J$, at demand point R_k. A path consists of a sequence of links originating at the top origin node 1 and denotes supply chain activities comprising manufacturing, storage, and transportation/shipment of the products to the demand nodes. Let x_p^j denote the nonnegative flow of product j on path p. Let P_{R_k} denote the set of all paths joining the origin node 1 with destination (demand) node R_k.

The following conservation of flow equations must hold for each product j and each demand point R_k:

$$\sum_{p \in P_{R_k}} x_p^j = d_k^j, \quad j = 1, \ldots, J; \quad k = 1, \ldots, n_R, \tag{1}$$

that is, the demand for each product must be satisfied at each demand point.

Links are denoted by a, b, etc. Let f_a^j denote the flow of product j on link a. We must have the following conservation of flow equations satisfied:

$$f_a^j = \sum_{p \in P} x_p^j \delta_{ap}, \quad j = 1 \ldots, J; \quad \forall a \in L, \tag{2}$$

where $\delta_{ap} = 1$ if link a is contained in path p and $\delta_{ap} = 0$, otherwise. Here P denotes the set of *all* possible paths in Figure 1. The path flows must be nonnegative, that is,

$$x_p^j \geq 0, \quad j = 1, \ldots, J; \quad \forall p \in P. \tag{3}$$

We group the path flows into the vector x.

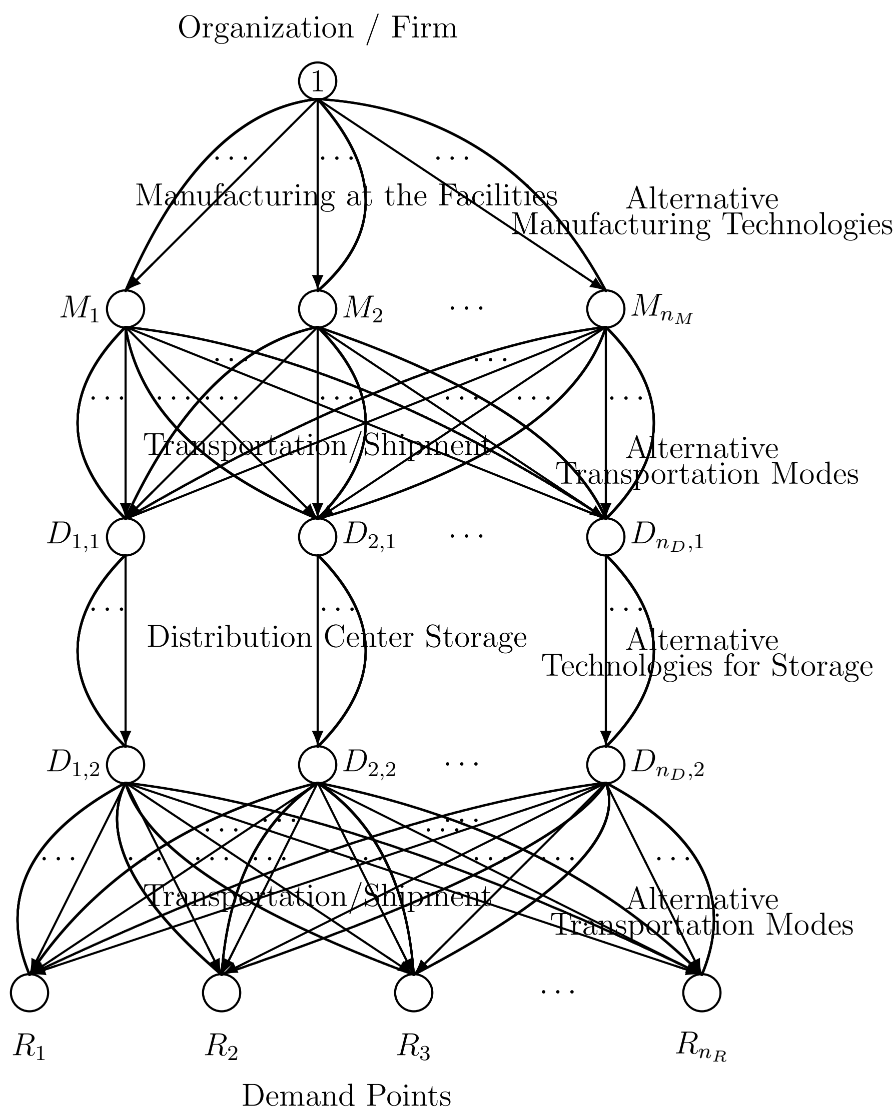

Figure 1: Initial Supply Chain Network Topology for the Optimal Design

Note that the different healthcare products flow on the supply chain network depicted in Figure 1. To capture the costs, we proceed as follows. There is a total cost associated with each product j; $j = 1, \ldots, J$, and each link (cf. Figure 1) of the network. We denote the total cost on a link a associated with product j by $\hat{c}_a^j$.

The total cost of a link associated with a healthcare product, be it a manufacturing link, a transportation/shipment link, or a storage link is assumed to be a function of the flow of all the healthcare products on the link. Hence, we have that

$$\hat{c}_a^j = \hat{c}_a^j(f_a^1, \ldots, f_a^J), \quad j = 1, \ldots, J; \quad \forall a \in L. \tag{4}$$

The top tier links in Figure 1 have multiproduct total cost functions associated with them that capture the manufacturing costs of the products using the identified possible alternative technologies; the second tier links have multiproduct total cost functions associated with them that correspond to the total costs associated with the subsequent transportation/distribution to the storage facilities via alternative modes, and the third tier links, since they are the storage links, have associated with them multiproduct total cost functions that correspond to storage using alternative technologies. Finally, the bottom-tiered links, since they correspond to the alternative modes of transportation/shipment links to the demand points, have multiproduct total cost functions associated with them.

The total cost associated with each product and each link is assumed to be a *generalized cost*, which can capture not only the capital cost, but also the time consumption, risk, etc, associated with the various supply chain activities. For instance, yield uncertainty is an important issue in vaccine production, considering its specific complex process (see Jacobson, Sewell and Jokela (2007)). Moreover, there may be risk, which can be captured in our nonlinear cost functions, associated with using specific modes of transportation in disasters. Furthermore, the siting of certain storage facilities in specific locations may also have different associated risks. By allowing for nonlinear generalized cost functions, the decision-makers can explore different scenarios more effectively. We also assume that the total cost function for each product on each link is convex, continuously differentiable, and has a bounded second order partial derivative. Such conditions will guarantee convergence of the proposed algorithmic scheme that we use in this paper.

Furthermore, we denote the nonnegative existing capacity on a link a by $\bar{u}_a$, $\forall a \in L$. We assume that the firm is considering the addition of capacity to link a, $\forall a \in L$. Of course, if for a link a, we have that $\bar{u}_a = 0$, this means that the link, in effect, does not yet exist but is being considered in the design option. We denote the total investment cost of adding investment capacity u_a on a link a by $\hat{\pi}_a$, $\forall a \in L$, and assume that

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

that is, the total cost associated with adding investment capacity u_a on a link a is a function of the added capacity on the link. These functions are assumed to have the same properties as the multiproduct total link cost functions (4).

The organization seeks to determine the optimal levels of capacity investments in its supply chain network activities coupled with the optimal levels of each product processed on each supply chain network link subject to the minimization of the total cost where the total cost includes the total cost of operating the various links for each of the products and the total cost of capacity investments. Hence, the firm must solve the following problem:

$$\text{Minimize} \quad \sum_{j=1}^{J} \sum_{a \in L} \hat{c}_a^j(f_a^1, \ldots, f_a^J) + \sum_{a \in L} \hat{\pi}_a(u_a) \tag{6}$$

subject to: constraints (1) – (3) and the following capacity constraints:

$$\sum_{j=1}^{J} \alpha_j f_a^j \leq \bar{u}_a + u_a, \quad \forall a \in L, \tag{7}$$

$$u_a \geq 0, \quad \forall a \in L. \tag{8}$$

The term α_j denotes the volume taken up by product j. Constraint (7) guarantees that the flows of all the products on a link do not exceed that link's capacity. Constraint (8) indicates that the existing capacities are not allowed to be reduced in this problem, but can be increased or remain unchanged. Such constraints are especially relevant in the context of humanitarian healthcare applications, including vaccine production, since in this case the health and well-being of the population would be of primary concern and, therefore, the capacities would not be expected to be reduced but, rather, to remain the same or to be increased. Note that, in the case of outsourcing links, those links would have no associated investment cost functions and the total costs would represent contracting costs.

Under the above imposed assumptions and the assumption that in the initial topology (see Figure 1) there exists one (or more) path from the origin node 1 to each destination node R_k; $k = 1, \ldots, n_R$, this optimization problem is a convex optimization problem, and it follows from the standard theory of nonlinear programming (cf. Bazaraa, Sherali, and Shetty (1993)) that an optimal solution exists.

We associate the Lagrange multiplier λ_a with constraint (7) for link a and we denote the associated optimal Lagrange multiplier by λ_a^*. This term may also be interpreted as the price or value of an additional unit of capacity on link a; it is also sometimes referred to as the *shadow price*. We group the Lagrange multipliers into the vector λ.

Let $\mathcal{K}$ denote the feasible set such that

$$\mathcal{K} \equiv \{(f, u, \lambda) | \exists x, \text{ such that } (1) - (3) \text{ and } (8) \text{ hold, and } \lambda \geq 0\},$$

where f is the vector of link flows, u is the vector of link enhancement capacities, and x is the vector of path flows.

We now provide the variational inequality formulation of the problem.

Theorem 1

The optimization problem (6) subject to constraints: (1)–(3), (7), and (8) is equivalent to the variational inequality problem: determine the vector of link flows, link enhancement capacities, and Lagrange multipliers $(f^*, u^*, \lambda^*) \in \mathcal{K}$, such that:

$$\sum_{j=1}^{J}\sum_{l=1}^{J}\sum_{a\in L}[\frac{\partial \hat{c}^l_a(f^{1*}_a,\ldots,f^{J*}_a)}{\partial f^j_a} + \alpha_j \lambda^*_a] \times [f^j_a - f^{j*}_a] + \sum_{a\in L}[\frac{\partial \hat{\pi}_a(u^*_a)}{\partial u_a} - \lambda^*_a] \times [u_a - u^*_a]$$

$$+ \sum_{a\in L}[\bar{u}_a + u^*_a - \sum_{j=1}^{J}\alpha_j f^{j*}_a] \times [\lambda_a - \lambda^*_a] \geq 0, \quad \forall (f, u, \lambda) \in \mathcal{K}. \tag{9}$$

Proof: See Bertsekas and Tsitsiklis (1989) and Nagurney (1999).

In the special case in which there is only a single product to be produced and delivered, we have the following result, with the proof being straightforward.

Corollary 1

In the case of a single product, the variational inequality formulation (9) collapses to: determine $(f^*, u^*, \lambda^*) \in \mathcal{K}$, such that

$$\sum_{a\in L}[\frac{\partial \hat{c}_a(f^*_a)}{\partial f_a} + \alpha\lambda^*_a] \times [f_a - f^*_a] + \sum_{a\in L}[\frac{\partial \hat{\pi}_a(u^*_a)}{\partial u_a} - \lambda^*_a] \times [u_a - u^*_a]$$

$$+ \sum_{a\in L}[\bar{u}_a + u^*_a - \alpha f^*_a] \times [\lambda_a - \lambda^*_a] \geq 0, \quad \forall (f, u, \lambda) \in \mathcal{K}, \tag{10}$$

where we have suppressed the superscript "1" on the total link cost functions, the link flows, and the product volume factor (and the same is done for the conservation of flow equations: (1) – (3)).

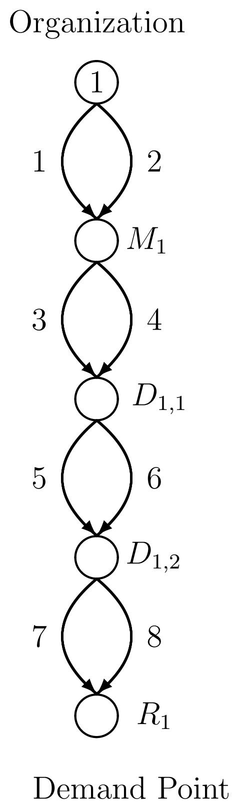

Figure 2: The Initial Supply Chain Network Topology for Example 1

To illustrate the model, we now present several examples for which we provide the complete input data and the optimal solution.

Example 1: Supply Chain Network Design

Example 1 is a single product example and, hence, governed by variational inequality (10). We assumed that there were no initial capacities on the links and, therefore, $\bar{u}_a = 0$ for all links $a \in L$ where L is as depicted in Figure 2. Specifically, the organization was involved in the production of a single product, such as a vaccine, and had two distinct technologies available for production of the product at a single manufacturing plant; two modes of shipment that it was considering to the single distribution center, which, in turn, had two alternative technologies associated with storage. There were also two possible modes of shipment that the organization was considering from the distribution center to the demand point. The demand at the demand point was $d_{R_1} = 1,000$. We assumed that $\alpha = 1$.

The total cost functions are as reported in Table 1 where we also provide the computed solution using the modified projection method (see Korpelevich (1977) and Nagurney (2006)).

Table 1: Total Cost Functions and Solution for Example 1

Link a	$\hat{c}_a(f_a)$	$\hat{\pi}_a(u_a)$	f_a^*	u_a^*	λ_a^*
1	$f_1^2 + 2f_1$	$.5u_1^2 + u_1$	571.15	571.15	572.15
2	$.5f_2^2 + f_2$	$1.5u_2^2 + 3u_2$	428.85	428.85	$1,286.59$
3	$.5f_3^2 + f_3$	$2.5u_3^2 + u_3$	454.91	454.91	$2,275.54$
4	$f_4^2 + f_4$	$1.5u_4^2 + 5u_4$	545.09	545.09	$1,640.27$
5	$.5f_5^2 + f_5$	$u_5^2 + 2u_5$	188.92	188.92	379.84
6	$.25f_6^2 + f_6$	$.1u_6^2 + u_6$	811.08	811.09	163.22
7	$1.5f_7^2 + 2f_7$	$u_7^2 + u_7$	56.32	56.32	113.64
8	$.1f_8^2 + .5f_8$	$.05u_8^2 + u_8$	943.68	943.68	95.37

We used this algorithm for all the numerical examples in this paper. We embedded it with the general equilibration algorithm of Dafermos and Sparrow (1969) to solve the fixed demand network optimization problems at each step for the product flows. The resolution of the modified projection method for the multiproduct supply chain network design yields closed form expressions for the capacity investments and the Lagrange multipliers at each iterative step. Hence, it is an easy algorithm to implement for the new modeling framework developed in this paper.

The value of the objective function (cf. (6)) at the computed optimal solution for this problem, which reflects the minimal total cost, was: 2,656,176.75.

Note that the optimal capacities on all the links are positive, as are the optimal link flows. Hence, the optimal supply chain network design for Example 1 consists of the network topology depicted in Figure 2.

Increasing Demand Examples

We then conducted sensitivity analysis for Example 1 in which we increased the demand of $1,000$ to $2,000$, to $3,000$, to $4,000$, and, finally, to $5,000$. The minimal computed total costs at these demands (and at the original demand of 1,000) are displayed in Figure 3. For definiteness, and easy reproducibility, we now also provide these values: the minimal total cost at $d_{R_1} = 2,000$ was $10,604,506.00$; the minimal total cost at $d_{R_1} = 3,000$ was $23,844,958.00$; the minimal total cost at $d_{R_1} = 4,000$ was $42,377,556.00$, and the minimal total cost at $d_{R_1} = 5,000$ was $66,202,280.00$.

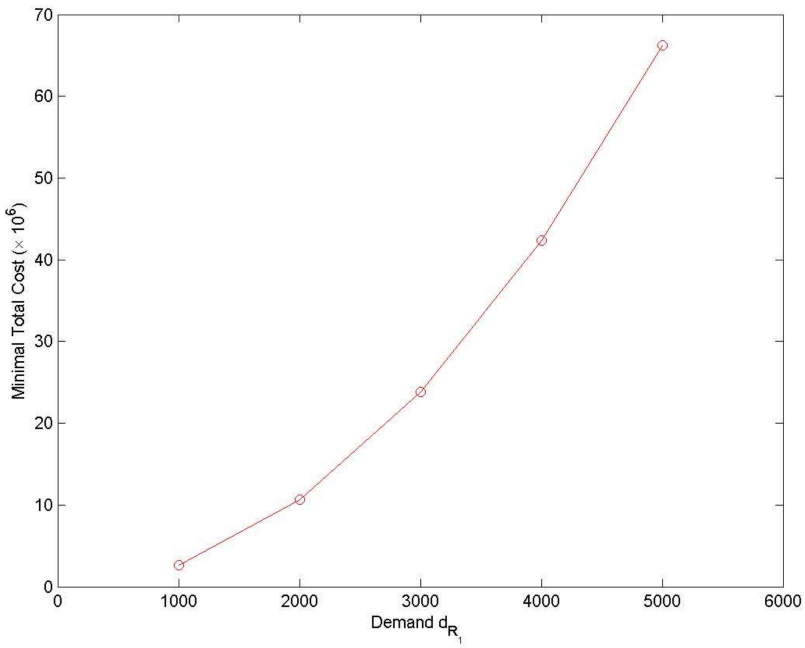

Figure 3: Minimal Total Cost Obtained for Example 1 Supply Chain Network Design as Demand Increases

Example 2: Supply Chain Network Redesign

In Example 2 we considered the following scenario. Suppose that the firm has been operating according to the optimal design for the particular production period but now the demand for the product has doubled from the original level of $1,000$ so that $d_{R_1} = 2,000$. The total link cost functions remain as in Example 1 as do the link capacity investment functions. However, now the firm already has the link capacities determined in the optimal solution to Example 1. Example 2 is, hence, a supply chain network redesign problem.

The complete input data and the solution to this problem are reported in Table 2. The total cost was: $5,885,470.50$.

Iterated Redesign with Increasing Demands

We then proceeded to investigate the impact on the minimal total cost of iterated redesign as follows. We considered a series of supply chain network redesigns. Proceeding from Example 2, we utilized the new link capacities determined for the demand of 2,000 as inputs to compute the redesign for a demand of 3,000, and, so on, until the demand was 5,000. The minimal total costs obtained are displayed in Figure 4. For definiteness, we also now

Table 2: Total Cost Functions, Initial Capacities, and Solution for Example 2

Link a	$\hat{c}_a(f_a)$	$\hat{\pi}_a(u_a)$	$\bar{u}_a$	f_a^*	u_a^*	λ_a^*
1	$f_1^2 + 2f_1$	$.5u_1^2 + u_1$	571.15	1,040.80	469.65	470.65
2	$.5f_2^2 + f_2$	$1.5u_2^2 + 3u_2$	428.85	959.20	530.35	1,594.05
3	$.5f_3^2 + f_3$	$2.5u_3^2 + u_3$	454.91	967.57	512.66	2,564.30
4	$f_4^2 + f_4$	$1.5u_4^2 + 5u_4$	545.09	1,032.43	487.34	1,467.01
5	$.5f_5^2 + f_5$	$u_5^2 + 2u_5$	188.92	436.38	247.46	496.93
6	$.25f_6^2 + f_6$	$.1u_6^2 + u_6$	811.08	1,563.61	752.53	151.51
7	$1.5f_7^2 + 2f_7$	$u_7^2 + u_7$	56.32	116.37	60.05	121.10
8	$.1f_8^2 + .5f_8$	$.05u_8^2 + u_8$	943.68	1,883.63	939.95	95.00

provide these numerical values: the minimal total cost at $d_{R_1} = 2,000$ was $5,885,470.00$; the minimal total cost at $d_{R_1} = 3,000$ was $12,231,536.00$; the minimal total cost at $d_{R_1} = 4,000$ was $17,356,920.00$, and the minimal total cost at $d_{R_1} = 5,000$ was $25,985,176.00$.

3. Multiproduct Supply Chain Network Design Case Study

In this Section, we present a multiproduct supply chain network design case study in which we compute solutions to both design and redesign problems. We consider an organization involved in the production of two vaccines, which correspond to two products, such as, for example, a seasonal flu vaccine and the H1N1 vaccine, which we refer to as vaccine 1 and 2, respectively.

3.1 Design Problem – Example 3

We assumed that the organization is considering two manufacturing plants, each of which has the potential to produce the two vaccines, and two distribution centers at which the vaccines may be stored. It must supply two different demand points. Hence, the initial possible topology that this organization is considering is as depicted in Figure 5.

The link total cost functions are given Table 3 and the capacity investment cost functions provided in Table 4. Note that in the design problem, we have that the initial link capacities are all zero, that is, $\bar{u}_a = 0$ for all links $a = 1, \ldots, 12$. Also, since the two vaccines are similar in size we assumed, for transparency and simplicity, that $\alpha_1 = \alpha_2 = 1$. The demands for the two vaccines at the demand points were:

$$d_{R_1}^1 = 100, \quad d_{R_2}^1 = 200, \quad d_{R_1}^2 = 300, \quad d_{R_2}^2 = 400.$$

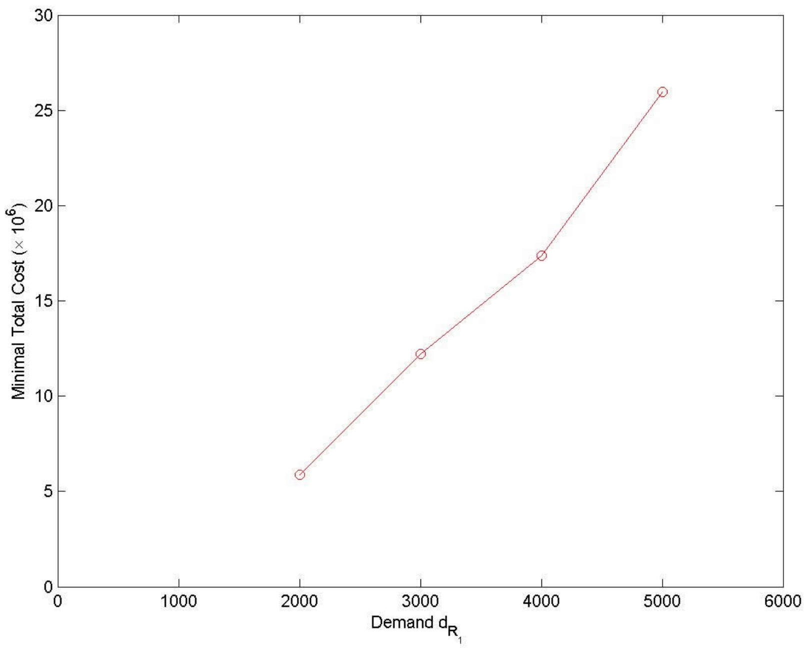

Figure 4: Minimal Total Cost Obtained for Example 2 Iterated Supply Chain Network Redesigns as Demand Increases

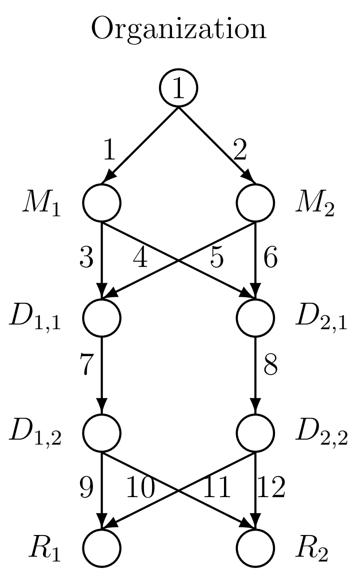

Figure 5: Initial Supply Chain Network Topology for the Multiproduct Vaccine Manufacturer

Table 3: Total Cost Functions for Design Problem Example 3

Link a	$\hat{c}_a^1(f_a^1, f_a^2)$	$\hat{c}_a^2(f_a^1, f_a^2)$
1	$1(f_1^1)^2 + .2f_1^2f_1^1 + 11f_1^1$	$3(f_1^2)^2 + .2f_1^2f_1^1 + 7f_1^2$
2	$2(f_2^1)^2 + .4f_2^2f_2^1 + 8f_2^1$	$4(f_2^2)^2 + .4f_2^2f_2^1 + 4f_2^2$
3	$3(f_3^1)^2 + .25f_3^2f_3^1 + 7f_3^1$	$4(f_3^2)^2 + .25f_3^2f_3^1 + 6f_3^2$
4	$4(f_4^1)^2 + .3f_4^2f_4^1 + 3f_4^1$	$4(f_4^2)^2 + .3f_4^2f_4^1 + 6f_4^2$
5	$1(f_5^1)^2 + .2f_5^2f_5^1 + 6f_5^1$	$1(f_5^2)^2 + .2f_5^2f_5^1 + 4f_5^2$
6	$3(f_6^1)^2 + .3f_6^2f_6^1 + 4f_6^1$	$4(f_6^2)^2 + .3f_6^2f_6^1 + 9f_6^2$
7	$4(f_7^1)^2 + .2f_7^2f_7^1 + 7f_7^1$	$4(f_7^2)^2 + .2f_7^2f_7^1 + 7f_7^2$
8	$4(f_8^1)^2 + .3f_8^2f_8^1 + 5f_8^1$	$2(f_8^2)^2 + .3f_8^2f_8^1 + 5f_8^2$
9	$1(f_9^1)^2 + .3f_9^2f_9^1 + 4f_9^1$	$4(f_9^2)^2 + .3f_9^4f_9^1 + 3f_9^2$
10	$2(f_{10}^1)^2 + .6f_{10}^2f_{10}^1 + 3.5f_{10}^1$	$3(f_{10}^2)^2 + .6f_{10}^2f_{10}^1 + 4f_{10}^2$
11	$1(f_{11}^1)^2 + .5f_{11}^2f_{11}^1 + 4f_{11}^1$	$4(f_{11}^2)^2 + .5f_{11}^2f_{11}^1 + 6f_{11}^2$
12	$4(f_{12}^1)^2 + .6f_{12}^2f_{12}^1 + 6f_{12}^1$	$3(f_{12}^2)^2 + .6f_{12}^2f_{12}^1 + 4f_{12}^2$

As mentioned in Section 2, we used the modified projection method for the solution of all the numerical examples in this paper, embedded with the general equilibration algorithm of Dafermos and Sparrow (1969) (see also, e.g., Nagurney (1999)). The convergence criterion was that the absolute value of two successive iterates of each of the flows, each of the investment capacities, and each of the Lagrange multipliers was less than or equal to the convergence tolerance, which was set to .00001.

The optimal computed solution consisting of the optimal multiproduct link flows, the optimal link capacity investments, and the associated optimal Lagrange multipliers is reported in Table 5. The total cost (cf. (6)) was: 8,160,102.00.

Hence, we assumed that the demand for the new vaccine was higher since people were not expected to have immunity against the associated new flu.

From the optimal solution, reported in Table 5, it is clear that the optimal supply chain network design is as depicted in Figure 5 since all links representing the supply chain activities have capacities greater than zero. The second manufacturing plant produces more of vaccine 1 than the first plant, whereas the first manufacturing plant produces more of vaccine 2. The first distribution center stores more of vaccine 1 than the second distribution center does, whereas the second distribution center stores more of vaccine 2 than the first center does.

Table 4: Link Capacity Investment Cost Functions for Design Problem Example 3

Link a	$\hat{\pi}_a(u_a)$
1	$5u_1^2 + 100u_1$
2	$4u_2^2 + 80u_2$
3	$u_3^2 + 20u_3$
4	$u_4^2 + 10u_4$
5	$1.5u_5^2 + 10u_5$
6	$u_6^2 + 15u_6$
7	$4u_7^2 + 110u_7$
8	$4.5u_8^2 + 120u_8$
9	$u_9^2 + 10u_9$
10	$.5u_{10}^2 + 15u_{10}$
11	$u_{11}^2 + 20u_{11}$
12	$.5u_{12}^2 + 10u_{12}$

Table 5: Optimal Multiproduct Flows, Link Capacities, and Lagrange Multipliers for Design Problem Example 3

Link a	f_a^{1*}	f_a^{2*}	u_a^*	λ_a^*
1	97.84	392.69	490.51	5005.05
2	202.16	307.31	509.44	4155.55
3	53.65	197.92	251.58	523.15
4	44.19	194.77	238.96	487.91
5	118.06	145.71	263.77	801.23
6	84.10	161.60	245.70	506.40
7	171.10	343.64	515.32	4232.54
8	128.29	356.36	484.63	4481.70
9	30.23	188.32	218.56	447.11
10	141.47	155.31	296.78	311.78
11	69.77	111.68	181.44	382.89
12	58.53	244.69	303.22	313.21

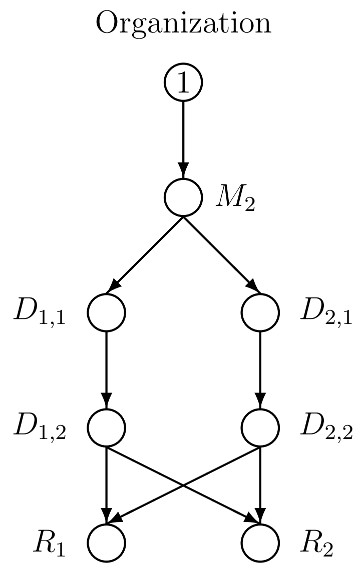

Figure 6: Optimal Supply Chain Network Topology for the Multiproduct Vaccine Manufacturer Under the High Fixed Capacity Cost for Plant 1

3.1.1 Sensitivity Analysis

We then asked the following question: At what fixed cost associated with the investment capacity on link 1, corresponding to the first manufacturing plant, would the total cost minimizing optimal solution be such that the capacity $u_1^* = 0.00$? Hence, the first manufacturing plant would not be constructed and the manufacturing of both vaccines would take place exclusively at manufacturing plant 2. Please refer to Table 4 for the original $\hat{\pi}_a$; $a = 1, \ldots, 12$, functions. Specifically, we varied the fixed unit cost term associated with $\hat{\pi}_1$, which was originally equal to 100, until we observed, computationally, that the optimal solution was such that $u_1^* = 0.00$, which means that there is no capacity on link 1 and, hence, link 1, which corresponds to plant 1, should not be constructed. We found that when the fixed term was equal to 20,000 (or greater) then $u_1^* = 0.00$, and also then we had that both u_3^* and u_4^* were also equal to 0.00. Therefore, since the first manufacturing plant had zero capacity, it did not produce any vaccines, and there was no need to invest in the transportation/shipment capacities associated with transportation out of that possible plant.

The final supply chain network topology, consequently, in this case, which reflects the optimal design, was as depicted in Figure 6.

Table 6: Link Capacities (Original) for Redesign Problem Example 4

Link a	$\bar{u}_a$
1	400.00
2	500.00
3	200.00
4	200.00
5	300.00
6	300.00
7	500.00
8	400.00
9	200.00
10	200.00
11	100.00
12	300.00

3.2 Redesign Problem – Example 4

In Example 4, we considered the following situation. We assumed that the supply chain network link capacities, $\bar{u}_a$; $a = 1, \dots, 12$, were as in Table 6. Note that these values that are lower than the optimal values, the u_a^*s, for Example 3, except for $\bar{u}_5$, which is higher than u_5^*, and the same for link 6, where $\bar{u}_6$ is higher than u_6^*. We assumed that the demands were as in Example 3 as was the remainder of the input data.

The computed optimal solution for Example 4 is given in Table 7. The total cost (cf. (6)) at the optimal solution was: 3,217,957.50, which is significantly lower than that encountered in the design problem Example 3, since there were positive initial capacities on all the links.

With some existing positive capacities on all the links, we see that although the production quantities of vaccine 2 produced at the two plants do not change much relative to the optimal amounts for Example 3, there is now a substantial decrease in production of vaccine 1 at the first manufacturing plant and a corresponding increase in the second plant. There is also a shift in storage of vaccine 1 from the second distribution center to the first one. Also, since there is sufficient capacity already on link 6 there is no need to increase that link's capacity and, therefore, $u_6^* = 0.00$, as reported in Table 7. Similarly, only a small investment is needed for link 5.

Table 7: Optimal Multiproduct Flows, Enhanced Link Capacities, and Lagrange Multipliers for Redesign Problem Example 4

Link a	f_a^{1*}	f_a^{2*}	u_a^*	λ_a^*
1	89.38	391.00	80.37	903.70
2	210.62	309.00	19.63	237.00
3	43.30	190.40	33.70	87.39
4	46.08	200.60	46.68	103.36
5	141.16	159.61	0.76	12.29
6	69.47	149.39	0.00	0.00
7	184.45	350.01	34.46	385.65
8	115.55	349.99	65.54	709.84
9	49.48	196.62	46.10	102.21
10	134.97	153.39	88.35	103.35
11	50.52	103.38	53.90	127.79
12	65.03	246.61	11.65	21.65

4. Summary and Conclusions

In this paper, we developed a multiproduct supply chain network design model with applications to humanitarian healthcare applications. The variables in the model are supply chain network link capacities as well as the healthcare product flows associated with the supply chain activities of production, transportation/shipment, and storage/distribution. We demonstrated that the optimization problem underlying this multiproduct supply chain network design problem can be formulated and solved as a variational inequality problem, with nice features for computational purposes. Numerical examples, including a case study, were presented in order to demonstrate the flexibility and generality of the modeling framework, which allows for both design and redesign problems to be handled in a unified manner. When the capacities are sufficient to meet the demands and no enhancement of capacity is needed, the model collapses to a humanitarian healthcare operations optimization model.

The solution of the model yields the optimal investment capacities and product flows on the links at minimal total cost, with the demand for the various products being satisfied at the various demand points. With this information, a firm or organization involved in the production and distribution of healthcare products can identify the total cost associated with the provision of its products. The framework can handle both the design and the redesign problem with the latter being especially relevant for healthcare, since, for example, vaccine manufacturers may have to regear from year to year depending on the forecasted flu viruses; the same holds for the manufacture of associated medicines.

Given the paucity of multiproduct supply chain network mathematical models and associated methodologies in the literature that can handle both link capacities and product flows as decision variables, along with nonlinear cost functions to capture congestion, as well as risk, we hope that, with this paper, we have made a contribution of specific relevance to humanitarian healthcare supply chains. Possible extensions might include the consideration of demand uncertainty as well as cost uncertainty (see, for example, Nagurney et al. (2005)) and the explicit incorporation of perishability factors for particular healthcare products.

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