Freight Service Provision for Disaster Relief: A Competitive Network Model with Computations

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Abstract: In this paper, we develop a competitive freight service provision network model for disaster relief. A humanitarian relief organization is interested in determining its most cost-effective deliveries of needed supplies in a crisis setting. Multiple freight service providers are engaged in competition to acquire the business of carrying the supplies in the amounts desired to the destinations. We describe the objective functions faced by the various decision-makers and their underlying constraints, and present the optimality conditions. We then define the freight service provision network equilibrium for disaster relief and formulate it as a variational inequality problem. We provide qualitative results for the equilibrium product shipment pattern in terms of existence and uniqueness. For completeness, we also construct a new cooperative system-optimization model and discuss the price of anarchy relating the two models, along with additional theoretical results. In addition, we propose algorithmic schemes that take advantage of the underlying network structure of the problem. We present a case study on the shipment of personal protection equipment (PPE) supplies in the context of the Ebola humanitarian healthcare crisis in west Africa. The computational results in this paper yield insights on the equilibrium shipment and price patterns in the freight service provision sector for humanitarian operations in terms of enhanced or reduced competition, as well as increases in demand.

Keywords: freight services, transportation, disaster relief, humanitarian logistics, networks, variational inequalities, price of anarchy, Ebola, healthcare

1. Introduction

Without transportation, no needed supplies can be delivered to victims in the case of humanitarian crises or post disasters. Hence, effective transportation is essential to humanitarian operations and disaster relief. At the same time, it is well-recognized that costs associated with transportation are second only to personnel for humanitarian organizations (see Pedraza Martinez, Stapleton, and Van Wassenhove (2011)).

In this paper, we explore freight service provision, with a focus on disaster relief, in order to gain insights in terms of pricing and costs incurred by a disaster relief (humanitarian) organization. Although certain large humanitarian organizations have their own fleets and are responsible for the management thereof, many smaller humanitarian organizations must make use of freight service providers such as UPS, DHL, and/or others for delivery of the supplies to points of demand post a disaster or a humanitarian crisis. Such organizations must be transparent to their constituents, including donors, in ensuring that the donated funds have been utilized in a cost-effective manner. Moreover, as noted in Kumar (2011), utilizing industry experts in logistics, shipping, and supply chain management, allows for better management and coordination of relief efforts.

Recent research on humanitarian logistics has begun to increasingly explore important issues surrounding transportation for disaster relief. Nevertheless, the majority of studies have emphasized centralized decision-making. We are unaware of any research that captures competition associated with freight service provision in this application domain. The survival of relief organizations, especially smaller ones, some of which are established after disasters and humanitarian crises, is critically dependent on wise budgeting and financial management and, hence, the effective use of freight services is essential. Moreover, an organization's very reputation, and its relationships with donors and benefactors, depend on its appropriate allocation of its financial resources. Since the number of disasters is growing, as well as the number of people affected them (see Nagurney and Qiang (2009)), plus climate change is also affecting the movement of people as well as diseases (cf. Knobler et al. (2006)), effective analytical tools for all phases of disaster management are needed.

Transportation in disaster relief settings and humanitarian operations has been addressed in the research literature from different perspectives, including evacuation (see, e.g., Sheffi, Mahmassani, and Powell (1982), Sherali, Carter, and Hobelka (1991), Barbarosoglu, Ozdamar, and Cevik (2002), Regnier (2008), Miller-Hooks and Sorrel (2008), Saadatseresht, Mansourian, and Taleal (2009), Vogiatzis, Walteros, and Pardalos (2013), Na and Banerjee (2015), Vogiatzis and Pardalos (2016)), the distribution of relief supplies, including last mile issues (Sheu (2007), Yi and Kumar (2007), Barbarosoglu and Arda (2004), Tzeng, Cheng, and Huang (2007), Balcik, Beamon, and Smilowitz (2008), Mete and Zabinsky (2010), Vitoriano et al. (2011), Rottkemper, Fischer, and Blecken (2012), Huang, Smilowitz, and Balcik (2012)), in the context of supply chains (Van Wassenhove (2006), Falasca and Zobel (2011), Nagurney, Yu, and Qiang (2012), Qiang and Nagurney (2012), Nagurney and Masoumi (2012), Nagurney, Masoumi, and Yu (2015), Nagurney and Nagurney (2016)), in fleet management (see Pedraza Martinez, Stapleton, and Van Wassenhove (2010) and the references therein), in cooperative settings to assess synergy (see Nagurney and Qiang (2012)), and in donor collections (Lodree, Carter, and Barbee (2016)). Balcik and Ak (2014) present a stochastic programming model for supplier selection in terms of framework agreements for humanitarian relief. Such agreements are long term ones. The suppliers provide the needed relief items, purchased by the organization, and also are responsible for the transportation. Our framework, in contrast, builds on the research in supply chain network equilibrium, in which there is competition among decision-makers in each tier, originating with the work of Nagurney, Dong, and Zhang (2002), and we explicitly determine the equilibrium prices. Such research in the freight context has recently examined price and quality competition among manufacturers and freight service providers (see Nagurney et al. (2015)) and time-based supply chain network competition (see Nagurney et al. (2014)). Moreover, the models developed in this paper emphasize the humanitarian sector and the quantities demanded are no longer elastic and price-sensitive but, rather, fixed, since we are dealing with life or death situations and the needed product supplies must be delivered.

The paper is organized as follows. In Section 2, we present the new competitive model of freight service provision for disaster relief and identify both the disaster relief organization optimization problem and those of the competing freight service providers. We define the governing equilibrium conditions and formulate them as a variational inequality problem. We present several small examples, for illustrative purposes, and to explore the impacts of increased or decreased freight service competition on shipments and prices. We provide qualitative properties, notably, in terms of existence and uniqueness results for the equilibrium product shipment pattern. Also, we detail an algorithm, the exact equilibration algorithm (cf. Dafermos and Sparrow (1969), Nagurney (1999)), which yields the exact solution in the case of quadratic, separable costs faced by the organization and the freight service providers when there is a single demand point, by exploiting the special network structure.

In Section 3, for completeness, we present a new, cooperative system-optimized freight service provision network model in which the total costs associated with the humanitarian operation of delivering the needed supplies in a timely manner is minimized. We also give the price of anarchy (cf. Roughgarden (2005)) relating the total costs for the two models. We then show that, in the case of separable cost functions faced by the freight service providers, the solutions to both the competitive, noncooperative model and that of the cooperative, system-optimized, one, coincide.

In Section 4, we detail a path-based projection algorithm, due to Bertsekas and Gafni (1982), which, because of the network structure of our competitive freight service provision problem for disaster relief, yields an effective computation scheme, which we embed with the exact equilibration algorithm. In Section 5, we apply the algorithmic scheme to a case study on the shipment of protective personal equipment to west Africa to assist healthcare personnel in fighting Ebola. More than 11,000 people in west Africa died because of Ebola in the most severe outbreak ever recorded (Ap (2015)). As noted in Fischer, Hynes, and Perl (2014), the Ebola outbreak also surpassed all previous ones in terms of the number of healthcare workers that were infected. One of the contributing factors, as discussed therein, was the insufficient supply of personal protective equipment (PPE). Such equipment consists of gloves, face masks, and gowns, which should be impermeable to the Ebola viruses. Insufficient amounts of PPE requires that healthcare workers choose between providing care with increased risk or not treating patients with this horrible disease. We report the equilibrium shipments, prices, and the costs incurred by the disaster relief organization, and the profits of the freight service providers.

In Section 6, we summarize our results, and present our conclusions.

2. The Competitive Freight Service Provision Model for Disaster Relief

We consider a disaster relief (humanitarian) organization, which is seeking to determine the freight service providers to utilize for transport of the relief supplies post a disaster to demand points. The relief product can correspond to water, food, clothing, blankets, shelter items, medicines, and, as our case study in Section 5 details, personal protective equipment that is needed by medical professionals treating the victims post a humanitarian healthcare crisis. The disaster relief organization seeks to minimize the total cost associated with such operations since it must act in a financially responsible manner with its donors. There are multiple freight service providers that are seeking business from the relief organization and they compete for the shipments (and payments) from the organization. Each freight service provider seeks to maximize its profits associated with the transport and ultimate delivery.

The model can be used for both local relief supply deliveries as well as for international relief. It is assumed that the freight service providers are responsible for the final delivery to the points of distribution. Also, the freight service provider deals with the consignees and any associated paperwork at the relief destinations that may be required. For example, the United Nations High Commissioner for Refugees (UNHCR) (2015) report notes Global Freight Agreements that govern most of the transport arrangements from vendors and from the UNHCR stockpiles to the final destination. The organization, typically, deals with two freight service providers in the case of air shipments. The UNOPS (2014) manual emphasizes that, when including freight in the specifications, evaluation must be made on the total cost, delivered to final destination, taking into consideration the contracting separately for the freight. In addition, Oxfam (see Hoxtell, Norze, and Teicke (2015)) regularly subcontracts companies to provide products and services, such as the transportation of relief supplies. As also noted therein, the services that are regularly subcontracted by humanitarian organizations include logistics services, such as the transportation of supplies and equipment. Today, there exist freight companies in the United States that specialize in emergency response freight strategies for the most challenging transportation scenarios (cf. Apex (2015)). Indeed, as emphasized by Hoxtell, Norze, and Teicke (2015), two basic forms of business engagement exist in the framework of humanitarian response and disaster risk management: commercial engagement, in which companies are paid for their products and services, as in the model we consider here, and non-commercial engagement in which companies partner with humanitarian organizations for reasons other than direct payment.

Relief organizations, such as the International Federation of Red Cross and Red Crescent Societies (IFRC), may often have specific policies in terms of transportation of relief supplies, depending upon whether they have them in stock, in which case the transportation to the final port of entry would take place from such locations (cf. International Federation of Red Cross and Red Crescent Societies (2016)).

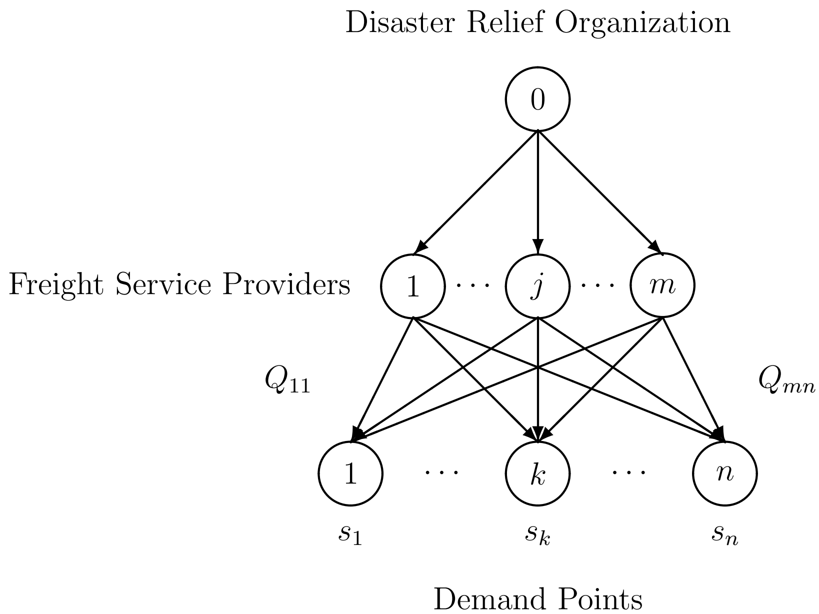

Figure 1: Network Structure of the Competitive Freight Service Provision Model for Disaster Relief

The network structure of the model is depicted in Figure 1. Specifically, the organization is denoted by node 0. The m freight service providers, who are engaged in competition, are denoted, by nodes: $1, 2, \ldots, m$, respectively, with a typical freight service provider given by j. The demand points at which the supplies of the disaster relief product will be distributed are denoted by nodes: $1, 2, \ldots, n$, with a typical disaster relief distribution point given by k.

We first describe the behavior of the disaster relief organization and then that of the freight service providers. We then state the freight service provision network equilibrium conditions for disaster relief and derive the variational inequality formulation. Qualitative properties of the equilibrium pattern are, subsequently, provided, along with examples for illustrative purposes, as well as a special-purpose algorithm.

2.1 Behavior of the Disaster Relief Organization

The disaster relief organization has determined the amounts: $s_1, s_2, \ldots, s_m$ of the relief item that are needed at the respective demand points, which it is capable of supplying, and which it has stored in a central location. Let Q_{jk} denote the amount of the product that it contracts with freight service provider j to have delivered to demand point k. We group the product shipments of each freight service provider j into the vector $Q_j \in R^n_+$ and then we group all the freight service providers' shipments into the vector $Q \in R_+^{mn}$. All vectors are assumed to be column vectors. The per unit price that freight service provider j charges the organization for delivery to k is denoted by ρ^*_{jk}. The organization is faced with a total cost $\hat{c}_j$ associated with transacting with freight service provider j. This cost includes the cost associated with handling the product until pickup by provider j and interacting with provider j. For example, if the organization has done business in the past with a specific freight service provide then it may have a stronger relationship with it and more trust and the cost may be lower. On the other hand, if a freight service provider requires the organization to transport its relief supplies to another location for freight service processing then this cost would include such expenses. Hence, the total cost $\hat{c}_j$; $j = 1, \ldots, m$ includes all the costs associated with contracting with a respective freight service provider. The freight service providers, as we discuss in Section 2.2, are responsible for delivering the disaster relief products in a timely manner and cost and price accordingly.

The optimization problem faced by the disaster relief organization is as follows.

$$\text{Minimize} \quad \sum_{j=1}^{m} \sum_{k=1}^{n} \rho^*_{jk} Q_{jk} + \sum_{j=1}^{m} \hat{c}_j (\sum_{k=1}^{n} Q_{jk}) \tag{1}$$

subject to:

$$\sum_{j=1}^{m} Q_{jk} = s_k, \quad k = 1, \ldots, n, \tag{2}$$

$$Q_{jk} \geq 0, \quad k = 1, \ldots, n. \tag{3}$$

The first term preceding the plus sign in the objective function (1) corresponds to the payout to the freight service providers whereas the term following the plus sign corresponds to the total costs associated with transacting with the freight service providers. Equation (2) guarantees that the relief supplies are delivered to the points of demand. We define the feasible set K where $K \equiv \{Q | Q \geq 0 \, \text{and satisfies} \, (2)\}$.

We note that the total cost functions $\hat{c}_j$; $j = 1, \ldots, m$, can also include the cost of purchasing the needed supplies, in addition to the freight service provision transaction costs. Such costs would be encumbered if the relief organization does not have the supplies in stock.

We assume that the total cost functions $\hat{c}_j$; $j = 1, \ldots, m$, are continuously differentiable and convex. Under these assumptions, and the fact that K is convex, we know that a solution to the above optimization problem coincides with a solution to the variational inequality problem: determine $Q^* \in K$, such that

$$\sum_{j=1}^{m}\sum_{k=1}^{n}\left[\frac{\partial \hat{c}_j(\sum_{k=1}^{n} Q^*_{jk})}{\partial Q_{jk}} + \rho^*_{jk}\right] \times \left[Q_{jk} - Q^*_{jk}\right] \geq 0, \quad \forall Q \in K. \tag{4}$$

This result follows from the standard theory of variational inequalities (cf. Kinderlehrer and Stampacchia (1980) and Nagurney (1999)).

2.2 Behavior of the Freight Service Providers

As mentioned earlier, the freight service providers are profit-maximizers since they need to cover their costs in order to stay in business. The cost associated with freight service provider j delivering the relief items to demand point k is denoted by c_{jk}, where here we assume, for the sake of generality, and in order to effectively capture competition, that

$$c_{jk} = c_{jk}(Q), \quad j = 1, \ldots, m, \tag{5}$$

with the freight service provider cost functions being assumed to be continuously differentiable and convex. Note that, according to (5), the cost faced by provider j in delivering the relief items to demand point k depends not only on the volume of the disaster relief items that it delivers to the demand points but also on the amounts delivered by the other freight service providers. We expect these functions to be nonlinear in order to capture congestion that may occur at delivery points, which is a recognized problem in disaster relief situations. For example, in the case of the devastating earthquake that hit Nepal on April 25, 2015, according to Woods (2015), quoting Justin Lancaster, speaking on behalf of Air Charter Services (ACS), relief flights had been taking "up to four days to be processed" due to the congestion. "The logistical challenges trying to help victims of the Nepalese earthquake were some of the most difficult that we have ever had to overcome." In addition, such nonlinear cost functions can also capture competition for resources associated with freight deliveries in compromised settings as may occur following disasters. Moreover, as mentioned earlier, the deliveries are contracted to occur in a timely manner. For example, water and food may be needed within 48 to 72 hours.

Finally, such functions can also incorporate explicit capacities associated with how much can be transported by a freight service provider to a destination as is standard in many transportation network models (see, e.g., Nagurney and Qiang (2009)). Indeed, in our modeling framework, the relief organization has the flexibility of contracting with multiple freight service providers since the volume of shipments may necessitate this.

The optimization problem faced by freight service provider j; $j = 1, \ldots, m$, is given by:

$$\text{Maximize} \quad \sum_{k=1}^{n} \rho_{jk}^* Q_{jk} - \sum_{k=1}^{n} c_{jk}(Q) \tag{6}$$

subject to:

$$Q_{jk} \geq 0, \quad k = 1, \ldots, n. \tag{7}$$

Since we assume that the freight service providers compete noncooperatively among one another for the product shipments, the optimality conditions of all freight service providers must satisfy the variational inequality problem (cf. Gabay and Moulin (1980), Nagurney (1999, 2006)): determine $Q^* \in R_+^{mn}$ such that:

$$\sum_{j=1}^{m} \sum_{k=1}^{n} \left[\sum_{l=1}^{n} \frac{\partial c_{jl}(Q^*)}{\partial Q_{jk}} - \rho_{jk}^* \right] \times \left[Q_{jk} - Q_{jk}^* \right] \geq 0, \quad \forall Q \in R_+^{mn}. \tag{8}$$

We are now ready to state the freight service provision network equilibrium conditions for disaster relief.

Definition 1: Freight Service Provision Network Equilibrium for Disaster Relief

A freight service provision network equilibrium for disaster relief is said to be established if the disaster relief product flows between the two tiers of decision-makers coincide and the product flows and prices satisfy the sum of variational inequalities (4) and (8).

Note that, according to Definition 1, the disaster relief organization as well as the freight service providers must agree on the amounts of the product shipments that they deliver to the demand points. This agreement is accomplished through the prices ρ_{jk}^*; $j = 1, \ldots, m$; $k = 1, \ldots, n$. After presenting the variational inequality formulation of the above equilibrium conditions we will demonstrate how to recover the prices.

Theorem 1: Variational Inequality Formulation of Freight Service Provision Network Equilibrium for Disaster Relief

A disaster shipment pattern $Q^* \in K$, is a freight service provision network equilibrium for disaster relief if and only if it satisfies the variational inequality problem:

$$\sum_{j=1}^{m} \sum_{k=1}^{n} \left[\frac{\partial \hat{c}_j(\sum_{k=1}^{n} Q_{jk}^*)}{\partial Q_{jk}} + \sum_{l=1}^{n} \frac{\partial c_{jl}(Q^*)}{\partial Q_{jk}} \right] \times \left[Q_{jk} - Q_{jk}^* \right] \geq 0, \quad \forall Q \in K. \tag{9}$$

Proof: We first establish necessity, that is, if $Q^* \in K$ is an equilibrium according to Definition 1 then it also satisfies variational inequality (9). Indeed, summation of (4) and (8) yields variational inequality (9) with the flows coinciding.

We now establish sufficiency. We rewrite variational inequality (9) as:

$$\sum_{j=1}^{m}\sum_{k=1}^{n}\left[\frac{\partial \hat{c}_j(\sum_{k=1}^{n} Q^*_{jk})}{\partial Q_{jk}} + \sum_{l=1}^{n}\frac{\partial c_{jl}(Q^*)}{\partial Q_{jk}} - \rho^*_{jk} + \rho^*_{jk}\right] \times \left[Q_{jk} - Q^*_{jk}\right] \geq 0, \quad \forall Q \in K. \quad (10)$$

But (10) may be expressed as:

$$\sum_{j=1}^{m}\sum_{k=1}^{n}\left[\frac{\partial \hat{c}_j(\sum_{k=1}^{n} Q^*_{jk})}{\partial Q_{jk}} + \rho^*_{jk}\right] \times \left[Q_{jk} - Q^*_{jk}\right]$$

$$+\sum_{j=1}^{m}\sum_{k=1}^{n}\left[\sum_{l=1}^{n}\frac{\partial c_{jk}(Q^*)}{\partial Q_{jk}} - \rho^*_{jk}\right] \times \left[Q_{jk} - Q^*_{jk}\right] \geq 0, \quad \forall Q \in K. \quad (11)$$

(11) corresponds to Definition 1 holding for the price and shipment pattern $Q^* \in K$. □

Note that in order to recover the equilibrium prices ρ^*_{jk}, $\forall j, k$, one just sets, according to (8): $\rho^*_{jk} = \sum_{l=1}^{n} \frac{\partial c_{jl}(Q^*)}{\partial Q_{jk}}$, $\forall j, k$. By setting the freight delivery prices thus, variational inequality (8) holds, so each freight service provider has optimized his profits. In addition, rewriting (11) (which coincides with variational inequality (9)), we then have that:

$$\sum_{j=1}^{m}\sum_{k=1}^{n}\left[\frac{\partial \hat{c}_j(\sum_{k=1}^{n} Q^*_{jk})}{\partial Q_{jk}} + \rho^*_{jk}\right] \times \left[Q_{jk} - Q^*_{jk}\right]$$

$$-\sum_{j=1}^{m}\sum_{k=1}^{n}\left[\sum_{l=1}^{n}\frac{\partial c_{jk}(Q^*)}{\partial Q_{jk}} - \rho^*_{jk}\right] \times \left[Q_{jk} - Q^*_{jk}\right] = 0, \quad \forall Q \in K.$$

Hence, we can conclude that variational inequality (4) also holds, under the pricing scheme, and, therefore, the disaster relief organization has minimized its total costs with the equilibrium product shipment pattern.

We now put variational inequality (9) into standard form (cf. Nagurney (1999)): determine $X^* \in \mathcal{K}$, such that

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

where $F(X)$ is a N-dimensional vector which is a continuous function from $\mathcal{K}$ to R^N, X is an N-dimensional vector, $\mathcal{K}$ is closed and convex, and $\langle \cdot, \cdot \rangle$ denotes the inner product in N-dimensional Euclidean space. We define $\mathcal{K} \equiv K$, $X \equiv Q$, and component F_{jk} of $F(X)$ as:

$F_{jk}(X) \equiv \frac{\partial \hat{c}_j(\sum_{k=1}^n Q_{jk})}{\partial Q_{jk}} + \sum_{l=1}^n \frac{\partial c_{jl}(Q)}{\partial Q_{jk}}$; $j = 1, \ldots, m$; $k = 1, \ldots, n$. Then variational inequality (9) takes on the standard form (12).

2.3 Qualitative Properties of the Freight Equilibrium Shipment Pattern for Disaster Relief

We now turn to the examination of qualitative properties of the equilibrium pattern corresponding to the solution Q^* of variational inequality (9).

Since the feasible set K is closed and bounded, that is, it is compact, we know from the classical theory of variational inequalities that a solution to (9) is guaranteed to exist since the function $F(X)$ is continuous under our imposed assumptions that the various cost functions are continuously differentiable. Hence, the following result is immediate.

Theorem 2: Existence of a Freight Service Provision Equilibrium Shipment Pattern

A solution $X^* \in K$ to variational inequality (9) is guaranteed to exist.

Proof: This follows from the classical theory of variational inequalities (see Kinderlehrer and Stampacchia (1980) and Nagurney (1999)). □

In addition, under the assumption of strict monotonicity of $F(X)$, we have the following result, which also comes from classical variational inequality theory.

Theorem 3: Uniqueness of a Freight Service Provision Equilibrium Pattarn

If $F(X)$ is strictly monotone, that is,

$$\langle F(X^1) - F(X^2), X^1 - X^2 \rangle > 0, \quad \forall X^1, X^2 \in \mathcal{K}, \quad X^1 \neq X^2, \tag{13}$$

then X^* satisfying (9) is unique.

We know that if the Jacobian of $F(X)$, $\nabla F(X)$, is positive definite over $\mathcal{K}$, then $F(X)$ is strictly monotone.

2.4 An Illustrative Example and Variant

We now present an illustrative example and variant. The problem consists of two freight service providers and a single demand point for disaster relief as depicted in Figure 2. The data are as follows. The total costs faced by the disaster relief organization in transacting with the two freight service providers are: $\hat{c}_1(Q_{11}) = Q_{11}^2$ and $\hat{c}_2(Q_{21}) = Q_{21}^2$. The cost faced by freight service provider 1 is: $c_{11}(Q_{11}) = 5Q_{11}^2$ and that faced by freight service provider 2 is: $c_{21}(Q_{21}) = 3Q_{21}^2$.

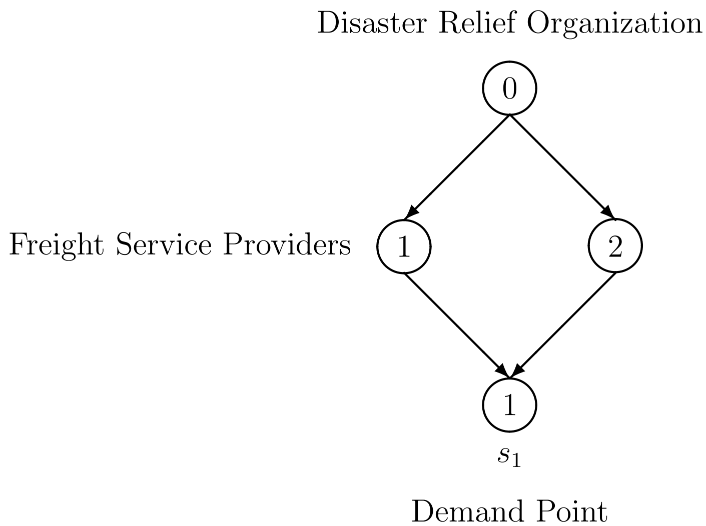

Figure 2: Network Topology for the Illustrative Example

The organization wishes to have 100 units of the disaster relief item delivered to demand point 1; hence, $s_1 = 100$.

Variational inequality (9) takes on the following form for this problem: determine $Q^* = (Q_{11}^*, Q_{21}^*) \in \mathcal{K}$, where $\mathcal{K} \equiv \{Q_{11} \geq 0, Q_{21} \geq 0 \,\text{and}\, (2)\,\text{holds}\}$ such that:

$$[12Q_{11}^*] \times [Q_{11} - Q_{11}^*] + [8Q_{21}^*] \times [Q_{21} - Q_{21}^*] \geq 0, \quad \forall Q \in \mathcal{K}. \tag{14}$$

It is easy to see (cf. Nagurney (1999)) that (14) can be solved (indeed, variational inequality (14) is, in fact, equivalent to the solution of an optimization problem since for this problem $\nabla F(X)$ is symmetric) as a system of equations:

$$12Q_{11}^* = 8Q_{21}^*$$

$$Q_{11}^* + Q_{21}^* = 100.$$

Clearly, $Q_{11}^* = 40$ and $Q_{21}^* = 60$ is the solution.

The prices, as discussed above, are recovered as: $\rho_{11}^* = 400$, since $\rho_{11}^* = \frac{\partial c_{11}(Q_{11}^*)}{\partial Q_{11}} = 10Q_{11}^* = 10(40) = 400$, and $\rho_{21}^* = 360$, since $\rho_{21}^* = \frac{\partial c_{21}(Q_{21}^*)}{\partial Q_{21}} = 6Q_{21}^* = 6(60) = 360$. This solution, which is unique, corresponds to the organization encumbering costs of 42,800 for delivery of the disaster relief items with freight service provider 1 having a profit of 8,000 and freight service provider a profit of 10,800.

We now consider the following scenario. Suppose that only freight service provider 1 is available to offer its services. The relief organization still must have the 100 units delivered. Clearly, $Q^*_{11} = 100$ with the price charged by the freight service provider 1 being: $1,000$. The organization now, in the absence of competition, incurs a cost of $110,000$ since the price $\rho^*_{11} = 1,000$ with the freight service provider 1 obtaining a profit of 50,000. These simple examples demonstrate the importance of competition in freight service provision in disaster relief.

2.5 A Special-Purpose Algorithm

We now consider the freight service provision scenario depicted in Figure 3 in which the relief organization is examining m freight service providers for delivery of its relief item to a single demand point. We present a special-purpose algorithm for the solution of the freight service provision problem for such networks where the total cost functions of the organization and those of the freight service providers are quadratic and separable. Such a scheme can be embedded in the more general algorithm that we outline in Section 4 for the solution of the subproblems.

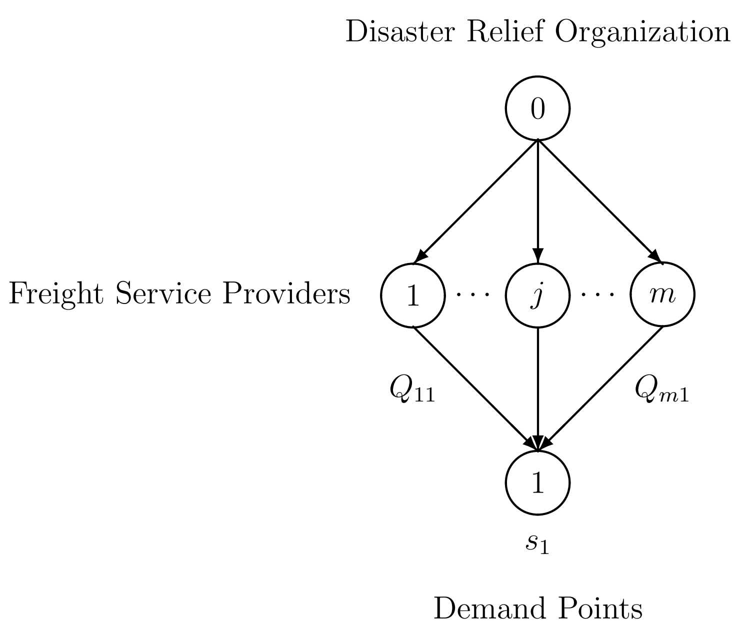

Figure 3: Network Topology for Special-Purpose Algorithm

Specifically, we assume that the disaster relief organization has total cost functions of the form:

$$\hat{c}_j = a_j Q_{j1}^2 + b_j Q_{j1} + d_j, \quad j = 1, \ldots, m, \tag{15}$$

and that the freight service providers have total cost functions given by:

$$c_{j1} = e_j Q_{j1}^2 + f_j Q_{j1} + h_j, \quad j = 1, \ldots, m, \tag{16}$$

since there is only a single demand point 1.

It is easy to see that, in this special case, variational inequality (9) then simplifies to: determine $Q^* \in \mathcal{K}$, such that:

$$\sum_{j=1}^{m} \left[\frac{\partial \hat{c}_j(Q_{j1}^*)}{\partial Q_{j1}} + \frac{\partial c_{j1}(Q_{j1}^*)}{\partial Q_{j1}} \right] \times \left[Q_{j1} - Q_{j1}^* \right] \geq 0, \quad \forall Q \in \mathcal{K}, \tag{17}$$

which, by use of (15) and (16), reduces to:

$$\sum_{j=1}^{m} \left[2a_j Q_{j1}^* + b_j + 2e_j Q_{j1}^* + f_j \right] \times \left[Q_{j1} - Q_{j1}^* \right] \geq 0, \quad \forall Q \in \mathcal{K}, \tag{18}$$

or

$$\sum_{j=1}^{m} \left[(2a_j + 2e_j) Q_{j1}^* + (b_j + f_j) \right] \times \left[Q_{j1} - Q_{j1}^* \right] \geq 0, \quad \forall Q \in \mathcal{K}. \tag{19}$$

We define

$$g_j \equiv (2a_j + 2e_j); \quad \jmath = 1, \ldots, m$$

and

$$h_j \equiv (b_j + f_j); \quad j = 1, \ldots, m.$$

Variational inequality (19) is then equivalent to the optimization problem:

$$\text{Minimize} \quad \sum_{j=1}^{m} \frac{1}{2} g_j Q_{j1}^2 + \sum_{j=1}^{m} h_j Q_{j1}, \tag{20}$$

subject to:

$$Q \in \mathcal{K}. \tag{21}$$

Interestingly, the above problem has a traffic network equilibrium representation (cf. Nagurney (1999)) and interpretation. Indeed, it corresponds to the problem on the network topology given by Figure 4 in which the "user" link cost functions on a link α_j, denoted by $\tilde{c}_{\alpha_j}$, are given by:

$$\tilde{c}_{\alpha_j}(Q_{\alpha_{j1}}) = g_{\alpha_j} Q_{\alpha_{j1}} + h_{\alpha_j}; \quad j = 1, \ldots, m$$

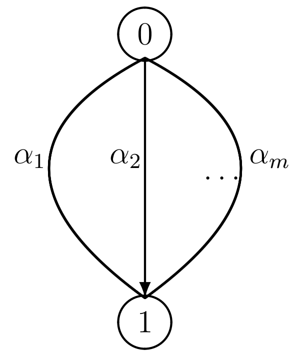

Figure 4: Isomorphic Traffic Network Equilibrium Representation

with the "travel" demand $d_{01} = s_1$ and with $g_{\alpha_j} = g_j$, $h_{\alpha_j} = h_j$, and $Q_{\alpha_{j1}} = Q_{j1}$.

This problem can be easily solved using the Exact Equilibration Algorithm of Dafermos and Sparrow (1969); see also Nagurney (1999), which we state below for easy reference and completeness.

Exact Equilibration Algorithm for the Specially Structured Freight Service Provision Network Problem

[**Step 1**:] Sort the h_{α_i} parameters in non-decreasing order and relabel accordingly. We assume, henceforth, that the links are relabled.

Set iteration count $r = 1$ and $h_{\alpha_{m+1}} = \infty$.

[**Step 2**:] Compute

$$\lambda_{01}^r = \frac{d_{01} + \sum_{i=1}^{r} \frac{h_{\alpha_i}}{g_{\alpha_i}}}{\sum_{i=1}^{r} \frac{1}{g_{\alpha_i}}}.$$

[**Step 3**:] Check
If

$$h_{\alpha_r} < \lambda_{01}^r \le h_{\alpha_{r+1}},$$

then STOP.

Set the critical $s = r$;

$$Q^*_{\alpha_{r1}} = \frac{\lambda^r_{01} - h_{\alpha_r}}{g_{\alpha_r}}; \quad r = 1, ..., s;$$

$$Q^*_{\alpha_{r1}} = 0; \qquad r = s+1, ..., m.$$

Else, set $r = r + 1$ and go to Step 2.

The Exact Equilibration Algorithm is guaranteed to converge to the solution in a finite number of steps.

We now apply the algorithm to an example.

We return to the illustrative example of Section 2.4 but we now add a new freight service provider 3 to see the impacts of enhanced competition on the product shipments and equilibrium prices. The data for the first two freight service providers remain as in the illustrative example but now the disaster relief organization faces a total cost of $\hat{c}_3 = Q^2_{31}$ in dealing with freight service provider 3. That freight service provider, in turn, is faced with a cost of $c_{31} = 3Q^2_{31}$. Note that, in applying the Exact Equilibration Algorithm, we have that: $g_{\alpha_1} = 12$, $g_{\alpha_2} = 8$, and also $g_{\alpha_3} = 8$, with $h_{\alpha_i} = 0$ for $i = 1, 2, 3$. The critical $s = 3$ with $\lambda^3_{01} = 300$, which results in: $Q^*_{11} = 25$ and $Q^*_{21} = Q^*_{31} = 37.5$. The new equilibrium prices are: $\rho^*_{11} = 250$ and $\rho^*_{21} = \rho^*_{31} = 225$. The disaster relief organization, hence, has a total cost now of $26,562.50$. Freight service provider 1 earns a profit of 5,625. Freight service providers 2 and 3 each earn a profit of $7,031.25$.

Hence, as compared to the example with only two freight service providers, the disaster relief organization, under enhanced competition among freight service providers, has a reduction in total cost of 37%, whereas freight service provider now experiences a drop in profit of 28% and freight service provider 2 a drop in profit of 34%.

3. Relationship to a Cooperative System-Optimized Model

We now identify the relationship to the competitive freight service provision network model in Section 2 with that of a cooperative, system-optimized model that we introduce in this section. Specifically, we now assume that the costs in the entire freight service provision network are minimized and that the freight service providers no longer compete for delivery of the disaster relief items to the points of demand.

Hence, in the cooperative, system-optimized model, the problem becomes that of minimizing the total costs with the costs consisting of those of the disaster relief organization and those of the freight service providers.

Thus, the cooperative, system-optimized model in which the costs to society are minimized is given by:

$$\text{Minimize} \quad \sum_{j=1}^{m} \hat{c}_j(\sum_{k=1}^{n} Q_{jk}) + \sum_{j=1}^{m}\sum_{k=1}^{n} c_{jk}(Q) \tag{22}$$

subject to (21).

Under the previously imposed assumptions on the cost functions, we know that an optimal solution to (22), subject to (21), coincides with the solution to the variational inequality given below. This follows from the standard theory of variational inequalities (see Nagurney (1999)) since the objective function in (22) is convex and continuously differentiable and the feasible set $\mathcal{K}$ is convex.

Theorem 4: Variational Inequality Formulation of the Cooperative System-Optimized Freight Service Provision Network Model

A solution $Q^* \in \mathcal{K}$ is an optimal solution to the above cooperative, system-optimized freight service provision network model for disaster relief if and only if it also satisfies the variational inequality:

$$\sum_{j=1}^{m}\sum_{k=1}^{n}\left[\frac{\partial \hat{c}_j(\sum_{k=1}^{n} Q^*_{jk})}{\partial Q_{jk}} + \sum_{h=1}^{m}\sum_{l=1}^{n}\frac{\partial c_{hl}(Q^*)}{\partial Q_{jk}}\right] \times \left[Q_{jk} - Q^*_{jk}\right] \geq 0, \quad \forall Q \in \mathcal{K}. \tag{23}$$

Moreover, we can introduce a *price of anarchy* (see Roughgarden (2005)) in this new setting, where the price $\mathcal{P}$ is defined below:

$$\mathcal{P} = \frac{\text{TC(Equilibrium Solution)}}{\text{TC(System-Optimized Solution)}}, \tag{24}$$

where the total cost TC$=\sum_{j=1}^{m} \hat{c}_j(\sum_{k=1}^{n} Q_{jk}) + \sum_{j=1}^{m}\sum_{k=1}^{n} c_{jk}(Q)$ is evaluated at the equilibrium solution satisfying variational inequality (9) in the numerator of (24) and at the system-optimized solution, satisfying variational inequality (21), in the denominator of (24).

Remark

If the costs faced by the freight service providers are separable, that is, if $c_{jk} = c_{jk}(Q_{jk})$, $\forall j, k$, then it follows that the variational inequality (23) coincides with variational inequality

(9), in this special case, and these collapse to the variational inequality problem: determine: $Q^* \in \mathcal{K}$, such that

$$\sum_{j=1}^{m}\sum_{k=1}^{n}\left[\frac{\partial \hat{c}_j(\sum_{k=1}^{n} Q^*_{jk})}{\partial Q_{jk}} + \frac{\partial c_{jk}(Q^*_{jk})}{\partial Q_{jk}}\right] \times \left[Q_{jk} - Q^*_{jk}\right] \geq 0, \quad \forall Q \in \mathcal{K}. \tag{25}$$

With this result, the theoretical analysis is complete.

4. The Algorithm

The algorithm that we use in Section 5 to compute solutions to variational inequality (9) is the projection method of Bertsekas and Gafni (1982). The algorithm therein was applied to the traffic network equilibrium problem with fixed demands and is path-based, rather than link-based, as is the projection method of Dafermos (1980).

Specifically, in referring to Figure 1, and, as also noted in Section 2, the paths joining the origin node 0 with each demand point k; $k = 1, \ldots, n$, have a special structure. Moreover, if we assign costs of zero to the topmost links in the network in Figure 1, and each link (j, k) joining a freight service node j with demand point k is assigned a "user" link cost of:

$$\left[\frac{\partial \hat{c}_j(\sum_{k=1}^{n} Q_{jk})}{\partial Q_{jk}} + \sum_{l=1}^{n}\frac{\partial c_{jl}(Q)}{\partial Q_{jk}}\right]$$

then the variational inequality (9) can be viewed as a solution to a traffic or transportation network equilibrium problem (Dafermos (1980), Patriksson (1994), Nagurney (1999)), with the equilibrium solution Q^*_{jk}; $j = 1, \ldots, m$; $k = 1, \ldots, n$, flowing on the respective path p_{jk}, originating at node 0, and connecting freight service node j and demand point node k. The demand for an O/D pair $(0, k)$ is equal to s_k; $k = 1, \ldots, n$.

Specifically, the path-based projection method here takes the form below, where $F(X)$ is as in (12).

Path-Based Projection Method

Step 0: Initialization

Start with an $X^0 \in \mathcal{K}$. Set $\tau := 1$ and select β, where β is a step size that is sufficiently small. Set $\tau := 1$, and go to Step 1.

Step 1: Computation

Compute X^τ by solving the variational inequality subproblem:

$$\langle X^\tau + (\beta F(X^{\tau-1} - X^{\tau-1}), X - X^{\tau-1})\rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{26}$$

Step 2: Convergence Verification

If $|X_l^\tau - X_l^{\tau-1}| \leq \epsilon$, for all l, with $\epsilon > 0$, a prespecified tolerance, then stop; else, set $\tau := \tau+1$, and go to Step 1.

It is well-known that this projection method is guaranteed to converge to the solution of variational inequality (9), if $F(X)$ is strongly monotone, that is:

$$\langle F(X^1) - F(X^2), X^1 - X^2\rangle \geq \gamma \|X^1 - X^2\|^2, \quad \forall X^1, X^2 \in \mathcal{K}, \tag{27}$$

with $\gamma > 0$, and Lipschitz continuous, that is:

$$\|F(X^1) - F(X^2)\| \leq L\|X^1 - X^2\|, \quad X^1, X^2 \in \mathcal{K} \tag{28}$$

where $L > 0$.

The subproblem (26) corresponds to a separable quadratic programming problem, which decomposes into n subproblems of the special network structure discussed in Section 2.5, each of which can then be solved using the exact equilibration algorithm.

In the next section we apply the above procedures to a case study inspired by the recent Ebola healthcare crisis.

5. Case Study Inspired by the Ebola Healthcare Crisis

In 2014 and 2015, the world was transfixed by the Ebola healthcare crisis that hit western Africa, notably, the countries of: Liberia, Sierra Leone, and Guinea. This contagious disease, with numerous deaths, put immense pressures on the healthcare systems of these countries, which already had been challenged. No vaccines were available and medical professionals were in dire need of supplies including personal protective equipment. According to the Centers for Disease Control and Prevention (2016), as of December 27, 2015, based on World Health Organization (WHO) kept statistics, there were 2,536 deaths in Guinea attributed to Ebola, 3,955 deaths in Sierra Leone, and 4,806 deaths in Liberia, with confirmed cases, respectively, of: 3,351, 8,704, and 3,151, and with suspected, probable, and confirmed cases, respectively,

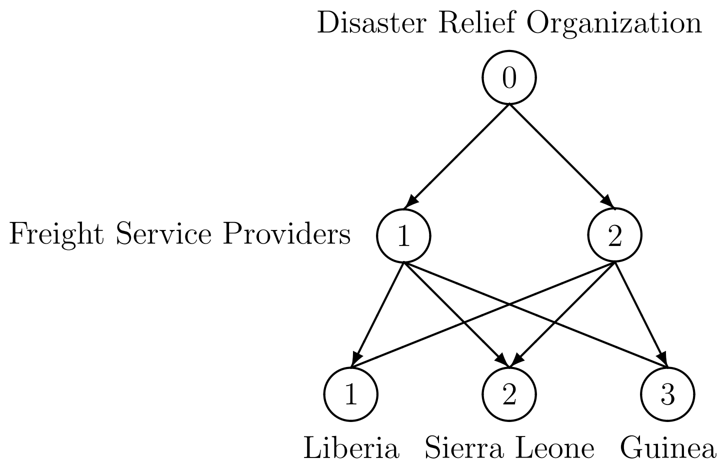

Figure 5: Network Topology for the Ebola Case Study

of: 3,804, 14,122, and 10,666. For a very personal perspective on this crisis and the challenges faced by medical professionals in responding to this crisis, see Wilson (2015). According to a report by the World Health Organization (2015), over 800 health care workerrs contracted Ebola during this crisis. In the WHO report, the term "health worker includes not only clinical staff, but all those who worked in health services, including drivers, cleaners, burial teams, and community-based workers amongst others.

In this section, we consider the network in Figure 5. Hence, the disaster relief organization is considering two freight service providers and shipping the needed supplies, that is, the PPEs, to each of the three noted countries.

We used The World Bank (2016) data to identify the cost of transport of a container of 20 feet, which can hold 1360 cubic feet of supplies, via ship from the US to these countries. We then multiplied the cost by 14, as per the United States Department of Commerce (2016), to obtain an estimated cost for air freight since time was of the essence since, as noted earlier, healthcare workers were also contracting Ebola.

The disaster relief organization wishes to ship 10,000 PPE items to each of the three destinations.

We initialized the projection method so that the flows for each demand point were equally distributed among the paths connecting the origin node to that demand point. We set $\beta = 1$. The convergence tolerance ϵ eas set to 10^{-4}.

The data were estimated to be as follows.

The disaster relief organization was faced with the following total costs:

$$\hat{c}_1 = 4.50 \times (Q_{11} + Q_{12} + Q_{13}), \quad \hat{c}_2 = 4.25 \times (Q_{21} + Q_{22} + Q_{23}).$$

In our case study, we assume that the relief organization has to purchase the PPE items and, hence, the $\hat{c}_j$; $j = 1, 2$, cost functions include also the purchase cost. The total cost associated with freight service provider 1, $\hat{c}_1$, is higher than that for freight service provider 2, $\hat{c}_2$, since it does not have as much experience with the former provider and the transfer cost is higher per unit.

The freight service provider total costs, in turn, are estimated to be the following:

For freight service provider 1:

$$c_{11} = .0001Q_{11}^2 + 18.48Q_{11}, \quad c_{12} = .001Q_{12}^2 + 16.59Q_{12}, \quad c_{13} = .001Q_{13}^2 + 12.81Q_{13};$$

For freight service provider 2:

$$c_{21} = .001Q_{21}^2 + 18.48Q_{21}, \quad c_{22} = .0001Q_{22}^2 + 16.59Q_{22}. \quad c_{23} = .01Q_{23}^2 + 12.81Q_{23}.$$

Note that the nonlinear terms in the cost functions faced by the freight service provider capture the risk associated with transporting the supplies to the points of demand.

The computed solution is:

$$Q_{11}^* = 8,976.31, \quad Q_{12}^* = 796.43, \quad Q_{13}^* = 9,079.99,$$

$$Q_{21}^* = 1,023.69, \quad Q_{22}^* = 9,203.57, \quad Q_{23}^* = 920.01.$$

The prices charged by the freight service providers are:

$$\rho_{11}^* = 20.28, \quad \rho_{12}^* = 18.18, \quad \rho_{13}^* = 30.97,$$

$$\rho_{21}^* = 20.53, \quad \rho_{22}^* = 18.43, \quad \rho_{23}^* = 31.23.$$

The value of the objective function of the disaster relief organization (cf. (1)) is: 829,254.38. The payout to the freight service providers for transport is: 697,041.25, which means that 84% is for transport. This is reasonable since, as noted earlier, about 80% of disaster relief organizations' budgets are towards transportation in disasters. The value of freight service provider 1's objective function (cf. (6)), which coincides with his profits, is: 91,137.94 and that of freight service provider 2 is: 17,982.72. The equilibrium conditions are satisfied.

From the results, we see that freight service provider 1 delivers the bulk (the majority) of the PPE supplies to Liberia and Guinea, whereas freight service provider delivers the bulk of the supplies to Sierra Leone.

A Variant

We now proceed to investigate the following scenario. The demand for PPEs in Liberia has increased due to the spread of Ebola and emphasis on containment. The data remain as in the above example except that now s_1 has doubled to: $20,000$.

The new computed equilibrium product shipment pattern is:

$$Q_{11}^* = 18,067.12, \quad Q_{12}^* = 795.92, \quad Q_{13}^* = 9,079.99,$$

$$Q_{21}^* = 1,932.88, \quad Q_{22}^* = 9,204.08, \quad Q_{23}^* = 920.01.$$

The new freight service provider prices are:

$$\rho_{11}^* = 22.09, \quad \rho_{12}^* = 18.18, \quad \rho_{13}^* = 30.97$$

$$\rho_{21}^* = 22.35, \quad \rho_{22}^* = 18.43, \quad \rho_{23}^* = 31.21.$$

The total cost faced by the disaster relief organization is now 1,113,372.63 with the payout to the freight service providers being: 936,386.88. The percentage of the organization's total cost that this payout entails is 84%.

Freight service provider 1 now has a profit of 115,721.75 and freight service provider 2 a profit of 20,671.77. Since now both freight service provider 1 and freight service provider 2 transport a greater volume of the PPE supplies to Liberia, the prices that they charge have increased and their profits have as well. Freight service provider 1 again dominates the shipments to Liberia and Guinea, whereas freight service provider carries the bulk of the PPEs to Sierra Leone.

6. Summary and Conclusions

Inn this paper, we formulated a plethora of freight service provision models for disaster relief. We first presented a general competitive freight service provision model in which the demands for the disaster relief supplies must be met at demand points. The disaster relief organization seeks to minimize the total costs associated with having the needed supplies delivered by the freight service providers, who are competing profit-maximizers, to the points of demand. We presented the governing freight service provision network equilibrium conditions and derived the variational inequality formulation, which was then analyzed qualitatively. The total costs faced by the decision-makers are nonlinear in order to capture capacities, competition, and also congestion and risk, all critical aspects in disaster relief situations.

We presented illustrative examples to demonstrate the impacts of enhanced or reduced freight service competition on equilibrium product shipments and prices. We also considered a specially structured network problem, in which there is a single demand point and the cost functions faced by both the disaster relief organization and the freight service providers are quadratic and separable. We proposed a special-purpose algorithm, which yields the exact solution. For the general model, we also presented a path-based projection algorithm, which we then embedded with the special-purpose algorithm to compute solutions to a case study inspired by the recent Ebola healthcare crisis, in which PPEs were essential products to protect healthcare workers so that they could treat victims of this horrible disease and contain its spread.

In addition, we also presented a cooperative, system-optimized model, in which the total costs of both the disaster relief organization and those of the freight service providers are minimized. We discussed the price of anarchy, which relates the total costs under our competitive model solution and its cooperative, system-optimized counterpart.

This paper adds to the growing literature on transportation in disaster relief and humanitarian operations but with the distinctive focus on freight service provision, which has only minimally been addressed rigorously, thus far. The contributions in this paper are also relevant to the corporate domain, especially in the case of healthcare crises in which, for example, vaccines or medicines must be delivered and pharmaceutical companies, or even governments, wish to determine the most cost-effective means for delivery.

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