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

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Outline

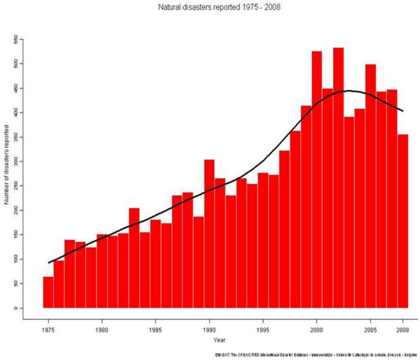
- Background and Motivation
- An Overview of the Relevant Literature
- The Multiproduct Supply Chain Network Design Model
- Potential Applications
- The Algorithm
- Numerical Examples
- Summary and Conclusions

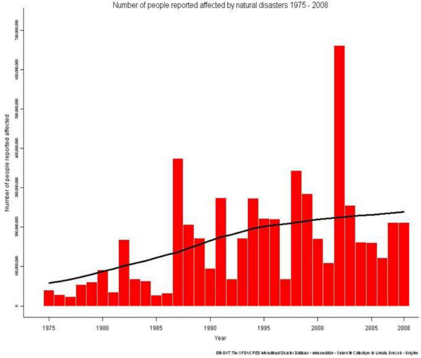
Background and Motivation

When it comes to healthcare supply chains, appropriate supply chain designs may positively affect the health and wellbeing of citizens, with broader impacts on the economy and even national security (Raja and Heinen (2009)).

Healthcare supply chains are extremely important in the case of disasters, whether natural or man-made.

Natural Disasters (1975–2008)





Background and Motivation

There have been numerous dramatic examples of humanitarian healthcare supply chains that failed to deliver the necessary medicines and vaccines.

There were severe shortages of medicine post Hurricane Andrew in 1992, and lessons were not learned so that when Hurricane Katrina struck in 2005, there were again severe shortages of medicine (Jones (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 (Cefalu et al. (2006)).

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Background and Motivation

During ongoing strife in Africa, vaccines and their dissemination have become essential components of humanitarian operations, as in Sudan, as well as in drought and famine-ravaged Somalia (see United Nations Office for the Coordination of Humanitarian Affairs (2011)).

With the advent of increasing globalization, viruses are spreading more quickly and creating new challenges for medical and health professionals, researchers, and government officials.

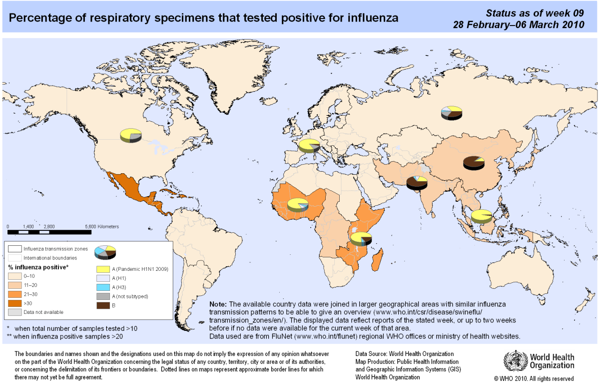

Figure 1: Map of Influenza Activity and Virus Subtypes (WHO (2010))

Background and Motivation

The vaccine supply chain often relies on only one or two manufacturers for critical products (see Mowery and Mitchell (1995), and Treanor (2004)). The number of licensed vaccine manufacturers in the United States decreased from 26 in 1967 to only 6 in 2006 (Klein and Myers (2006)).

Between 2000 and 2004 there were nationwide shortages in the United States of six recommended childhood vaccines.

New illnesses, in turn, pose further stresses for vaccine (and medicine) development, production, and distribution.

H1N1 (Swine) Flu

The epidemic of the H1N1 virus (also known as the swine flu) in 2009 took more than 18,449 lives with over 214 countries reporting confirmed cases (WHO (2010)).

Parts of the globe experienced serious flu vaccine shortages, both seasonal and H1N1 (swine) ones, in late 2009.

H1N1 (Swine) Flu

As reported, the five corporations originally planned on producing only slightly more than 118 million units of the seasonal flu vaccine.

However, one firm cut its run by half because of production problems. And another producer's yield was reduced by 10%.

With the urgent demand for H1N1 vaccine, all five flu vaccine manufacturers switched from the production of seasonal flu vaccine to the production of the H1N1 vaccine, causing increased shortages of the former and delayed deliveries of the latter.

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Cytarabine

In the past year, the US experienced shortages of the critical drug, cytarabine, due to manufacturer production problems.

Due to the severity of this medical crisis for leukemia patients, Food and Drug Administration is exploring the possibility of importing this medical product (Larkin (2011)).

Hospira re-entered the market in March 2011 and has made the manufacture of cytarabine a priority ahead of other products.

Background and Motivation

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.

An Overview of the Relevant Literature

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.

However, there have been few studies that integrate systems and network approaches to assist in the understanding of healthcare processes (Keen, Moore, and West (2006)).

Hence, an appropriate framework for humanitarian healthcare supply chains must capture the entire relevant network.

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An Overview of the Relevant Literature

- Altay and Green III (2006), Jacobson, Sewell, and Jokela (2007), Shah et al. (2008), Sinha and Kohnke (2009), and Tetteh (2009);
- Papageorgiou, Rotstein, and Shah (2001), Pacheco and Casado (2005), Tsang, Samsatli, and Shah (2006), Banerjee (2009), Chahed et al. (2009), and Reimann and Schiltknecht (2009);
- Beamon and Kotleba (2006a, 2006b), Balcik and Beamon (2008), Salmerón and Apte (2010), Mete and Zabinsky (2010), Nagurney, Masoumi, and Yu (2011), and Qiang and Nagurney (2011).

An Overview of the Relevant Literature

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

Jahre et al. (2010) 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, which is much needed in humanitarian logistics.

Haghani and Oh (1996) further noted the importance of including nonlinearities in relief operations modeling, due to the reality of congestion.

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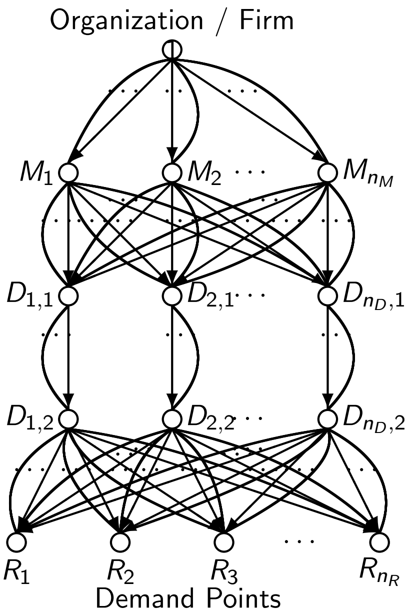
Supply Chain Network Topology



The Multiproduct Supply Chain Network Design Model

The organization is involved in the production, storage, and distribution of multiple products. It seeks to determine:

- the optimal levels of capacity investments in its supply chain network activities, and
- the optimal levels of each product processed on each supply chain network link,

so as to minimize the total cost, including

- the total cost of capacity investments, and
- the total cost of operating the various links for each of the products.

Demands, Path Flows, and Link Flows

Let d_k^j denote the demand for product j; $j = 1, \ldots, J$, at demand point R_k. Let x_p^j denote the nonnegative flow of product j on path p. Let f_a^j denote the flow of product j on link a.

The following conservation of flow equations

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

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

The Operating Costs, and Investment Costs

The total cost of a link associated with a product is assumed to be a function of the flow of all the products on the link.

$$\hat{c}_a^j = \hat{c}_a^j(f_a^1, \ldots, f_a^J), \quad j = 1, \ldots, J; \quad \forall a \in L. \tag{3}$$

The nonnegative existing capacity on a link a is denoted by $\bar{u}_a$, $\forall a \in L$. We assume that the organization is considering the addition of capacity to link a, $\forall a \in L$.

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

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.

The total cost functions are assumed to be convex and continuously differentiable.

$$\text{Minimize} \quad \sum_{j=1}^{J} \sum_{a \in L} \hat{c}_a^j(f_a^1, \ldots, f_a^J) + \sum_{a \in L} \hat{\pi}_a(u_a) \tag{5}$$

subject to: Constraints (1), (2), and

$$\sum_{j=1}^{J} \alpha_j f_a^j \leq \bar{u}_a + u_a, \quad \forall a \in L, \tag{6}$$

$$u_a \geq 0, \quad \forall a \in L, \tag{7}$$

$$x_p^j \geq 0, \quad j = 1, \ldots, J; \quad \forall p \in P. \tag{8}$$

Variational Inequality Formulation

The optimization problem 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:*

$$\sum_{j=1}^{J}\sum_{l=1}^{J}\sum_{a\in L}\left[\frac{\partial \hat{c}_a^l(f_a^{1*},\ldots,f_a^{J*})}{\partial f_a^j} + \alpha_j \lambda_a^*\right] \times [f_a^j - f_a^{j*}]$$

$$+ \sum_{a\in L}\left[\frac{\partial \hat{\pi}_a(u_a^*)}{\partial u_a} - \lambda_a^*\right] \times [u_a - u_a^*]$$

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

where

$$\mathcal{K} \equiv \{(f,u,\lambda) | \exists x, \textit{ such that} (1), (2), (7), \textit{and} (8) \textit{ hold, and} \lambda \geq 0\}.$$

Corollary

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

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

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

Potential Applications

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.

By realizing what the minimal total costs are, the firm can then plan accordingly and also contract wisely with the cognizant governments or other authorities, including humanitarian organizations.

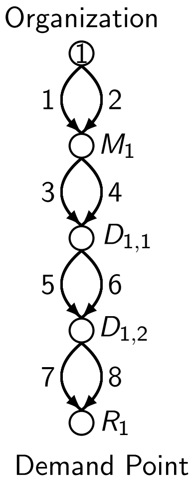
In addition, we explicitly allow for alternative technologies associated with manufacturing, different storage technologies, and different modes of transportation/shipment.

The Algorithm

We adopted the modified projection method (see Korpelevich (1977) and Nagurney (2006)) for all the numerical examples . 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.

Numerical Examples with a Single Product



Example 1: Supply Chain Network Design

There were no initial capacities on the links. The demand at the demand point was $d_{R_1} = 1,000$, and α was assumed to be 1.

Table 1: Total Cost Functions and Solution

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

Increasing Demand Examples

The demand of 1,000 was increased to 2,000, to 3,000, to 4,000, and, finally, to 5,000.

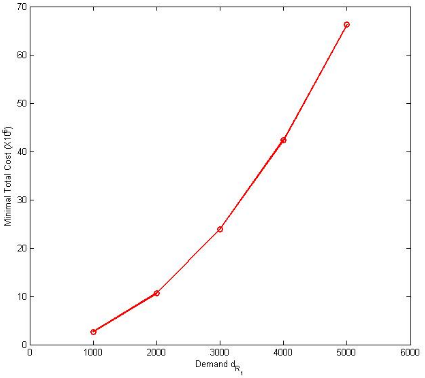


Figure 2: Minimal Total Cost Obtained for Example 1 Supply Chain Network Design as Demand Increases

Example 2: Supply Chain Network Redesign

Suppose that the organization has been operating according to the optimal design for the particular production period but now $d_{R_1} = 2,000$.

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

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

Iterated Redesign with Increasing Demands

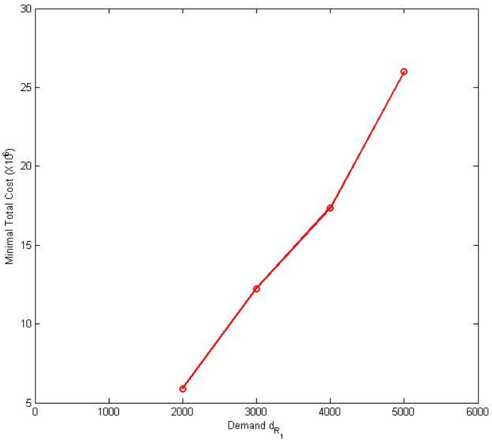
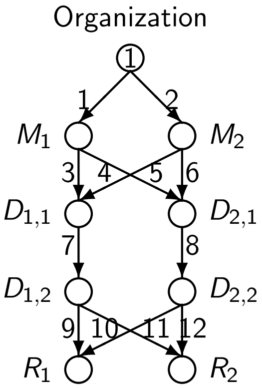


Figure 3: Minimal Total Cost Obtained for Example 2 Iterated Supply Chain Network Redesigns as Demand Increases

Multiproduct Supply Chain Network Design Case Study

An organization is assumed to be involved in the production of two vaccines, which correspond to two products, such as, for example, a seasonal flu vaccine and the H1N1 vaccine, referred to as vaccine 1 and 2, respectively.



In the design problem, 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 assumed to be similar products in size, for transparency and simplicity, we set $\alpha_1 = \alpha_2 = 1$. The demands for the two vaccines at the demand points were:

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

Table 3: Total Cost Functions

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

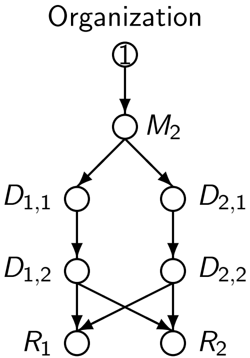
Table 4: Link Capacity Investment Cost Functions

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	$.5u_{12}^2 + 10u_{12}$

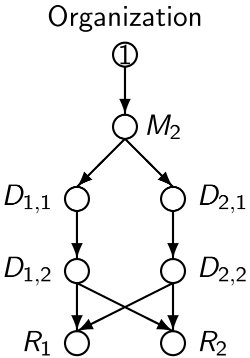
Table 5: Optimal Multiproduct Flows, Link Capacities, and Lagrange Multipliers

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

Sensitivity Analysis



When the fixed cost associated with the investment capacity on link 1 was equal to 20,000 (or greater), the first manufacturing plant would not be constructed and the manufacturing of both vaccines would take place exclusively at manufacturing plant 2.



When the fixed cost associated with the investment capacity on link 1 was equal to $20,000$ (or greater), the first manufacturing plant would not be constructed and the manufacturing of both vaccines would take place exclusively at manufacturing plant 2.

Example 4: Redesign Problem

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

Table 7: Optimal Multiproduct Flows, Enhanced Link Capacities, and Lagrange Multipliers

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

Summary and Conclusions

- We developed a multiproduct supply chain network design model with applications to humanitarian healthcare, which can handle both link capacities and product flows as decision variables, along with nonlinear cost functions to capture congestion, as well as risk.
- The framework can handle both the design and the redesign problems.
- Our model allows for the evaluation of alternative technologies associated with supply chain activities.
- Our modeling framework 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.

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Summary and Conclusions

- We developed a multiproduct supply chain network design model with applications to humanitarian healthcare, which can handle both link capacities and product flows as decision variables, along with nonlinear cost functions to capture congestion, as well as risk.
- The framework can handle both the design and the redesign problems.
- Our model allows for the evaluation of alternative technologies associated with supply chain activities.
- Our modeling framework 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.

Thank You!