

An Integrated Disaster Relief Supply Chain Network Model With Time Targets and Demand Uncertainty



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The original model is based on the following paper:

Anna Nagurney, Amir H. Masoumi, and Min Yu, in *Regional Science Matters: Studies Dedicated to Walter Isard*, P. Nijkamp, A. Rose, and K. Kourtit, Editors, Springer International Publishing Switzerland (2015), pp 287–318.

Outlook

- Background and Introduction
- Integrated Network Model for Disaster Relief Supply Chains
- Numerical Example and Results
- Summary and Conclusion

Background: Natural Disasters

The number of natural disasters and the sizes of the populations affected by such events have been growing (Schultz, Koenig, and Noji (1996) and Nagurney and Qiang (2009)).

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For instance, tropical cyclones which include **hurricanes** in the US are expected to be stronger as a result of global warming (Sheppard (2011) and Borenstein (2012)).

21st Century's Deadliest Natural Disasters

10. Great East [Japan](#) "Triple Disaster", 2011. Death toll: [18,400](#).
9. Gujarat earthquake, [India](#) and [Pakistan](#), 2001. Death toll: [19,700](#).
8. [European](#) heat wave, 2003. Death toll: [40,000](#).
7. Bam earthquake, [Iran](#), 2003. Death toll [26,000 – 43,000](#).
6. [Russian](#) heat wave, 2010. Death toll: [56,000](#).
5. Sichuan earthquake, [China](#), 2008. Death toll: [69,200](#).
4. Kashmir earthquake, [Pakistan](#), [India](#), and [Afghanistan](#), 2005. Death toll: [75,000 – 86,000](#).
3. Cyclone Nargis, [Myanmar](#), 2008. Death toll: [146,000](#).
2. Indian Ocean Tsunami, [Indonesia](#), [Sri Lanka](#), and [India](#), 2004. Death toll: [230,000](#).
1. [Haiti](#) earthquake, 2010. Death toll: [316,000](#).

Background: Tornadoes in the US

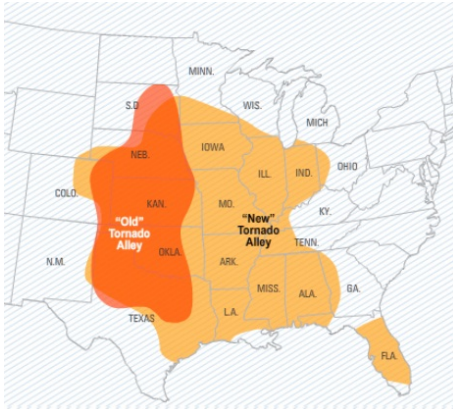


Figure 1: "Tornado Alley" grows wider
(CoreLogic, Storm Prediction Center)

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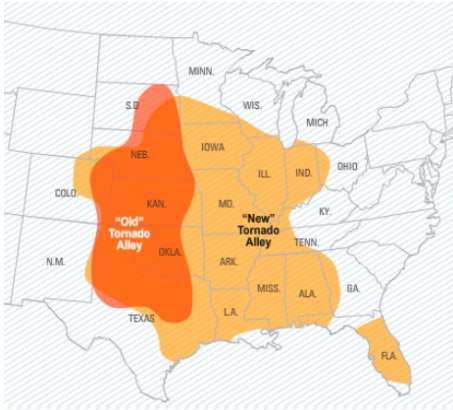


Figure 1: "Tornado Alley" grows wider (CoreLogic, Storm Prediction Center)

The traditional boundaries of **Tornado Alley** which has centered on the Plains states of Texas, Oklahoma, Kansas, Nebraska and South Dakota should be expanded to include **much of the Midwest and Deep South**, because the frequency and severity of tornadoes in those areas is much more widespread than commonly believed (Core Logic, April 2012).

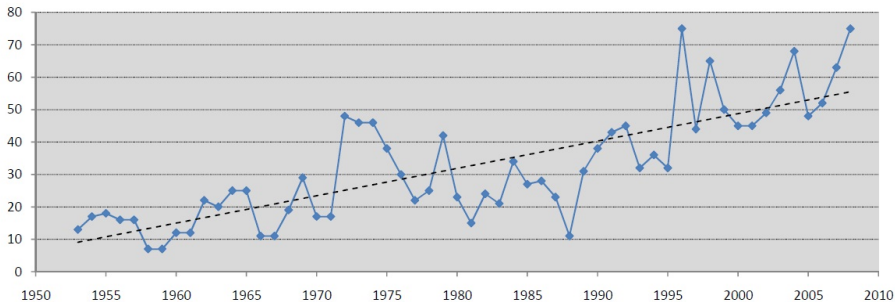
Background: Facts

In the US alone, the average number of disasters per year that **exceeded a cost of 1 billion dollars** in damages increased from 3.6 in the 2001-2005 period to 5.8 in 2006-2010 (NOAA).

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U.S. Federal Disaster Declarations
(1953-2008)



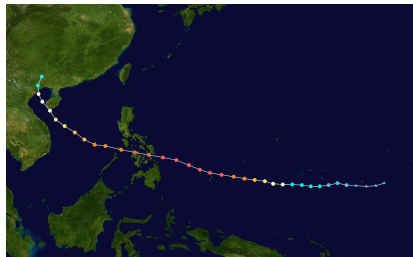
U.S. Federal Disaster Declarations, 1953-2008 with trend line (Source Data: FEMA)



More Recent Disasters: Typhoon Haiyan in 2013

A catastrophic tropical cyclone devastated the Philippines and other parts of Southeast Asia, in November 2013. Haiyan was:

- the deadliest Philippine typhoon recorded in modern history, killing at least **6,300** people in that country alone,
- the strongest storm recorded at landfall,
- the strongest typhoon ever recorded in terms of one-minute sustained wind speed.



More Recent Disasters: Nepal Earthquake in 2015



The April 2015 Nepal earthquake with a magnitude of 7.8 killed more than 8,800 people and injured more than 23,000.

Hundreds of thousands of people were made homeless with entire villages flattened across the country. About 700,000 people were pushed below the poverty line in the Himalayan nation, which is one of the worlds poorest.

Natural Disasters

The amount of damage and loss following a disaster depends on the **vulnerability** of the affected region, and on its ability to respond (and recover) in a timely manner, also referred to as **resilience**.

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Hence, being prepared against potential disasters leads to reduced vulnerability and a lower number of fatalities.

“During a natural disaster, one has only two options: **to become a victim, or to become a responder**” (Alvencia-Quero (2012)).

Disaster Relief Supply Chains

The *complexity* of disaster relief supply chains originates from *several inherent factors*:

- **Large demands** for relief products,
- Level of **uncertainty**,
- **Irregularities** in the size, the timing, and the location of relief product demand patterns,
- Disaster-driven supply chains are typically **incident-responsive**, and
- Develop new networks of relationships within **days** or even **hours**, and have very **short life-cycles**.



Criticality of *Time*

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FEMA's key benchmarks in response and recovery:

- To meet the survivors initial demands within 72 hours,
- To restore basic community functionality within 60 days, and
- To return to as normal of a situation within 5 years.

Relevant Literature

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Mathematical Model

We propose an **integrated** supply chain network model for disaster relief.

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Our mathematical framework is of **system-optimization** type where the organization aims to satisfy the uncertain demands subject to the minimization of total operational costs while the sequences of activities leading to the ultimate delivery of the relief good are **targeted to be completed within a certain time**.

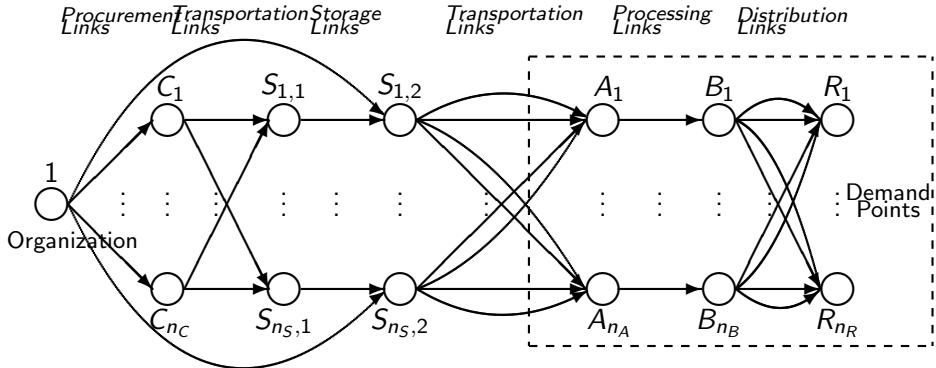


Figure 2: Network Topology of the Integrated Disaster Relief Supply Chain

$G = [N, L]$: supply chain network graph,
 N : set of nodes,
 L : set of links (arcs).

Mathematical Model

Notations:

$\mathcal{P}_k$: set of paths connecting the origin (node 1) to demand point k ,

$\mathcal{P}$: set of all paths joining the origin node to the destination nodes, and

n_p : total number of paths in the supply chain.

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Total Operational Cost Function

$$\hat{c}_a(f_a) = f_a \times c_a(f_a), \quad \forall a \in L, \quad (1)$$

where:

f_a : flow of the disaster relief product on link a , and
 $c_a(f_a)$: unit operational cost function on link a .

Probability Distribution of Demand

$$P_k(D_k) = P_k(d_k \leq D_k) = \int_0^{D_k} \mathcal{F}_k(t) dt, \quad k = 1, \dots, n_R, \quad (2)$$

where:

d_k : actual value of demand at point k ,

P_k : probability distribution function of demand at point k ,

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Demand Shortage and Surplus

$$\Delta_k^- \equiv \max\{0, d_k - v_k\}, \quad k = 1, \dots, n_R, \quad (3a)$$

$$\Delta_k^+ \equiv \max\{0, v_k - d_k\}, \quad k = 1, \dots, n_R, \quad (3b)$$

where:

v_k : “projected demand” for the disaster relief item at point k .

Expected Values of Shortage and Surplus

$$E(\Delta_k^-) = \int_{v_k}^{\infty} (t - v_k) \mathcal{F}_k(t) dt, \quad k = 1, \dots, n_R, \quad (4a)$$

$$E(\Delta_k^+) = \int_0^{v_k} (v_k - t) \mathcal{F}_k(t) dt, \quad k = 1, \dots, n_R. \quad (4b)$$

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$$E(\Delta_k^+) = \int_0^{v_k} (v_k - t) \mathcal{F}_k(t) dt, \quad k = 1, \dots, n_R. \quad (4b)$$

Expected Penalty due to Shortage and Surplus

$$E(\lambda_k^- \Delta_k^- + \lambda_k^+ \Delta_k^+) = \lambda_k^- E(\Delta_k^-) + \lambda_k^+ E(\Delta_k^+), \quad k = 1, \dots, n_R, \quad (5)$$

where:

λ_k^- : unit penalty associated with the shortage of the relief item at point k ,
 λ_k^+ : unit penalty associated with the surplus of the relief item at point k .

Path Flows

$$x_p \geq 0, \quad \forall p \in \mathcal{P}. \quad (6)$$

x_p : flow of the disaster relief goods on path p joining node 1 with a demand node.

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Relationship between Path Flows and Projected Demand

$$v_k \equiv \sum_{p \in \mathcal{P}_k} x_p, \quad k = 1, \dots, n_R. \quad (7)$$

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Relationship between Link Flows and Path Flows

$$f_a = \sum_{p \in \mathcal{P}} x_p \delta_{ap}, \quad \forall a \in L. \quad (8)$$

δ_{ap} is equal to 1 if link a is contained in path p and is 0, otherwise.

Capturing Time Aspect in Formulation

Completion Time

$$\tau_a(f_a) = g_a f_a + h_a, \quad \forall a \in L, \quad (9)$$

where:

τ_a : completion time of the activity on link a . Note: $h_a \geq 0$, and $g_a \geq 0$.

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Completion Time on Paths

$$\tau_p = \sum_{a \in L} \tau_a(f_a) \delta_{ap} = \sum_{a \in L} (g_a f_a + h_a) \delta_{ap}, \quad \forall p \in \mathcal{P}. \quad (10)$$

Where:

τ_p : completion time of the sequence of activities on path p .

$$h_p = \sum_{a \in L} h_a \delta_{ap}, \quad \forall p \in \mathcal{P}. \quad (11)$$

Hence,

$$\tau_p = h_p + \sum_{a \in L} g_a f_a \delta_{ap}, \quad \forall p \in \mathcal{P}. \quad (12)$$

h_p : sum of the uncongested terms h_a s on path p .

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Time Targets

$$\tau_p \leq T_k, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R, \quad (13)$$

T_k : target for the completion time of the activities on paths corresponding to demand point k determined by the organization's decision-maker.

$$\sum_{a \in L} g_a f_a \delta_{ap} \leq T_k - h_p, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R. \quad (14)$$

$$T_{kp} = T_k - h_p, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R. \quad (15)$$

T_{kp} : target time for demand point k with respect to path p .

$$\sum_{a \in L} g_a f_a \delta_{ap} \leq T_{kp}, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R. \quad (16)$$

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$$\sum_{a \in L} g_a f_a \delta_{ap} \leq T_{kp}, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R. \quad (16)$$

Late Delivery (Deviations) with Respect to Target Times

$$\sum_{a \in L} g_a f_a \delta_{ap} - z_p \leq T_{kp}, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R. \quad (17)$$

z_p : amount of deviation with respect to target time T_{kp} corresponding to the “late” delivery of product to point k on path p .

Non-negativity

$$z_p \geq 0, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R. \quad (18)$$

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Time Constraint

$$\sum_{q \in \mathcal{P}} \sum_{a \in L} g_a x_q \delta_{aq} \delta_{ap} - z_p \leq T_{kp}, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R. \quad (19)$$

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$$\sum_{q \in \mathcal{P}} \sum_{a \in L} g_a x_q \delta_{aq} \delta_{ap} - z_p \leq T_{kp}, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R. \quad (19)$$

$$\hat{C}_p(x) = x_p \times C_p(x) = x_p \times \sum_{a \in L} c_a(f_a) \delta_{ap}, \quad \forall p \in \mathcal{P}, \quad (20)$$

$\hat{C}_p(x)$: total operational cost function on path p .

C_p : unit operational cost on path p .

$\gamma_k(z)$: **tardiness penalty function** corresponding to demand point k .

Optimization Formulation

$$\text{Minimize } \sum_{p \in \mathcal{P}} \hat{C}_p(x) + \sum_{k=1}^{n_R} (\lambda_k^- E(\Delta_k^-) + \lambda_k^+ E(\Delta_k^+)) + \sum_{k=1}^{n_R} \gamma_k(z), \quad (21)$$

subject to: constraints (6), (18), and (19).

$\gamma_k(z)$: **tardiness penalty function** corresponding to demand point k .

Optimization Formulation

$$\text{Minimize } \sum_{p \in \mathcal{P}} \hat{C}_p(x) + \sum_{k=1}^{n_R} (\lambda_k^- E(\Delta_k^-) + \lambda_k^+ E(\Delta_k^+)) + \sum_{k=1}^{n_R} \gamma_k(z), \quad (21)$$

subject to: constraints (6), (18), and (19).

Feasible Set

$$K = \{(x, z, \omega) | x \in R_+^{n_p}, z \in R_+^{n_p}, \text{ and } \omega \in R_+^{n_p}\}, \quad (23)$$

where x is the vector of path flows, z is the vector of time deviations on paths, and ω is the vector of Lagrange multipliers corresponding to (19).

Variational Inequality Formulation

The optimization problem (21), subject to its constraints (6), (18), and (19), is equivalent to the variational inequality problem: determine the vector of optimal path flows, the vector of optimal path time deviations, and the vector of optimal Lagrange multipliers $(x^*, z^*, \omega^*) \in K$, such that:

$$\begin{aligned}
 & \sum_{k=1}^{n_R} \sum_{p \in \mathcal{P}_k} \left[\frac{\partial \hat{C}_p(x^*)}{\partial x_p} + \lambda_k^+ P_k \left(\sum_{q \in \mathcal{P}_k} x_q^* \right) - \lambda_k^- (1 - P_k \left(\sum_{q \in \mathcal{P}_k} x_q^* \right)) \right. \\
 & + \sum_{q \in \mathcal{P}} \sum_{a \in L} \omega_q^* g_a \delta_{aq} \delta_{ap} \times [x_p - x_p^*] + \sum_{k=1}^{n_R} \sum_{p \in \mathcal{P}_k} \left[\frac{\partial \gamma_k(z^*)}{\partial z_p} - \omega_p^* \right] \times [z_p - z_p^*] \\
 & \left. + \sum_{k=1}^{n_R} \sum_{p \in \mathcal{P}_k} \left[T_{kp} + z_p^* - \sum_{q \in \mathcal{P}} \sum_{a \in L} g_a x_q^* \delta_{aq} \delta_{ap} \right] \times [\omega_p - \omega_p^*] \geq 0, \quad \forall (x, z, \omega) \in K, \right. \\
 & \left. \right. \tag{24}
 \end{aligned}$$

where

$$\frac{\partial \hat{C}_p(x)}{\partial x_p} \equiv \sum_{a \in L} \frac{\partial \hat{c}_a(f_a)}{\partial f_a} \delta_{ap}, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R. \tag{25}$$

Solution Method and Numerical Examples



Solution Algorithm

Explicit Formulae for the Euler Method Applied to the Variational Inequality (24)

At iteration $\tau + 1$:

$$x_p^{\tau+1} = \max\{0, x_p^{\tau} + a_{\tau}(\lambda_k^{-}(1 - P_k(\sum_{q \in \mathcal{P}_k} x_q^{\tau})) - \lambda_k^{+}P_k(\sum_{q \in \mathcal{P}_k} x_q^{\tau}) - \frac{\partial \hat{C}_p(x^{\tau})}{\partial x_p} - \sum_{q \in \mathcal{P}} \sum_{a \in L} \omega_q^{\tau} g_a \delta_{aq} \delta_{ap})\}, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R, \quad (31)$$

$$z_p^{\tau+1} = \max\{0, z_p^{\tau} + a_{\tau}(\omega_p^{\tau} - \frac{\partial \gamma_k(z^{\tau})}{\partial z_p})\}, \quad \forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R, \text{ and} \quad (32)$$

$$\omega_p^{\tau+1} = \max\{0, \omega_p^{\tau} + a_{\tau}(\sum_{q \in \mathcal{P}} \sum_{a \in L} g_a x_q^{\tau} \delta_{aq} \delta_{ap} - T_{kp} - z_p^{\tau})\},$$

$$\forall p \in \mathcal{P}_k; \quad k = 1, \dots, n_R. \quad (33)$$

A Large Scale Numerical Example

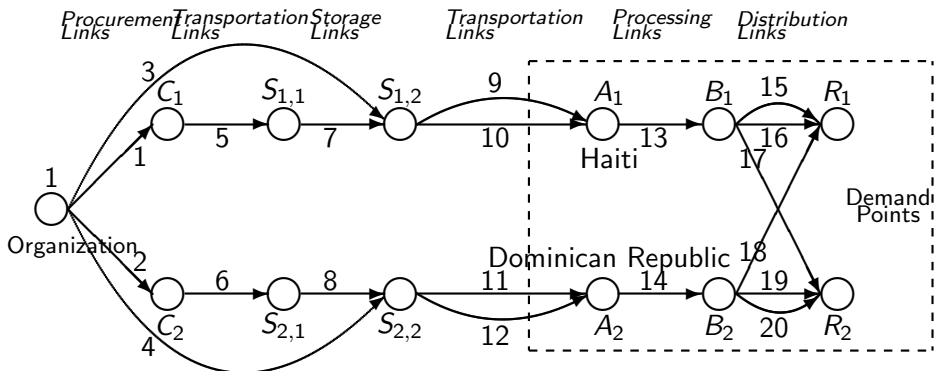


Figure 3: Network Topology of the Larger Disaster Relief Supply Chain Numerical Example

Numerical Example Data

R_1 is assumed to have a higher demand for relief goods due to a **larger population** and its **potential higher vulnerability** to the disasters as compared to R_2 .

The demand for the relief item at R_1 and R_2 is assumed to follow a **uniform distribution** on the intervals $[25,40]$ and $[10,20]$, respectively.

Unit shortage and surplus penalties at demand points R_1 and R_2 :

$$\lambda_{R_1}^- = 10,000, \lambda_{R_1}^+ = 100,$$

$$\lambda_{R_2}^- = 7,500, \lambda_{R_2}^+ = 150.$$

Target times of delivery at demand points:

$$T_{R_1} = 72, T_{R_2} = 70.$$

Tardiness penalty functions at demand points:

$$\gamma_{R_1}(z) = 3\left(\sum_{p \in \mathcal{P}_{R_1}} z_p^2\right), \quad \gamma_{R_2}(z) = 3\left(\sum_{p \in \mathcal{P}_{R_2}} z_p^2\right).$$

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The Euler method (cf.(31)–(33)) for the solution of variational inequality (24) was implemented in FORTRAN on a PC. We set the sequence as $\{a^r\} = .1(1, \frac{1}{2}, \frac{1}{2}, \dots)$, and the convergence tolerance was 10^{-6} .

Table 2: Functions and the Optimal Flows on **Links** in the Numerical Example

Link	$\hat{c}_a(f_a)$	$\tau_a(f_a)$	f_a^*
1	$3f_1^2 + 2f_1$	0	19.22
2	$2f_2^2 + 2.5f_2$	0	20.02
3	$5f_3^2 + 4f_3$	$3f_3 + 3$	0.00
4	$4.5f_4^2 + 3f_4$	$4f_4 + 2$	0.00
5	$f_5^2 + 2f_5$	0	19.22
6	$f_6^2 + .5f_6$	0	20.02
7	$2.5f_7^2 + 3f_7$	0	19.22
8	$3.5f_8^2 + 2f_8$	0	20.02
9	$7f_9^2 + 5f_9$	$2f_9 + 2$	19.22
10	$4f_{10}^2 + 6f_{10}$	$10f_{10} + 6$	0.00
11	$2.5f_{11}^2 + 4f_{11}$	$7.5f_{11} + 5$	0.23
12	$4.5f_{12}^2 + 5f_{12}$	$1.5f_{12} + 1.5$	19.79
13	$2f_{13}^2 + 4f_{13}$	$2f_{13} + 2$	19.22
14	$f_{14}^2 + 3f_{14}$	$1.5f_{14} + 1$	20.02
15	$4f_{15}^2 + 5f_{15}$	$3f_{15} + 3$	13.95
16	$2.5f_{16}^2 + 2f_{16}$	$5f_{16} + 4$	5.28
17	$3f_{17}^2 + 4f_{17}$	$6.5f_{17} + 3$	0.00
18	$4f_{18}^2 + 4f_{18}$	$7f_{18} + 5$	6.85
19	$3f_{19}^2 + 3f_{19}$	$4f_{19} + 5$	5.68
20	$3.5f_{20}^2 + 5f_{20}$	$3.5f_{20} + 4$	7.49

Table 3: Path Definitions, Target Times, **Optimal Path Flows**, Time Deviations, and Lagrange Multipliers for the Numerical Example

$\mathcal{P}_{R_1}$: Set of Paths Corresponding to Demand Point R_1	Path Definition	T_{kp}	x_p^*	z_p^*	ω_p^*
	$p_1 = (1, 5, 7, 9, 13, 15)$	65	13.95	53.66	321.99
	$p_2 = (1, 5, 7, 9, 13, 16)$	64	5.28	39.23	235.39
	$p_3 = (1, 5, 7, 10, 13, 15)$	61	0.00	19.32	115.90
	$p_4 = (1, 5, 7, 10, 13, 16)$	60	0.00	4.83	28.99
	$p_5 = (2, 6, 8, 11, 14, 18)$	61	0.06	18.67	112.03
	$p_6 = (2, 6, 8, 12, 14, 18)$	64.5	6.79	43.12	258.75
	$p_7 = (3, 9, 13, 15)$	62	0.00	56.66	339.99
	$p_8 = (3, 9, 13, 16)$	61	0.00	42.23	253.39
	$p_9 = (3, 10, 13, 15)$	58	0.00	22.34	134.05
	$p_{10} = (3, 10, 13, 16)$	57	0.00	7.84	47.03
	$p_{11} = (4, 11, 14, 18)$	59	0.00	20.71	124.24
	$p_{12} = (4, 12, 14, 18)$	62.5	0.00	45.24	271.46
$\mathcal{P}_{R_2}$: Set of Paths Corresponding to Demand Point R_2	$p_{13} = (1, 5, 7, 9, 13, 17)$	63	0.00	13.87	83.25
	$p_{14} = (1, 5, 7, 10, 13, 17)$	59	0.00	0.00	0.00
	$p_{15} = (2, 6, 8, 11, 14, 19)$	59	0.13	0.00	0.00
	$p_{16} = (2, 6, 8, 11, 14, 20)$	60	0.04	0.00	0.00
	$p_{17} = (2, 6, 8, 12, 14, 19)$	62.5	5.55	19.91	119.44
	$p_{18} = (2, 6, 8, 12, 14, 20)$	63.5	7.45	22.40	134.43
	$p_{19} = (3, 9, 13, 17)$	60	0.00	16.90	101.41
	$p_{20} = (3, 10, 13, 17)$	56	0.00	0.00	0.00
	$p_{21} = (4, 11, 14, 19)$	57	0.00	0.00	0.00
	$p_{22} = (4, 11, 14, 20)$	58	0.00	0.00	0.00
	$p_{23} = (4, 12, 14, 19)$	60.5	0.00	21.96	131.77
	$p_{24} = (4, 12, 14, 20)$	61.5	0.00	24.48	146.85

Numerical Example: A Variant

We assumed that the organization will now procure the items **locally** and, hence, the time functions associated with the direct procurement links 3 and 4 are now greatly reduced. The remainder of the input data remains as in the previous example.

As in Table 4, now both the storage links for pre-positioning (links 7 and 8) and for post-disaster procurement (links 3 and 4) have positive flows.

Table 4: Numerical Example Variant - Optimal Link Flows

Link	$\hat{c}_a(f_a)$	$\tau_a(f_a)$	f_a^*
1	$3f_1^2 + 2f_1$	0	12.02
2	$2f_2^2 + 2.5f_2$	0	11.21
3	$5f_3^2 + 4f_3$	$.1f_3 + 1$	7.35
4	$4.5f_4^2 + 3f_4$	$.1f_4 + 1$	8.88
5	$f_5^2 + 2f_5$	0	12.02
6	$f_6^2 + .5f_6$	0	11.21
7	$2.5f_7^2 + 3f_7$	0	12.02
8	$3.5f_8^2 + 2f_8$	0	11.21
9	$7f_9^2 + 5f_9$	$2f_9 + 2$	19.37
10	$4f_{10}^2 + 6f_{10}$	$10f_{10} + 6$	0.00
11	$2.5f_{11}^2 + 4f_{11}$	$7.5f_{11} + 5$	0.24
12	$4.5f_{12}^2 + 5f_{12}$	$1.5f_{12} + 1.5$	19.86
13	$2f_{13}^2 + 4f_{13}$	$2f_{13} + 2$	19.37
14	$f_{14}^2 + 3f_{14}$	$1.5f_{14} + 1$	20.10
15	$4f_{15}^2 + 5f_{15}$	$3f_{15} + 3$	14.04
16	$2.5f_{16}^2 + 2f_{16}$	$5f_{16} + 4$	5.33
17	$3f_{17}^2 + 4f_{17}$	$6.5f_{17} + 3$	0.00
18	$4f_{18}^2 + 4f_{18}$	$7f_{18} + 5$	6.84
19	$3f_{19}^2 + 3f_{19}$	$4f_{19} + 5$	5.72
20	$3.5f_{20}^2 + 5f_{20}$	$3.5f_{20} + 4$	7.53

Summary and Conclusions

A network optimization model was developed for the supply chain management of a disaster relief (humanitarian) organization in charge of procurement and distribution of relief items to a geographic region **prone to natural disasters**. The model:

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- includes **penalties associated with shortages/surpluses** at the demand points with respect to the uncertain demand, and
- enables **prioritizing the demand points** based on the population, geographic location, etc., by assigning different time targets.

Thank You!



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