Stochastic Optimization for Humanitarian Aid Supply and Distribution of World Food Programme (WFP) in Ethiopia

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Abstract
To ensure that limited resources are allocated efficiently, we develop a two-stage linear stochastic program for the humanitarian aid supply and distribution optimization, where uncertainty is introduced through demand and roads/ hubs accessibility. The optimization model was applied to WFP's operations in Ethiopia. Results show high potential cost savings.

Keywords: Humanitarian logistics, Stochastic optimization, Aid supply and distribution model

Introduction
The sharp increase in the number of people affected by natural and man-made disasters (e.g., war, conflicts, refugee crises) in recent decades (EM-DAT, 2011), have strained humanitarian organizations' relief and emergency operations. In addition, due to intense scrutiny by donors and contributions that have failed to meet aid requirements (OCHA, 2006), humanitarian organizations today must run more cost-effective operations (McGuire, 2000, Thomas and Kopczak, 2005).

To ensure that limited resources are allocated efficiently, humanitarian logistics services require better strategic (long term), tactical (medium term), and operational (short term) decisions. Salmerón and Apte (2010) state the need for strategic planning for more effective emergency preparedness. This paper deals with strategic decisions of food aid commodities purchasing, stock prepositioning and optimal distribution planning in an area historically affected by famine.

Decisions to support preparedness activities for disaster management, however, are challenging due to the uncertainties of events, the need to balance preparation and risk, and complications due to poor information and data (Mete and Zabinsky, 2010). In this regard, stochastic programming is an appropriate tool for planning due to its ability to handle uncertainty by probabilistic scenarios representing disasters and their outcomes. Actually, as stated by Mete and Zabinsky (2010), disaster management has a two-stage nature where the first stage refers to the choice of the preparedness level before the disaster occurs, and the second one refers to the reaction after the disaster strikes. As our case study covers a type of slow-onset disaster (famine), the preparedness decisions are represented by the food commodities supply and prepositioned stock level. Uncertainty is introduced through beneficiaries' demand for humanitarian aid and for the effects of flood in some areas which may lead to inaccessible routes or areas. The reaction decisions are represented by the humanitarian aid distribution plan.

The use of two-stage stochastic models in humanitarian operations related problems has increased over the past few years. Emergency relief distribution (Barbarosoglu and Arda, 2004; Falasca and Zobel, 2011; Rawls and Turnquist, 2012), relief item prepositioning (Salmerón and Apte, 2010), and facility location (Mete and Zabinsky, 2010) are examples of problems were two-stage stochastic optimization was applied in the humanitarian operations research area. Despite of these many contributions, the most of them consider suddenly-onset/ natural disasters. Our work has major similarities with to the one of Rottkemper *et al.* (2011), who proposed transshipment model for distribution and inventory relocation to reduce malaria mortality in Burundi. However, these authors do not use two-stage programming and consider the recovery phase of a disaster. No two-stage stochastic models applied to supply and distribution planning for famine relief problems have been found in our literature searches.

In this paper, we develop a transshipment network flow model that complements the current annual food aid distribution plan done by World Food Program (WFP) Ethiopia. Our transshipment model minimizes food aid supply and distribution costs for annually forecasted beneficiary demand, while maintaining the current service level. An important aspect of our model is that it captures the physical reality of WFP Ethiopia primary and secondary transport system, such as distances traveled and routes transportation. It also accounts for factors that impact the ability to reach beneficiaries, or "last mile" distribution issues, such as roads and hubs accessibility in flooded areas during the rainy season.

The Problem

Problem Overview

Humanitarian organizations frequently operate in countries where aid distribution networks are highly complex. In country aid distribution networks cover medium-distance routes for inter- and intra-regional routes (primary transport), and short-distance routes for the distribution of commodities from local warehouse to distribution points to beneficiaries (secondary transport). Primary transportation is characterized by surface transport between an overland country and a recipient one. Due to its high costs, air transport is only used exceptionally. Railway transport is often not an option due to poor infrastructure, lack of proper maintenance, and inadequate management and commercial focus. Hence, road transport is frequently the main mode of transport for overland humanitarian operations. Typically, humanitarian organizations receive aid commodities at the ports and transport it to distribution hubs, or extended delivery points (EDPs). Secondary transportation is characterized by in-country transport from one point to another, known as inland transport. Inland logistics is typically the most complex part of humanitarian supply chain management. Together primary and secondary distribution network complexity typically includes high port congestion, poor road infrastructure, limited availability of overland transport, limited inland registered trucks, limited warehousing, limited access due to poor road conditions, high transport costs and high insecurity. At times, the country is land-locked with no direct access to the sea. Hence, distribution depends on ports in neighboring countries for international shipments.

Here, we focus on the primary and secondary transport problem of a major humanitarian organization distributing humanitarian aid in a beneficiary country. The organization must make supply and prepositioning decisions as well as plan the distribution of aid to meet beneficiary demand in multiple final destination points (FDPs). At the same time, the organization must consider demand uncertainty, limited warehouse capacities, and limited accessibility at different times of the year.

Representation as a Two-Stage Stochastic Problem

We cope with the uncertainty in the problem by a two-stage stochastic linear programming model. In this approach, decision variables are cast into two groups, first and second stage variables (Dantzig, 1955). In our model, the first stage variables capture supply and prepositioning stock decisions and the second stage variables capture distribution flows from an origin to a destination as well as the level of unmet demand in a hub or final destination point (FDP). Demand variability, route availability and hub accessibility due to flooding during rainy season constitute the uncertainty sources.

Assumptions

The humanitarian organization sources aid items through ports, transports it to final destination points (FDPs) or to extended delivery points (EDPs or hubs), where commodities are routed to meet specific requirements in the FDPs. Local demand can also take place at EDPs. Local purchases in some EDPs can complement the humanitarian organization supply. Stocks can be prepositioned in EDPs, conditioned on available warehouse space, to address uncertainties in routes availability and FDP accessibility during rainy season. There are no cross flows between FDPs. Humanitarian aid deliveries to FDPs are routed to meet local beneficiary demand. We model the aid supply and distribution system as a transshipment model with ports as sources, EDPs as intermediate transshipment nodes, and FDPs as destinations. The model minimizes supply, stock, transportation, and unmet demand costs incurred by distributing humanitarian aid items in the primary and secondary transport network.

The Humanitarian Aid Supply and Distribution Model (HASD)

Model Overview

The model, denominated as the humanitarian aid supply and distribution model, was formulated as a two-stage stochastic linear program with fixed recourse (Dantzig, 1955). Uncertainties are discretely represented by a set of scenarios Ω, where ω ($\omega \in \Omega$) captures a possible realization of a scenario from a finite sample space. The probability that the *ω-th* scenario will occur is represented by P^ω ($P^\omega \geq 0, \sum_{\omega=1}^{|\Omega|} P^\omega = 1$). Below, we present the nomenclature adopted in our two-stage stochastic linear program:

Indices and index sets	
N	Set of nodes; $(n, n1) \in N$
I	Set of ports; $i \in I \subset N$
K	Set of extended delivery points/ hubs; $k \in K \subset N$
J	Set of final destination points – FDPs; $j \in J \subset N$
Ω	Set of scenarios; $\omega \in \Omega$
Deterministic parameters (unit)	
SC_n	Supply cost of food commodities to be delivered at node n; $n \in I \cup K$ (US$/t)
PC_k	Prepositioning cost of food commodities at node k; $k \in K$ (metric-tons - t)
M_k	Maximum limit for local purchases of food commodities to be delivered at node k; $k \in K$ (t)
L_k	Storage capacity at node k; $k \in K$ (t)
Scenario-dependent parameters (units)	
D_n^ω	Demand at node n under scenario ω; $n \in K \cup J$ (t)
Q_n^ω	Maximum limit for unmet demand at node n under scenario ω; $n \in K \cup J$ (t)
$TC_{n,n1}^\omega$	Transportation cost from origin n to destination $n1$ under scenario ω; $n \in I \cup K$ and $n1 \in K \cup J$ (US$/t) $TC_{n,n1}^\omega = c_{n,n1}^\omega * d_{n,n1}^\omega$, the transportation cost is given by the product of the transport rate $c_{n,n1}^\omega$ (US$/km/t) and the distance $d_{n,n1}^\omega$ – from origin n to destination $n1$ under scenario ω
A_n^ω	$\in \{0,1\}$, 1 if node n is accessible by any route under scenario ω, 0 otherwise; $n \in K \cup J$
W_n^ω	Penalty for unmet demand at node n under scenario ω; $n \in K \cup J$ (US$/t)
P^ω	Probability of scenario ω occurring
First-stage decision variables (unit)	
s_n	The amount of food commodities supplied to be delivered at node n; $n \in I \cup K$ (t)
e_k	The amount of food commodities prepositioned (stock level) at node k; $k \in K$ (t)
Second-stage decision variables (unit)	
$x_{n,n1}^\omega$	The amount of food commodities dispatched from origin n to destination $n1$ under scenario ω; $n \in I \cup K$ and $n1 \in K \cup J$ (t)
y_n^ω	The unsatisfied demand for food commodities at node n; under scenario ω $n \in K \cup J$ (t)

Mathematical Formulation

Our proposed stochastic model can be represented as follows:

$$Min \quad \sum_{n\in I\cup K}^{|I\cup K|}\left(SC_n s_n\right)+\sum_{k\in K}^{|K|}\left(\left(SC_n+PC_k\right)e_k\right)+\sum_{\omega\in\Omega}^{|\Omega|}\sum_{n\in I\cup K}^{|I\cup K|}\sum_{n1\in K\cup J}^{|K\cup J|}P^{\omega}\left(TC_{n,n1}^{\omega}x_{n,n1}^{\omega}+W_{n1}^{\omega}y_{n1}^{\omega}\right) \tag{1}$$

$$S.t.: \quad e_k \le L_k \quad \forall k\in K \tag{2}$$

$$s_k \le M_k \quad \forall k\in K \tag{3}$$

$$\sum_{n\in K\cup J}^{|K\cup J|}\left(A_n^{\omega}x_{i,n}^{\omega}\right)=s_i \quad \forall i\in I,\omega\in\Omega \tag{4}$$

$$\sum_{n\in K\cup J}^{|K\cup J|}\left(A_n^{\omega}x_{k,n}^{\omega}\right)\le s_k+e_k+\sum_{n\in I\cup K}^{|I\cup K|}\left(A_k^{\omega}x_{n,k}^{\omega}\right) \ \forall k\in K,\omega\in\Omega \tag{5}$$

$$y_k^{\omega}=D_k^{\omega}-\left(s_k+e_k+\sum_{n\in I\cup K}^{|I\cup K|}\left(A_k^{\omega}x_{n,k}^{\omega}\right)-\sum_{n\in K\cup J}^{|K\cup J|}\left(A_n^{\omega}x_{k,n}^{\omega}\right)\right) \ \forall k\in K,\omega\in\Omega \tag{6}$$

$$y_j^{\omega}=D_j^{\omega}-\left(\sum_{n\in I\cup K}^{|I\cup K|}\left(A_j^{\omega}x_{n,j}^{\omega}\right)\right) \ \forall j\in J,\omega\in\Omega \tag{7}$$

$$y_n^{\omega}\le Q_n^{\omega} \quad \forall n\in K\cup J,\omega\in\Omega \tag{8}$$

$$s_n, e_n, x_{n,n1}^{\omega}, y_j^{\omega}\in\Re^{+} \tag{9}$$

The objective function (1) contains a deterministic term ($SC_n s_n+\left(SC_n+PC_k\right)e_k$), which models the supply purchase and the prepositioning stock decisions. The second term of equation (1) contains the expected value of the second-stage objective ($P^{\omega}\left(TC_{n,n1}^{\omega}x_{n,n1}^{\omega}+W_{n1}^{\omega}y_{n1}^{\omega}\right)$) which models the cost of the stochastic network flow decisions (transportation and penalty costs) under first-stage decisions. Uncertainty is introduced through the demand for humanitarian aid, transport rates, and route accessibility.

Constraint (2) limits the prepositioned stock to the capacity of the EDPs and constraint (3) limits de local purchases at EDPs. Because we assume that the humanitarian organization distributes all sourced supply among beneficiaries, we state the constraints capturing the balance-of-flow rule for ports with an equal sign. Constraint (4) states that for each port i and scenario ω, the sum of all outflows equals the available internationally purchased supply (s_i). Constraint (5) determines that, for each hub k and scenario ω, local purchases (s_k) plus the prepositioned stock (e_k) and the sum of all inflows ($\sum_{n \in I \cup K}^{|I \cup K|} A_k^{\omega} x_{n,k}^{\omega}$) have to be greater than the sum of all outflows ($\sum_{n \in K \cup J}^{|K \cup J|} A_n^{\omega} x_{k,n}^{\omega}$). Constraints (6) and (7) define the unsatisfied demand for humanitarian aid items in EDPs and FDPs, respectively. Constraint (8) limits the unmet demand at EDPs and FDPs. Finally, constraints (9) define the non-negativity of the variables.

Case Study

We apply our model to WFP primary and secondary problem of distributing food aid in Ethiopia. WFP makes first-stage food supply and prepositioning decisions, and second-stage food aid distribution to meet beneficiary demand in multiple FDPs, taking into consideration, uncertainty in beneficiary demand, limited warehouse capacities, and limited hub accessibility during rainy season.

Country Overview: Ethiopia

Ethiopia, located in the eastern part of Africa, is the second most populous country in Africa with 82 million people and a high population growth rate of 2.9% per year. High population density and rapid population growth coupled with severe land degradation, low levels of rural investment and uneven rainfall patterns drive Ethiopia's food insecurity. Despite continued efforts, the government of Ethiopia requires external support to make food available to its people. For decades, the World Food Program has prominently collaborated with the government to feed Ethiopia's population. However, food distribution in Ethiopia poses significant logistics challenges. For instance, Ethiopia has no direct access to the sea, depending on neighboring countries ports' for international shipments and is bordered by Somalia in the East, Sudan in the West, Djibouti in the North, and Kenya in the South. The country is divided in 9 ethnic-based regions, plus the capital, Addis Ababa, and the city administration of Dire Dawa. WFP operates mainly in the Somali region of Ethiopia (one of the 9 ethnic-based regions).

Case Description

We used a number of different methods to gain deeper understanding of the problem. One of the authors, a logistics officer of WFP Ethiopia (1) engaged in discussions with WFP logistics experts, (2) made a number of field site visits to hubs and FDPs in the Somali Region, and (3) was deeply involved in WFP operations work. Finally, the authors reviewed all available WFP project literature relevant to the project.

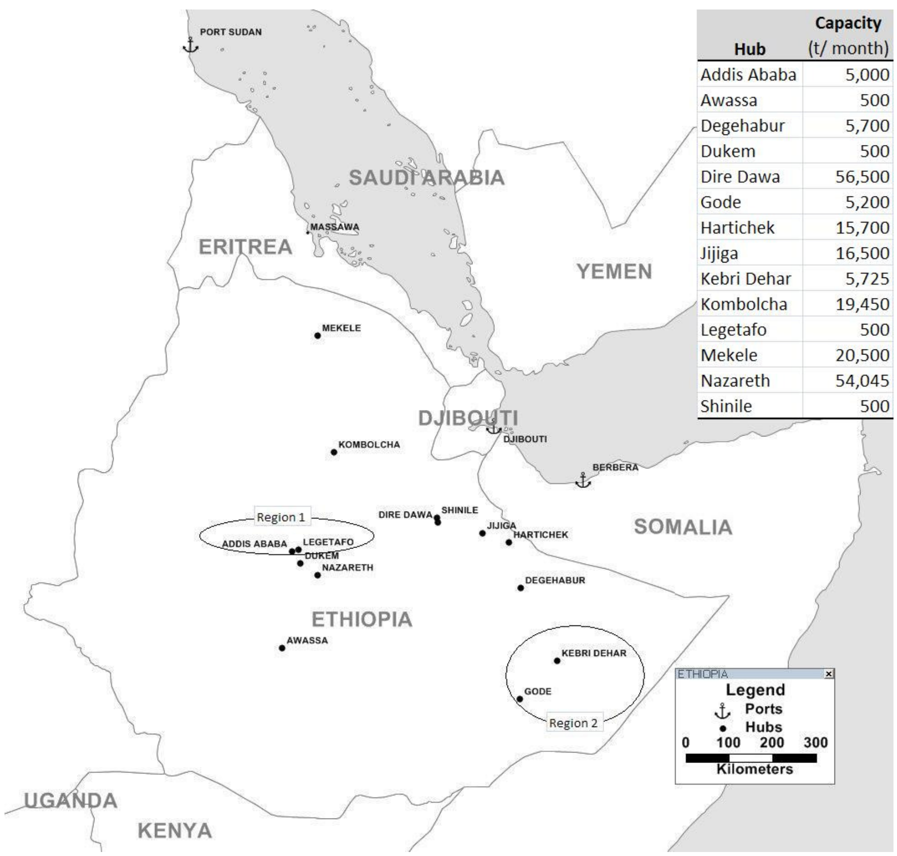
To implement our model, we use actual data from WFP Ethiopia's operations in 2009 and 2010. The collected data encompass all food aid delivered by WFP Ethiopia as part of its humanitarian programs, accounting for 98% of the food aid handled by WFP in the country. Table 1 summarizes the information about the case study:

Table 1 – General Case Description (US$/t)

Year	**Nodes**	SC_n (US$/t)	PC_k (US$/t)	**Average Demand** ('000 t)
2009	70 nodes (3 ports, 13 hubs, 54 FDPs)	371.2	44.5	970
2010	76 nodes (3 ports, 13 hubs, 60 FDPs)	390.6	46.9	671

The supply costs represent actual data available in WFP (2010a). Prepositioning costs accounted for 12% supply costs, according to WFP records. Local purchases for each hub were limited up actual supply purchases in 2009 and 2010. Total local purchases were limited up to 30% of international purchases. Unmet demand was limited up to 30% of the demand at each node. The penalty cost was set to US$ 100/t.

We establish the scenarios of the stochastic model based on the collected data and direct contraposition of primary and secondary research data. The scenarios capture the uncertainty in the demand and hub accessibility and are consistent with the real problem setting. Both scenarios and associated probabilities were validated by WFP Ethiopia's logistics experts. High and low demand scenarios consider 20% of deviation from the average demand. Given the regional topology, seasonal rains and flooding may also affect the accessibility of hubs in two different regions (Figure 1). In region 1, flooding may limit access to Addis Ababa and Legetafo; in region 2, it may limit access to Gode and Kebri Dehar. We consider both cases where (a) roads reaching regions 1 and 2 from the North are not accessible during rainy season, requiring access by alternative routes, and (b) all roads reaching these regions are not accessible, requiring the hub to shut down. In the case of a hub shut-down, the demand traditionally met by shipments from that hub can be met by a nearby hub (e.g., Dire Dawa can substitute for hubs in region 1 and Degehabur for those in region 2).



Hub	Capacity (t/ month)
Addis Ababa	5,000
Awassa	500
Degehabur	5,700
Dukem	500
Dire Dawa	56,500
Gode	5,200
Hartichek	15,700
Jijiga	16,500
Kebri Dehar	5,725
Kombolcha	19,450
Legetafo	500
Mekele	20,500
Nazareth	54,045
Shinile	500

Figure 1 – Ports and hubs locations and affected regions during the rainy season in Ethiopia

Assuming that the random variables are independent, these parameters can be combined to create the scenarios presented in Table 2.

Table 2 – Scenarios, probabilities, and description

Scenarios		Demand		
Hub accessibility		Base (50%)	High (30%)	Low (20%)
Normal road conditions	(40%)	ω_1 (20%)	ω_6 (12%)	ω_{11} (8%)
Region 1 not accessible by North	(20%)	ω_2 (10%)	ω_7 (6%)	ω_{12} (4%)
Hubs in region 1 shut down	(10%)	ω_3 (5%)	ω_8 (3%)	ω_{13} (2%)
Region 2 without access by North	(20%)	ω_4 (10%)	ω_9 (6%)	ω_{14} (4%)
Hubs in region 2 shut down	(10%)	ω_5 (5%)	ω_{10} (3%)	ω_{15} (2%)

Computational Results

The HASD model was implemented using the Advanced Integrated Multidimensional Modeling Software - AIMMS and solved using the CPLEX 12.4 solver on a 4 GB laptop computer. Table 3 summarizes the model statistics:

Table 3 – Model Statistics

Year	#Variables	#Constraints	#Nonzeros	Solution time (s)
2009	13,630	2,258	65,927	0.05
2010	15,097	2,438	73,130	0.05

Solution Interpretation and Analysis

Table 4 presents the actual data, the deterministic solution, and the stochastic solution considering the 15 scenarios of our case study.

Table 4 – Stochastic and Deterministic Solutions x Actual Data (million US$)

	2009			2010		
Costs (million US$)	**Stochastic Solution**	**Deterministic Solution**	**Actual data**	**Stochastic Solution**	**Deterministic Solution**	**Actual data**
Supply	405.77	340.26	360.15	275.70	244.17	262.25
Stock	22.73	22.27	43.22	23.61	20.25	31.47
Transportation	44.66	45.46	65.16	27.23	28.72	38.56
Penalty	7.16	-	-	17.90	-	-
Total	479.62	408.00	468.53	344.43	293.14	322.27
Savings	-11.09	60.53		-22.16	39.14	

In 2009 WFP Ethiopia handled over 970,000 metric tons (t) of food aid, with an associated supply cost of US$360 million, a stock cost of US$43 million, and a distribution cost of over US$65 million for transportation from ports to final delivery points. Taking the demand at hubs and final destination points as inputs to our model, the deterministic solution shows stock costs of US$22 million and distribution costs of US$45 million, without affecting service level. Hence, the optimal supply and distribution of commodities in 2009, would lead to potential cost savings of US$60 million (13% of the total US$468 million program cost). In half 2010 WFP handled about 670,000 t of food aid from ports to final delivery points with transportation costs of about US$39 million and stock costs of US$31 million. The deterministic model solution shows that the optimal transshipment moves 609,000 t for US$29 million and US$20 million of stock cost. Hence, the optimal transshipment of commodities in 2010, would lead to potential cost savings of 12% (of the US$332 million total), or US$39 million. These findings indicate that WFP Ethiopia can significantly reduce costs by incorporating optimization practices in its operations planning.

Considering that the standard food basket used in Ethiopia for relief and safety net project activities costs about US$44.82/person/month (for food only excluding other costs), the savings available for the deterministic solution in 2009 (US$ 60 million) would allow WFP to feed an additional 112,543 people for an entire year. The savings available for the deterministic solution in 2010 (of US$39 million) would allow WFP to feed 72,768 people for an entire year. Alternatively, considering the cost of US$ 50 to feed a child for an entire school year, savings in 2009 would provide meals for 1,210,605 children; savings from 2010 would provide meals for 782,754 children. Savings in supply and transportation costs could impact tens of thousands of people in need.

Compared to the deterministic solution, the stochastic solution increases total costs by 16% (US$66 million) in 2009 and 17% (US$49 million) in 2010. While transportation costs actually decrease in both instances, a total increase comes as a consequence of supply, stock, and penalty costs arising from addressing the uncertainty in demand and hub accessibility in the model. Total supply and stock of food aid in the stochastic solution are 18% and 13% higher than the deterministic solutions for 2009 and 2010, respectively. These additional amounts are needed to minimize unmet demand in the scenarios with high demand (18,350 t and 45,885 t for each one of the scenarios 6 to 10 in 2009 and 2010, respectively).

In order to properly evaluate the added-value of including uncertainty in the problem parameters, the models can be evaluated using the Expected Value of Perfect Information (EVPI) and the Value of the Stochastic Solution (VSS) (Birge and Louveaux, 1997). The EVPI measures the maximum amount the decision maker is willing to pay in order to get accurate information on the future. The VSS, on the other hand, can be interpreted as the benefit expected by the agent that has taken uncertainty into account. EVPI results for 2009 and 2010 reached US$ 63.14 million and US$ 45.22 million, respectively. VSS results for 2009 and 2010, on the other hand, reached US$ 102.24 million and US$ 104.92 million, respectively. So, these results highlight the benefit of incorporating uncertainty in the different model parameters of the food aid distribution chain, as expressive gains were obtained by the inclusion of uncertainty into the problem. Therefore, we concluded that the stochastic optimization results are suitable to the real planning activities of food aid distribution chain and that it may be a useful tool to support adequate decisions for WFP Ethiopia.

Conclusion

We propose a two-stage stochastic linear programming model for the strategic food aid supply and distribution planning to account for uncertainties in demand and road/ hubs accessibility in flooded areas during the rainy season. Based on data collected extensively at WFP Ethiopia's headquarter and several field locations, we find optimal solutions for food aid distribution routes and amounts for 2009 and 2010. Our results suggest that WFP Ethiopia can significantly improve its food aid distribution saving millions of dollars every year. The higher costs in the stochastic model reflect optimal decisions under significant uncertainty. In fact, optimal solutions of deterministic models may become infeasible even if the nominal data is only slightly perturbed. If some of the uncertain scenarios materialize, the actual costs of business-as-usual decisions would be much higher. Thus, uncertainties are inevitable and prevalent in enforcing the planning model to realistic solutions. The values obtained for EVPI and VSS also indicated the benefit of incorporating uncertainty into the model random parameters. The current model can be used by WFP logisticians to plan supply and transportation costs and food aid movement; to identify optimal routes and load point locations (ports, hubs and final delivery points); and to prepare budget forecasts for food aid transportation. In the future WFP is considering expanding the work to include cost-effectiveness analyzes and decisions on the quarterly plan for setting potential forward hubs requirements.

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