Tactical Network Planning for Food Aid Distribution in Kenya


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Outline

- Context: humanitarian logistics
- The network design problem
  - Field work and data collection
  - Mathematical formulation
- Results
- Conclusions and future research directions
Humanitarian logistics

The process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for the purpose of meeting the end beneficiaries’ requirements.

A. Thomas and M. Mizushima (2011)
Disaster response
The Federal Emergency Management Agency (FEMA) defines a disaster as:
« an event that causes 100 deaths or 100 human injuries or damage worth 1 million dollars »

Development projects
Also involve human suffering and economic damage, but **covering longer time-spans**
Their cause can usually not be traced back to a specific catastrophic event
East Africa struggles with...

- Extreme poverty and rapid population growth
- Wars and population migrations
- Diseases (malaria, HIV/AIDS, ...)
- Gender issues and lack of education
- Governance challenges
- Fragile food production systems
- Recurrent droughts and floods
- Food insecurity
Food insecurity

- Hunger and malnutrition are the greatest risks to global health (World Food Programme, UN)
- Eradicating extreme poverty and hunger is the first goal of the eight UN Millennium Development Goals
- Sub-Saharan Africa is the only region in the world suffering from persistent chronic food insecurity

Acute food insecurity as of today

Source: FEWS NET
Food aid as an instrument to reduce food insecurity

Food aid
- Providing food and related assistance to tackle hunger, either in emergency situations, or to help with deeper, longer term hunger alleviation and achieve food security
- This project focuses on in-kind food donations to beneficiaries

Kenya
- Between 1988 and 2011
  - 182,000 MT per year on average (FAO)
- Number of beneficiaries
  - 14.3 million people in 2013-2014
- Main causes
  - Poverty
  - Seasonal droughts
  - Refugee camps (about 480,000 refugees in Dadaab and Kakuma)
Objective of this project

- **Objective:** Improve the design of the food aid distribution network taking into account the welfare of multiple stakeholders

- **Scope:** Determination of final delivery points, last-mile of food aid distribution

- **Methodology:** Mathematical programming
  - Problem class: Facility location and coverage problems

- **Geographical coverage:** Garissa district, Kenya
The World Food Programme (WFP) of the United Nations
- The largest humanitarian agency, aims to fight against hunger in the world
- Know-how in the areas of food security analyses, nutrition, food procurement and logistics (transportation and warehousing)

Kenya Red Cross
- Run different projects (services): famine, education, blood, first aid, disaster and emergency
Scientific contributions

- The main challenge of the project lies more in modeling the problem, carrying out data collection and processing, and performing analyses than on algorithmic development.

- Describe the logistics processes of food aid distribution and estimate stakeholders’ costs.

- First paper to apply optimization tools using real data in the context of last-mile food aid distribution in Africa and computing stakeholders’ tradeoff costs.
Steps

1. Understand the food distribution process
2. Determine the network parameters
   - Demand
   - Potential FDP locations
   - Distances
3. Estimate the stakeholder cost functions
   - Beneficiaries
   - World Food Programme (WFP)
   - Kenya Red Cross
4. Formulate and solve the mathematical models
5. Estimate tradeoffs
Step 1: Understanding the food distribution process

- Field work
  - Interviews
  - Facility visits
  - Food distribution observation

- Food distribution process
Legend:
- Hub
- EDP
- FDP
- Primary transport
- Secondary transport
- Food entries (international transport)

Extended Delivery Point (EDP)

Final Delivery Point (FDP)
Food aid regional supply chain
Operations and stakeholders

Stakeholders

Operations

Food aid

WFP & Red-Cross

Red-Cross & Community

Beneficiaries

EDP Garissa

Secondary transport

FDPs

Hand-out (distribution)

Garissa and its surroundings

This project!
Why Garissa and its surroundings?

- One of the most vulnerable regions in Kenya
  - 35% of the region’s population received food aid in the last 12 years (62% during the most difficult period)
  - High poverty rate
  - Arid land with low rainfall
  - Pastoralism is the dominant livelihood system

- Food aid is constant
  - Fixed distribution system which justifies the need for an optimized network
Activities/Responsibilities at the EDP and a FDPs
Activities/Responsibilities at a FDP

- **“Community Relief Committee”**
  - Elected by the community
  - Trained by Red Cross
  - Targeting, record keeping, arrange food distribution, provide storage and ensure security

- **Red Cross**
  - Ensure that food assistance reaches beneficiaries
  - Assist the community
Activities/Responsibilities at a FDP

- **Food aid:**
  - Vegetable oil
  - Sorghum (cereal)

- **Unloading**
- **Truck arrival**
- **Records:**
  - Beneficiary book
  - Distribution book
Activities/Responsibilities at a FDP

- Shipment management
  - Counting
  - Signing waybill
  - Losses/damaged bags
Activities at a FDP

- Distribution
  - “Scooping”
  - Hand-out (distribution)
  - Donkey transportation service
Tactical “FDP” location problem

Nodes:
- Population points ($\mathcal{V}_1$)
- Potential FDP locations ($\mathcal{V}_2$

Costs:
- Transportation costs (WFP)
- Location and hand-out costs (Kenya Red Cross)
- Access costs (beneficiary opportunity costs)

Garissa EDP
Step 2: Determine the physical network structure

1. Demand
   - Population needs
   - Population locations

2. Potential FDP locations

3. Transportation network (distances)
   - Distance from each population point to closest road
   - Distance from Garissa EDP to each potential FDP locations
   - Distance from each population points to each potential FDP locations
Question 1 – Demand

- Where are the beneficiaries?
  - Geographic Information Systems (GIS) and gridded population data

- How much food are they entitled to?
  - 2012 Short Rain Need Assessment
Need assessment: Determination of the demand for the following 6 months.
Need assessment in Kenya

For each division of Kenya, two parameters are determined (effective for a period of 6 months):
- Number of beneficiaries
- Ration entitlement

Food basket

- 400g of cereal flour/rice/bulgur
- 60g of pulses
- 25 g of oil (vit. A fortified)
- 50 g of fortified blended foods (Corn Soya Blend)
- 15g of sugar
- 15g of iodized salt
2012 Short Rain Assessment for Garissa and its surroundings

Food aid requirement (tonnes/month)
Set of population points \( V_i \)

Source: GIS gridded population data

Needs \( q_i \) at population point \( i \):

\[
q_i = \frac{p_i}{P} B \times \text{ration}
\]

With \( p_i \) the population at \( i \), \( B \) the number of beneficiaries, \( P \) the total population and \( \text{ration} \) the entitled amount of food aid per beneficiary at smallest division level.
Question 2 – Potential FDP locations

- Where are the potential FDP locations?
  - Geographic Information Systems (GIS)
    - Road network
    - Population data
Set of potential FDP locations – $V_2$

Sources: GIS gridded population data and road vectors

Legend

- kenya_roads
- FDP

- Close to a road (≤ 200 m)
- Population center (≥ 20 people)
Question 3 – Transportation distances

- What are the network transportation distances?
  - Geographic Information Systems (GIS)
    - Road network
    - Population data
  - Algorithms
Distances within the network

- Garissa EDP to each potential FDP
  - Road distances
  - Source: Google maps API
  - 1460 distances

- Each population point to each potential FDP
  - Geographical distances
  - Source: GIS
  - 35,701,380 distances
## Network description

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Mean</th>
<th>Std dev.</th>
<th>Median</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population nodes ($</td>
<td>V_1</td>
<td>= 24,453$)</td>
<td>$V_1$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of people</td>
<td>$p_i$</td>
<td>17.36</td>
<td>221.15</td>
<td>5</td>
<td>3</td>
<td>13,793</td>
</tr>
<tr>
<td>Six-month food need per beneficiary (t)</td>
<td>$q_i$</td>
<td>0.02438</td>
<td>0.02442</td>
<td>0.01136</td>
<td>0.0396</td>
<td>0.11534</td>
</tr>
<tr>
<td>Geographical distance to closest route (km)</td>
<td>$d_{i}^{r}$</td>
<td>11.03</td>
<td>9.34</td>
<td>8.49</td>
<td>0</td>
<td>50.34</td>
</tr>
<tr>
<td>Geographical distance to closest potential DC (km)</td>
<td>$d_{ij}^{g}$</td>
<td>11.85</td>
<td>10.91</td>
<td>8.71</td>
<td>0</td>
<td>54.48</td>
</tr>
<tr>
<td>Potential DC nodes ($</td>
<td>V_2</td>
<td>= 1,460$)</td>
<td>$V_2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road distance to MW (km)</td>
<td>$d_{0j}$</td>
<td>106.32</td>
<td>71.41</td>
<td>107.16</td>
<td>0.05</td>
<td>268.93</td>
</tr>
</tbody>
</table>
Step 3: Estimate the stakeholder costs

- Stakeholders that bear costs
  - Beneficiary opportunity costs (access costs)
  - WFP (transportation costs)
  - Kenya Red Cross (location and hand-out costs)

- Data sources
  - Beneficiary questionnaires
  - Contracts between the WFP and the Kenya Red Cross
Beneficiary opportunity costs

- Value of walking time:
  \[0.25 \text{ h/km} \cdot 2 \cdot \text{distance to FDP (km)} \cdot 22.25 \text{ KSh/h}\]
  - Walking time (pace: 4 km/h)
  - Minimum wage rate for unskilled labor

- Value of food transport service (donkey):
  \[20 \text{ KSh} + 2.5 \text{ KSh/km} \cdot \text{distance to FDP (km)}\]
  - Statistics based on a monitoring report for WFP

- Beneficiary opportunity costs:
  \[11.4 \text{ KSh/km} \cdot \text{distance to FDP} (d_{ij}) + 20 \text{ KSh}\]
Transportation costs (WFP)

- The Red Cross contracts and coordinates with local transporters, but WFP fixes secondary transportation rates and pays for the services:

\[
\beta_j = \begin{cases} 
  c_0 & \text{if } d_{0j}^r \in [0, \bar{d}_0] \\
  c_1 d_{0j}^r & \text{if } d_{0j}^r \in (\bar{d}_0, \bar{d}_1] \\
  c_2 d_{0j}^r & \text{if } d_{0j}^r > \bar{d}_1.
\end{cases}
\]

- Transportation costs to serve the FDPs depend on the distance and the quantity of food delivered:

\[
Q_j = \sum_{i \in V_1} q_i x_{ij}
\]
Location and hand-out costs (Kenya Red Cross)

- **Fixed costs**: Relief comity training and registration validation
  - Two workdays for the Red Cross facilitator

- **Variable costs**: Monthly food distribution monitoring
  - Two workdays per month for the Red Cross staff (announcement, dispatch and distribution)

- **Total estimated costs**: $\gamma_j$ KSh
Step 4: Mathematical formulation of the problem

- Define the decision variables
- Determine the objective function
- Formulate the constraints
Decision variables and coverage radius

- **Decision variables**
  
  $y_j$: is equal to 1 if FDP $j$ is selected, 0 otherwise ($j \in V_2$)
  
  $x_{ij}$: proportion of the needs of population $i$ served by FDP $j$
  
  $(i \in V_1(r)$ and $(j \in W_i(r))$

- **Radius of coverage $r$ and $W_i(r)$**

\[ V_1(r) \neq \emptyset \]
Mathematical formulation – Cost Model

\[
\text{minimize } \sum_{i \in V_1(r)} \sum_{j \in W_i(r)} \alpha_{ij} x_{ij} + \sum_{i \in V_1(r)} \sum_{j \in W_i(r)} \beta_j q_i x_{ij} + \sum_{j \in V_2} \gamma_j y_j
\]

subject to

\[
\sum_{j \in W_i(r)} x_{ij} = 1 \quad i \in V_1(r)
\]

\[
x_{ij} \leq y_j \quad i \in V_1(r), \ j \in W_i(r)
\]

\[
x_{ij} \geq 0 \quad i \in V_1(r), \ j \in W_i(r)
\]

\[
y_j \in \{0, 1\} \quad j \in V_2
\]

- Beneficiaries opportunity costs
- Transportation costs (WFP)
- Location and hand-out costs (Kenya Red Cross)

- Demand
- Open FDPs
- Non negativity
- Binary
Step 5: Computational results

- Solve the problem using the CPLEX 12.5 library in a C++ program
  - Optimality gap: 0.1%

- Comparative analyses
  - Impact of the response system structure on the stakeholder welfare costs
  - Compare results of the cost model with classic covering models
Solution illustrations

(a) Solution with $r = 5$ km.
(b) Solution with $r = 55$ km.
## Solution characteristics

<table>
<thead>
<tr>
<th>Solution R (km)</th>
<th>Total Costs (KSh)</th>
<th>Beneficiary Costs (KSh)</th>
<th>Supply Costs (KSh)</th>
<th>Hand-out Costs (KSh)</th>
<th>DCs #</th>
<th>Covered people</th>
<th>Uncovered people</th>
<th>CPU time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>39,564,680</td>
<td>2,659,196</td>
<td>31,299,708</td>
<td>5,605,776</td>
<td>264</td>
<td>0.88</td>
<td>19.94</td>
<td>8.33</td>
</tr>
<tr>
<td>10</td>
<td>38,260,488</td>
<td>3,921,704.3</td>
<td>31,005,046</td>
<td>3,333,738</td>
<td>157</td>
<td>1.43</td>
<td>13.75</td>
<td>10.37</td>
</tr>
<tr>
<td>12</td>
<td>38,099,196</td>
<td>4,401,085</td>
<td>30,852,754</td>
<td>2,845,356</td>
<td>134</td>
<td>1.63</td>
<td>11.90</td>
<td>11.11</td>
</tr>
<tr>
<td>17</td>
<td>38,314,480</td>
<td>5,842,935</td>
<td>30,241,976</td>
<td>2,229,570</td>
<td>105</td>
<td>2.21</td>
<td>7.67</td>
<td>13.18</td>
</tr>
<tr>
<td>25</td>
<td>38,863,984</td>
<td>7,853,155</td>
<td>29,248,408</td>
<td>1,762,422</td>
<td>83</td>
<td>3.01</td>
<td>3.62</td>
<td>16.50</td>
</tr>
<tr>
<td>55</td>
<td>39,449,296</td>
<td>10,767,909</td>
<td>27,322,410</td>
<td>1,358,976</td>
<td>64</td>
<td>4.15</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: The table above shows the solution characteristics for different values of R (km), where R represents the radius of the service area. The columns include total costs, beneficiary costs, supply costs, hand-out costs, number of DCs, covered people, uncovered people, average walk time, proportion, and average walk time for covered and uncovered people. The CPU time is also provided for the CPLEX optimization process.
Covered people as a function of the coverage radius

% of the population covered as a function of $r$

Average walking time per beneficiary as a function of $r$
Uncovered people as a function of the coverage radius:

- Percentage of the population uncovered as a function of $r$

- Average walking time per beneficiary as a function of $r$

Assuming they register to the closest open FDP.
Stakeholder costs

- **Red Cross**: 5% of the total cost on average
- **Beneficiaries**: 22% of the total cost on average
- **WFP**: 73% of the total cost on average

Total welfare cost

- **WFP**: 73% of the total cost on average
- **Beneficiaries**: 22% of the total cost on average
- **Red Cross**: 5% of the total cost on average
Stakeholder costs per beneficiary

Fair and cost-efficient solutions obtained with: \( r = 10, 11, \ldots, 17. \)

**Fair?**

Complying with The Sphere Project Standards (2014), i.e. 90% of the beneficiaries should be covered within a one-day return walk.

Here, about 92% of the people are covered with an average walking time of 2 hours.
### Tradeoff between beneficiary and transportation costs

#### Minimizing beneficiary opportunity costs
- Average % of decrease in average walking time per beneficiary: 37%
- Average % of increase in transportation costs: 14%

#### Minimizing supply transportation costs (WFP)
- Average % of decrease in transportation costs: 15%
- Average % of increase in beneficiary average walking time: 188%

A small increase in WFP costs can yield a large reduction in beneficiary opportunity costs.
Coverage Model

- Maximize covered need with 156 FDPs

\[
\begin{align*}
\text{maximize} & \quad \sum_{i \in V_1(r)} q_i z_i \\
\text{subject to} & \quad z_i \leq \sum_{j \in W_i(r)} y_j \quad i \in V_1(r) \\
& \quad \sum_{j \in V_2} y_j = \bar{w} \\
& \quad 0 \leq z_i \leq 1 \quad i \in V_1(r) \\
& \quad y_j \in \{0, 1\} \quad j \in V_2.
\end{align*}
\]
Comparative analysis – Coverage

Comparison of the % of covered people obtained with the cost model and the coverage model with 156 FDPs

Less covered people when $r \leq 10$
Comparative analysis – Stakeholder costs

- Comparison of the stakeholder costs obtained with the cost model and the coverage model with 156 FDPs

Larger beneficiary and WFP costs for all $r$, but similar cost when $r = 10$ km
Conclusions

- Defined a framework to optimize food aid distribution networks (FDP locations)
- Highlighted the importance of valuing the beneficiaries’ time
- Found transportation costs to be the largest costs
- Found that, taking beneficiary opportunity costs into account, a relatively low value of $r$ minimizes total costs

Next steps:

- How to design food aid supply chains that will lead to a more sustainable response and favour long-term economic growth?
Emerging aid systems
Sustainable food security and resilient supply chains

- **Cash and Vouchers**
  - Cash transfers provide money to people who are struggling to provide food to their families
  - Vouchers can be redeemed for food items or « spent » in selected shops

- **Local purchase**
  - WFP purchases locally in developing countries in its criteria of price, quality and quantity can be met

- **Purchase for Progress**
  - Test new procurement approaches best suited for small producers
  - Support farmers to get better yields, reduce losses, improve the quality of their crops and connect them to markets
Future research

- Dynamic and stochastic problem at the national level

- Procurement:
  - International
  - Local

- Two type of commodities
  - Food
  - Cash & vouchers

- Effect on local markets and food production

- Stakeholders
  - WFP and Kenya Red Cross
  - Beneficiaries
  - Local producers and traders
  - Non beneficiaries
Discussion

Questions and discussion...