OR to the rescue: Increasing disaster preparedness by pre-positioning emergency supplies

Renata Turkeš, Kenneth Sörensen

Antwerp, 28th January 2019
Palestine: 2.5 million people in need of humanitarian assistance.
Yemen: 24 million people in need of humanitarian assistance.
Iraq: 6.7 million people in need of humanitarian assistance.
Somalia: 4.2 million people in need of humanitarian assistance.
Syria: 13 million people in need of humanitarian assistance.
Ukraine: 3.5 million people in need of humanitarian assistance.
Indonesia: 1.5 million people in need of humanitarian assistance.
Pre-positioning emergency supplies
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Scenario 1, \( P_1 = 0.9 \)

Scenario 2, \( P_2 = 0.18 \)
Pre-positioning emergency supplies

Scenario $s = 1$, $P^1 = 0.9$

Scenario $s = 2$, $P^2 = 0.1$
Pre-positioning emergency supplies

Problem definition

Develop a pre-positioning strategy that determines:

- Location and size of storage facilities ($x_i \in \{0, 1\}$),
- Quantities of various types of emergency supplies stocked in each facility ($y_k \in \mathbb{R}_+^0$),
- Distribution of the supplies to demand locations after an event ($z_{ij} \in \{0, 1\}$),

under uncertainty about demands, survival of pre-positioned supplies and transportation network availability.
Pre-positioning emergency supplies

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Pre-positioning emergency supplies

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\[(x, \text{location and size of storage facilities, } x_i \in \{0, 1\}), (y, \text{quantities of various types of emergency supplies stocked in each facility, } y_k \in \mathbb{R}_+), (z, \text{distribution of the supplies to demand locations after an event, } z_{ij} \in \{0, 1\})\]

under uncertainty about demands, survival of pre-positioned supplies and transportation network availability.
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Pre-positioning emergency supplies

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under uncertainty about demands, survival of pre-positioned supplies and transportation network availability.
Toy pre-positioning problem instance with 3 vertices, 2 facility categories, 2 commodity types and 2 scenarios.

<table>
<thead>
<tr>
<th>Facility category</th>
<th>Capacity (m$^3$)</th>
<th>Opening costs (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>small</td>
<td>1000</td>
<td>15000</td>
</tr>
<tr>
<td>big</td>
<td>7000</td>
<td>50000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Volume (m$^3$)</th>
<th>Acquisition cost (€)</th>
<th>Transportation cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>4.00</td>
<td>647.70</td>
<td>0.30</td>
</tr>
<tr>
<td>food</td>
<td>2.36</td>
<td>5420.00</td>
<td>0.40</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Budget type</th>
<th>Budget (€)</th>
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</thead>
<tbody>
<tr>
<td>opening facilities</td>
<td>100 000</td>
</tr>
<tr>
<td>aid procurement</td>
<td>320 000</td>
</tr>
<tr>
<td>transportation</td>
<td>170 000</td>
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</tbody>
</table>
Toy pre-positioning problem instance with 3 vertices, 2 facility categories, 2 commodity types and 2 scenarios.

Scenario $s = 1$, $P^1 = 0.9$

Scenario $s = 2$, $P^2 = 0.1$
Case studies and random instances
Case studies

- Chile 2010 earthquake and tsunami
- Turkey 1999 earthquake
- Senegal disaster threat
- US Gulf Coast hurricane threat

#vertices - #facility categories - #commodity types - #scenarios
Random instance generator

50-2-4-50
50-3-1-100
50-3-3-100
100-2-1-30
100-2-3-200

100-3-3-50
100-3-3-100
200-2-1-50
200-3-3-100
200-3-5-200

#vertices - #facility categories - #commodity types - #scenarios
Appropriate choice of objective function
Humanitarian logistics

The objective of disaster response in the humanitarian relief chain is to rapidly provide relief (emergency food, water, medicine, shelter, and supplies) to affected areas, so as to minimize human suffering and death.
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However, the objective in the most of the models in humanitarian logistics literature is to minimize costs. Why?
Common objective in the literature

\[ \min \sum_{i \in V} \sum_{q \in Q} A_q x_{iq} + \sum_{i \in V} \sum_{k \in K} B^k y_i^k + \sum_{s \in S} P^s \left( \sum_{i \in V} \sum_{j \in V} C^s_{ij} z_{ij}^s \right) + \sum_{i \in V} \sum_{k \in K} U^k u_i^k + \sum_{i \in V} \sum_{k \in K} O^k o_i^k \]
The objective is to provide assistance to the greatest number of people possible, as soon as possible, i.e., to minimize unmet demand

\[
\max \sum_{s \in S} P_s \sum_{i \in V} \sum_{j \in V} D_{sj} z_{si}
\]

response time

\[
\min \sum_{s \in S} P_s \sum_{i \in V} \sum_{j \in V} T_{sj} z_{si}
\]

in lexicographic order, such that the cost of opening the facilities, acquisition cost and transportation cost respect their budget limitations (and other capacity constraints are satisfied).
The objective is to provide assistance to the greatest number of people possible, as soon as possible, i.e., to minimize unmet demand and response time in lexicographic order, such that the cost of opening the facilities, acquisition cost, and transportation cost respect their budget limitations (and other capacity constraints are satisfied).
The objective is provide assistance to the greatest number of people possible, as soon as possible, i.e., to minimize

- unmet demand \( \max \sum_{s \in S} P^s \sum_{i \in V} \sum_{j \in V} D^s_{ij} z^s_{ij} \)
Alternative objective

The objective is to provide assistance to the greatest number of people possible, as soon as possible, i.e., to minimize

- unmet demand: \( \max \sum_{s \in S} P^s \sum_{i \in V} \sum_{j \in V} D^s_{j} Z^s_{ij} \)
- response time: \( \min \sum_{s \in S} P^s \sum_{i \in V} \sum_{j \in V} T^s_{ij} Z^s_{ij} \)
The objective is provide assistance to the greatest number of people possible, as soon as possible, i.e., to minimize

- unmet demand \( \max \sum_{s \in S} P^s \sum_{i \in V} \sum_{j \in V} D^s_{ij} z^s_{ij} \)

- response time \( \min \sum_{s \in S} P^s \sum_{i \in V} \sum_{j \in V} T^s_{ij} z^s_{ij} \)

in lexicographic order, such that the cost of opening the facilities, acquisition cost and transportation cost respect their budget limitations (and other capacity constraints are satisfied).
Theoretical comparison of different modelling approaches

**Theorem**

Let $f : X \rightarrow \mathbb{R}$, $g : X \rightarrow \mathbb{R}$ be arbitrary functions and $\alpha \in \mathbb{R}^+$ an arbitrary positive number. Let further $x_1^*$ be the optimal solution of the optimization problem

\[
\min\{\alpha f(x) + g(x) \mid x \in X\},
\]

and $x_2^*$ be the optimal solution of

\[
\min\{f(x) \mid x \in X \land g(x) \leq g(x_1^*)\}.
\]

Then $f(x_2^*) = f(x_1^*)$. 

For any under- and oversupply penalty costs $U^k = \alpha B^k$ and $O^k = \beta B^k$, the solutions of the two modelling approaches are obtained in comparable time using CPLEX.

<table>
<thead>
<tr>
<th>Instance</th>
<th>Minimize costs</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Minimize unmet demand</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Unmet demand (%)</td>
<td>User runtime (s)</td>
<td>Gap (</td>
<td>Unmet demand (%)</td>
<td>User runtime (s)</td>
<td>Gap (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>(%)</td>
<td></td>
<td></td>
<td>(%)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$\beta$</td>
<td>Unmet demand (%)</td>
<td>A (€)</td>
<td>B (€)</td>
<td>C (€)</td>
<td>Unmet demand (%)</td>
<td>User runtime (s)</td>
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<td>1500000</td>
<td>102905295.80</td>
<td>298546.38</td>
</tr>
</tbody>
</table>
Does putting a price on human life help to save lives?

Putting a price on human life can and therefore should be avoided.
Matheuristic
Since the pre-positioning problem is NP-hard, we developed a matheuristic solution algorithm, which outperforms CPLEX for any given computation time (especially for large instances).
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Are mathematical models and algorithms used in practice to optimize humanitarian logistics processes?
Deriving rules of thumb for facility planning
<table>
<thead>
<tr>
<th>Factor</th>
<th>Notation</th>
<th># levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of potential facility locations</td>
<td>$F$</td>
<td>3</td>
</tr>
<tr>
<td>Facility capacities</td>
<td>$QV$</td>
<td>3</td>
</tr>
<tr>
<td>Facility unit opening costs</td>
<td>$QAV$</td>
<td>3</td>
</tr>
<tr>
<td>Number of scenarios</td>
<td>$S$</td>
<td>3</td>
</tr>
<tr>
<td>Average proportion of aid that remains usable</td>
<td>$R$</td>
<td>3</td>
</tr>
<tr>
<td>Demand graphs</td>
<td>$D$</td>
<td>15</td>
</tr>
<tr>
<td>Transportation network damage</td>
<td>$L$</td>
<td>3</td>
</tr>
<tr>
<td>Facility budget</td>
<td>$AP$</td>
<td>3</td>
</tr>
<tr>
<td>Acquisition budget</td>
<td>$BP$</td>
<td>3</td>
</tr>
<tr>
<td>Transportation budget</td>
<td>$CP$</td>
<td>3</td>
</tr>
</tbody>
</table>
Experimental set-up

Full factorial experiment (with 3 replicates for each factor level combination):

\[ 3 \times 3 \times 3 \times 3 \times 3 \times 15 \times 3 \times 3 \times 3 \times 3 \times 3 = 885735 \] experimental units, i.e. pre-positioning problem instances.

Response variable Notation

Number of small open facilities \( X_1 \)

Number of big open facilities \( X_2 \)
Experimental set-up

Full factorial experiment (with 3 replicates for each factor level combination):

\[ 3 \times 3 \times 3 \times 3 \times 3 \times 15 \times 3 \times 3 \times 3 \times 3 = 885735 \]

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$$3 \times 3 \times 3 \times 3 \times 3 \times 15 \times 3 \times 3 \times 3 \times 3 \times 3 \times 3 = 885,735$$

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<table>
<thead>
<tr>
<th>Response variable</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of small open facilities</td>
<td>$X_1$</td>
</tr>
<tr>
<td>Number of big open facilities</td>
<td>$X_2$</td>
</tr>
</tbody>
</table>
Most important factors ($X_1$)
Most important factor interactions ($X_1$)

Regression model parameter estimates ($X_1$)

Factor interaction
The regression models that include the interactions explain additional 18% and 10% of the variability in the number of small and big open facilities, and thus play an important role in facility decision making.

<table>
<thead>
<tr>
<th>Response variable</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main effects</td>
</tr>
<tr>
<td>$X_1$</td>
<td>0.35</td>
</tr>
<tr>
<td>$X_2$</td>
<td>0.73</td>
</tr>
</tbody>
</table>
Rules of thumb for facility planning

Number of open facilities

$F \rightarrow$ Percentage of potential facility locations, $L \rightarrow$ Transportation network damage
Ignoring interactions can yield misleading conclusions.
Ignoring interactions can yield misleading conclusions.

\[ X_1, QAV = 0.5 \]
\[ X_1, QAV = 0.75 \]
\[ X_1, QAV = 1 \]
\[ X_2, QAV = 0.5 \]
\[ X_2, QAV = 0.75 \]
\[ X_2, QAV = 1 \]

\( BP \rightarrow \) Inventory budget, \( QAV \rightarrow \) Ratio between facility unit opening costs
Using a single case study can yield misleading conclusions.
Using a single case study can yield misleading conclusions

\[ BP \rightarrow \text{Inventory budget, } D \rightarrow \text{Demand graphs} \]
Concluding remarks
Summary of contributions

- Publicly shared set of diverse case studies and random problem instances to support further research.
- Discussion on the choice of the objective function in humanitarian logistics.
- A matheuristic to solve the pre-positioning problem.
- Extensive computational experiment that offers reliable insights into the problem, helps derive guidelines regarding the pre-positioning facility decision making, and promotes better experimental designs in humanitarian logistics.
THANK YOU / DANK U / HVALA

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