On- and off-shore prepositioning and delivery mechanism for sudden-onset disaster response

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Abstract
This paper develops an optimization model based on real-world cases to find a low-cost logistics solution for on- and off-shore based prepositioning of emergency supplies in combination with suitable modes of transport for timely satisfaction of demand of disaster relief items in the aftermath of sudden-onset disasters.

Keywords: Disaster relief, Off-shore, Inventory prepositioning, Optimization, Logistics

Introduction
Improved logistical preparedness has been identified as a key aspect for increasing the effectiveness and efficiency of disaster relief operations (Pettit and Beresford, 2005, Jahre and Heigh, 2008, Rawls and Turnquist, 2010). And prepositioning of emergency relief supplies is an important aspect of planning and preparedness (Majewski et al., 2010). While the strategy of prepositioning in the humanitarian logistics is relatively more recent, it has been practiced by the military in the past (Lee, 1999).

There are shipping lines, which are willing to contribute to the humanitarian organizations in a non-monetary form. This creates the opportunity to preposition disaster relief items at their port terminals (on-shore) as well as on board their ships (off-shore), while traditionally prepositioning of these items used to be only done on-shore at warehouses and distribution centers of the humanitarian organizations. Off-shore prepositioning of the items gives a higher degree of flexibility to the global supply chain of disaster relief with a lower cost. In the absence of on-board inventories, especially during the first weeks after a great disaster, where the need for disaster relief items is both greater and more emergent, humanitarian organizations have to send disaster relief items from far away sites by fast and expensive modes of transport, as air transport, to provide the disaster locations with the needed items on-time. During this early emergency period after disasters, use of the cheaper modes of transport, as sea transport, is limited because of lower speed. However, in case enough inventory of disaster relief
items is prepositioned on-board the vessels (ships) on a liner shipping route, the items can be delivered to a port close to the disaster location once a vessel visits the port. Shortly afterwards, another ship on the same route will visit the port and deliver further items. This helps creating a relatively fast, cheap and stable flow of disaster relief items to the disaster locations without any considerable effect on the schedule of the liner shipping company. Since each liner shipping route visits multiple ports in different geographical areas, prepositioning of items on-board the vessels gives the disaster relief supply chain higher flexibility and responsiveness without either holding high levels of inventories locally (on-shore) at many locations or using fast and expensive modes of transport extensively to supply the needed items on-time.

This paper formulates an optimization model to find levels of prepositioned inventory of disaster relief items both on-board the vessels and at the port terminals of a shipping company cooperating with humanitarian organizations. The model finds a solution that could have minimized the total logistical cost of providing a set of disasters happened in the past with the needed items. The model also considers options such as direct transport from the existing distribution centers and warehouses of the humanitarian organizations. The total logistical cost includes inventory holding, replenishment and transport costs. In addition, the model ensures on-time delivery of all the items needed at all disaster locations.

The rest of the paper is organized as follows. In the following section, the relevant literature will be reviewed. The next section, describes the problem and the corresponding assumptions for which the optimization model will be built. Afterwards, in the model formulation section, the optimization model will be formulated. Finally, in the last section, use, advantages, limitations and future works on the model will be discussed.

**Literature review**

In the context of humanitarian logistics, literature related to prepositioning mainly falls under three streams: facility location, inventory management and network flows (Duran et al., 2011). Akkihal (2006) has solved an array of formulations using mixed-integer linear programs in order to predict optimal facility configurations. Balci and Beamon (2008) have developed a mathematical model in order to determine the number and location of pre-positioning warehouses and suppliers. Additionally, Mecall (2006), Rawls and Turnquist (2010), Salmerón and Apte (2010), Balci and Ak (2013), Mete and Zabinsky (2010) and Jia et al. (2007a) have made significant contributions related to inventory management and pre-positioning of emergency supplies. All these studies have only taken into account land-based pre-positioning.

The concept of sea-based pre-positioning finds considerable attention in the context of military logistics and operations (Clark, 2002). There has been much research related to both conceptual and operational issues related to sea-basing in the military context. Although some of these research works have recognized the possibility and potential of using military’s sea-based pre-positioned assets for humanitarian assistance operations (Beach, (2010), Martinez (2008), Geis (1996), Salmerón et al. (2011), Degrange (2005)), the focus on this issue is understandably quite limited. Furthermore, even in the humanitarian logistics literature, only Tatham and Kovacs (2007) have conducted an investigation on the applicability of sea-basing in disaster relief operations. They have conceptually demonstrated the applicability of sea-basing in the context of 2005 Kashmir earthquake and have claimed that their study makes “a prima facie case for the use of sea-basing concept”. However, they have noted that their primary study needs much further research. Caunhye et al. (2012) in their literature review of optimization models in emergency
logistics have categorized the facility location models in 3 main categories, maximum coverage facility location, location-evacuation and location with relief distribution and stock pre-prepositioning. However, they have not taken into account the distinction between on shore and off shore prepositioning.

Problem statement and assumptions

This paper studies a problem where there is a set of disasters during a planning period in the past. Locations and magnitudes of the disasters are known. There is a set of disaster relief items needed at the disaster locations. Magnitude of each disaster is given in terms of the quantity of disaster relief items needed during the emergency period after the disaster, which is normally the first three months. There are several sources that can provide the disaster locations with the needed items. First of all, there are regional logistics units (RLU) or warehouses around the globe, normally operated by humanitarian organizations, which are replenished by the suppliers of disaster relief items. Also, there are quite big regional terminals, located at ports, belonging to affiliate shipping lines which are replenished directly by the aforementioned suppliers as well. It is assumed that the RLUs and regional terminals have always enough inventories whenever it is needed. The affiliate shipping lines run multiple shipping routes each of which visit a set of ports in a given schedule and sequence. The shipping lines may have smaller local port terminals at these ports. These port terminals can be used to store (preposition) a limited amount of disaster relief items which are replenished by regional terminals. Furthermore, each route is served by a number of vessels (ships) where also a limited amount of disaster relief items can be kept on-board (prepositioned). Vessels can deliver these items to the ports in case a disaster happens. Then, inventory on-board the vessels, if needed, will be replenished whenever they visit a regional terminal.

In order to deliver the items to the disaster locations, items must first be transferred to nearby distribution points. Each disaster location is assumed to have its own dedicated distribution points, where it makes no difference to which distribution point the items are delivered. It is assumed that the distribution points have no limit to receive and store the items. Moreover, there exists one preferred distribution point as the destination to the items sent from each source.

Items can be sent to the distribution points in different ways. They can be sent directly from RLUs and regional terminals by a fast mode of transport, e.g. air. RLUs can also send the items by slower modes of transport, e.g. sea and road, where the transport cost is lower. Regional terminals in addition have the option to send the items indirectly, first by ship to the ports, then from the ports by road or rail to the distribution points. When it comes to the inventory kept at the port terminals, they can be transferred to the distribution points by rail/road transport. If the inventory on-board the vessels is going to be used, it must be first delivered to the ports and then transferred to the distribution points. It is assumed that there is no limit in the capacity of the transport modes. Figure 1 shows an example of the distribution network described above.

Regarding the situation described above and given the capacity limits on-board the vessels and at the port terminals as well as the demand for disaster relief items at disaster locations through the time, two main research questions will be addressed in the paper:

1. How much inventory of each disaster relief item to be prepositioned on-board the vessels and at the port terminals.
2. How much of each item, from which sources, by which modes of transport to be sent to the corresponding distribution points, when a disaster happens.

![An example of the distribution network of disaster relief items](image)

In the next section, an optimization model will be formulated to answer the above questions at the same time. The objective of the model is to minimize the total cost including inventory holding costs on-board the vessels and at the port terminals, replenishment costs and transport costs. Replenishment costs include also costs that are not sometimes classified as replenishment costs, but are paid per replenishment. For example, replenishment cost of the inventory on-board the vessels include loading costs at the regional terminals, unloading cost at the destination ports, cost of loading on trucks, etc.

Other information needed to run the model are transportation costs and times for different modes of transport between the nodes of the network including RLUs, regional terminals, ports/port terminals and distribution points. Transportation times can be calculated given the distance between nodes, average speed and loading/unloading times. In addition, inventory holding rates must be given. These costs can be calculated based on the value of disaster relief items, interest rates and location-specific factors. Another important piece of information is the schedule and sequence of the ports on liner shipping routes. Specifically, the replenishment lead time of the inventory on-board the vessels and port terminals can be calculated based on the average speed of the vessels, stop times at the ports and their distance to the regional terminals. As for each disaster, the location of the vessels must be known when the disaster happens. Last but not least, the demand for the disaster relief items is needed per day/week during the 3-month emergency period after the disasters. Normally, the demand is known for the whole emergency period. A common way to find the demand per day/week is to assume that the aggregated demand is distributed uniformly over days/weeks during the emergency period.

Finally, the other assumptions needed to formulate the model are as follows. It is assumed that the disaster relief items delivered by the vessels on the liner shipping routes to the ports will be immediately dispatched to the corresponding distribution points and will not be stored at the terminals. Furthermore, we assume there is no limit for such deliveries at the ports. Inventory holding costs and replenishment costs at the RLUs, regional terminals and distribution points are not considered in the model, since they are almost not dependent on the decisions made by the model. In other words, the mentioned costs are almost fixed when the demand of the disaster relief items is to be met 100% on time. Moreover, the port terminals will immediately
issue a replenishment order, once they have dispatched items to the distribution points. In addition, transport, replenishment and inventory holding fees and values of the items are assumed to be fixed during the planning period. At last, it is assumed that all the data given, including costs, demand and transport times are deterministic and will not vary in a random manner.

**Model formulation**

The model will be formulated in five stages where indices and sets, data and parameters, decision variables, the objective function and the constraints will be introduced as follows:

**Sets of indices:**
- \( R \): Set of RLUs
- \( G \): Set of regional terminals
- \( P \): Set of ports
- \( V \): Set of vessels on liner shipping routes
- \( D \): Set of disasters
  Note: If multiple disasters happen in (almost) the same location, each disaster must be given a different index in the set.
- \( T \): Set of time periods
- \( S \): Set of disaster relief items

**Parameters/data:**
- \( c_{pdj}^P \): Cost of transporting 1 unit of disaster relief item \( j \) from port/port terminal \( p \) to disaster location (corresponding distribution point) \( d \) on road
- \( c_{rdj}^{RF} \): Cost of transporting 1 unit of disaster relief item \( j \) from RLU \( r \) to disaster location (corresponding distribution point) \( d \) by the faster and more expensive mode of transport (e.g. air)
- \( c_{rdj}^{RS} \): Cost of transporting 1 unit of disaster relief item \( j \) from RLU \( r \) to disaster location (corresponding distribution point) \( d \) by the slower and cheaper mode of transport (e.g. combination of sea and road)
- \( c_{gjp}^G \): Cost of shipping directly (not on liner shipping routes) 1 unit of disaster relief item \( j \) from regional terminal \( g \) to port \( p \)
- \( \tau_{pd}^P \): Transport time of disaster relief items from port/port terminal \( p \) to disaster location (corresponding distribution point) \( d \) on road
- \( \tau_{rdj}^{RF} \): Transport time of disaster relief items from RLU \( r \) to disaster location (corresponding distribution point) \( d \) by the faster and more expensive mode of transport
- \( \tau_{rdj}^{RS} \): Transport time of disaster relief items from RLU \( r \) to disaster location (corresponding distribution point) \( d \) by the slower and cheaper mode of transport
- \( \tau_{gjp}^G \): Direct shipping time of disaster relief items from regional terminal \( g \) to port \( p \)
- \( b_i^V \): Maximum capacity (volume) of vessel \( i \) that can be assigned to store disaster relief items on board
- \( b_p^P \): Maximum capacity (volume) of port terminal \( p \) that can be assigned to store disaster relief items
• $h_{ij}^V$: Cost of holding one unit of disaster relief item $j$ on board vessel $i$ for one time period
• $h_{pj}^P$: Cost of holding one unit of disaster relief item $j$ at port terminal $p$ for one time period
• $k_{ij}^V$: Cost of replenishing one unit of disaster relief item $j$ on vessel $i$
• $k_{pj}^P$: Cost of replenishing one unit of disaster relief item $j$ at port terminal $p$
• $q_{djt}$: Quantity of disaster relief item $j$ needed at disaster location $d$ at period $t$
• $a_{ipt}$: It is 1 if vessel $i$ visits port $p$ at period $t$, and 0 otherwise.
• $a_{igt}$: It is 1 if vessel $i$ visits regional terminal (port) $g$ at period $t$, and 0 otherwise.
• $\rho_p$: Replenishment lead time for port terminal $p$
• $\theta_d$: Time period where disaster $d$ happens
• $m_j$: Volume of one unit of disaster relief item $j$

Decision variables:
• $x_{ij}^V$: [Maximum] inventory of disaster relief item $j$ to be held on board vessel $i$
• $x_{pj}^P$: [Maximum] inventory of disaster relief item $j$ to be held at port terminal $p$
• $I_{ijt}^V$: Inventory level of disaster relief item $j$ on board vessel $i$ at the end of period $t$
• $I_{pjt}^P$: Inventory level of disaster relief item $j$ at port terminal $p$ at the end of period $t$
• $I_{djt}^D$: Total inventory level of disaster relief item $j$ at the distribution points of disaster location $d$ at the end of period $t$
• $y_{ipt}$: Quantity of disaster relief item $j$ delivered from vessel $i$ to port $p$ at period $t$ to be immediately dispatched towards the disaster location $d$
• $y_{pjt}$: Quantity of disaster relief item $j$ dispatched from the inventory held at port terminal $p$ to disaster location $d$ at period $t$
• $y_{rdjt}$: Quantity of disaster relief item $j$ dispatched from RLU $r$ by the faster and more expensive mode of transport to disaster location $d$ at period $t$
• $y_{rdjt}^RS$: Quantity of disaster relief item $j$ dispatched from RLU $r$ by the slower and cheaper mode of transport to disaster location $d$ at period $t$
• $y_{gtp}$: Quantity of disaster relief item $j$ dispatched from regional terminal $g$ to port $p$ at period $t$ to be immediately dispatched from the port towards the disaster location $d$

Objective function:
The objective of the model is to minimize the total cost including transport cost, inventory holding cost and replenishment cost formulated as follows:

• Replenishment cost = $\sum_{d \in D} \sum_{t \in T} \sum_{j \in J} \sum_{p \in P} (k_{pj}^P \cdot y_{pjt} + \sum_{i \in V} k_{ij}^V \cdot y_{ijt})$
• Inventory holding cost = $\sum_{j \in J} \sum_{t \in T} (h_{pj}^P \cdot l_{pjt} + \sum_{i \in V} h_{ij}^V \cdot l_{ijt})$
• Transport cost = $\sum_{d \in D} \sum_{t \in T} \sum_{j \in J} \sum_{p \in P} (c_{p}^P \cdot (y_{pjt} + \sum_{i \in V} y_{ijt}) + \sum_{r \in R} (c_{rd}^RF \cdot y_{rdjt} + c_{rd}^RS \cdot y_{rdjt})))$

Constraints:
• Demand and inventory constraints at disaster locations:
\[ I_{dj}^{p}(t) = I_{dj}^{p}(t-1) - q_{dj} + \sum_{p\in P} \left( y_{pdj}(t-t_{pd}) + \sum_{i\in V} y_{ipdj}(t-t_{pd}) + \sum_{g\in G} y_{gpdj}(t-t_{pd} - r_{pd}) \right) + \sum_{r\in R} \left( y_{rdj}(t-t_{rd}) + y_{rdj}^{RF}(t-t_{rd}) + y_{rdj}^{RS}(t-t_{rd}) \right), \quad \forall d \in D, j \in S, t \in T, t > 0 \] (4)

- \[ I_{dj}^{p} \geq 0, \quad \forall d \in D, j \in S \] (5)
- \[ I_{dj}^{p}(0) = 0, \quad \forall d \in D, j \in S \] (6)

- Inventory constraints at the port terminals:
  - \[ I_{pj}^{p} = I_{pj}^{p}(t-1) - \sum_{d\in D} y_{pdj}^{p} + \sum_{d\in D} y_{pdj}^{p}(t-\rho_{pd}), \quad \forall p \in P, j \in S, t \in T, t > 0 \] (7)
  - \[ I_{pj}^{p} \geq 0, \quad \forall p \in P, j \in S, t \in T, t > 0 \] (8)
  - \[ I_{pj}^{p}(0) = x_{pj}^{p}, \quad \forall p \in P, j \in S \] (9)

- Inventory constraints on the vessels:
  - \[ I_{ij}^{V} = I_{ij}^{V}(t-1) - \sum_{d\in D} y_{pdj}^{V} + a_{ij}^{V} \cdot (x_{ij}^{V} - I_{ij}^{V}(t-1)) \), \quad \forall i \in V, j \in S, t \in T, t > 0 \] (10)
  - \[ I_{ij}^{V} \geq 0, \quad \forall i \in V, j \in S, t \in T, t > 0 \] (11)
  - \[ I_{ij}^{V}(0) = x_{ij}^{V}, \quad \forall i \in V, j \in S \] (12)

- Delivery is possible only when a vessel visits a port:
  - \[ \sum_{d\in D} \sum_{j\in S} y_{pdj}^{V} \leq M \cdot a_{ipt}, \quad \forall i \in V, p \in P, t \in T \), where \( M \) is a very big positive number. \] (13)

- Capacity constraints on vessels:
  - \[ 0 \leq \sum_{j \in S} m_{j} \cdot x_{ij}^{V} \leq b_{i}^{V}, \quad \forall i \in V \] (14)

- Capacity constraints at ports terminals:
  - \[ 0 \leq \sum_{j \in S} m_{j} \cdot x_{jp}^{p} \leq b_{p}^{V}, \quad \forall p \in P \] (15)

- Constraints to assure no item can be dispatched towards a disaster location, before the disaster happens:
  - \[ y_{pdj}^{V} = y_{gdj}^{G} = y_{rdj}^{RF} = y_{rdj}^{RS} = 0, \quad \forall i \in V, p \in P, j \in S, g \in G, r \in R, d \in D, t \in T, t < \theta_{d} \] (16)

- Sign constraints:
  - \[ y_{pdj}^{V}, y_{gdj}^{G}, y_{rdj}^{RF}, y_{rdj}^{RS}, x_{ij}, x_{jp} \geq 0, \quad \forall i \in V, p \in P, j \in S, g \in G, r \in R, d \in D, t \in T \] (17)

Note: For the sake of readability and to avoid showing one group of constraints several times for specific cases, the inventory constraints at distribution points, port terminals and vessels are written such that the transport variables, i.e. \( y_{ipdj}^{V}, y_{pdj}^{p}, y_{gpdj}^{G}, y_{rdj}^{RF} \) and \( y_{rdj}^{RS} \), might sometimes take negative time index that is meaningless. Therefore, in the aforementioned constraints, let \( y_{ipdj}^{V}, y_{pdj}^{p}, y_{gpdj}^{G}, y_{rdj}^{RF} \) and \( y_{rdj}^{RS} \) be zero, wherever \( t < 0 \).

**Advantages and limitations of the model, further research and conclusion**

As for the advantages of the model, a major one is its comprehensiveness and flexibility. Many real-world cases can be formulated as specific examples of this very general model by just deactivating or adjusting some of its features. An example will be given later in this section.
Furthermore, the model above can be used for both tactical and operational planning. Tactical planning is to determine the level of inventory of disaster relief items on board the vessels and at the terminals, while operational planning is to decide on how much, when and by which mode to send disaster relief items from each node in the network to each other node. In order to perform only operational planning, decision variables that specify tactical decisions, i.e. $x_{ij}$'s and $x_{pj}$'s, must be fixed as parameters. Then, at the time a new disaster happens the model must be run to determine the other variables while the planning horizon is just the emergency period after the disaster. Moreover, the model ensures a 100% service level at the lowest cost possible when it comes to supply of emergency items for disasters. Last but not least, the model is a pure linear programming that makes it possible to be solved in reasonable time by the existing solvers, even for very large problems.

When it comes to the limitations of the model, it must be noted that the tactical decisions are dependent, though probably not significantly, to the locations of the vessels at the beginning of the planning period. To avoid that, a simulation model can be made to study the sensitivity of these decisions to various randomly generated scenarios for the initial locations of the vessels. After the simulation is run, the tactical solutions will be chosen that produce the minimum cost on average. Another limitation of the model is that strategic decisions like location of RLUs and regional terminals are assumed to be given as fixed inputs to the model. However, by defining corresponding variables, such decisions can also be easily incorporated in the model. Nevertheless, the model will no longer be a pure linear programming, but a linear mixed integer programming, that makes it difficult, and even sometimes impossible, for very large problems to be solved. Finally, the most important limitation of the model is its deterministic, retrospective and static approach to decision making. The tactical decisions are made based on deterministic data from the past disasters. These tactical decisions will be used as a framework for future operational decisions. Nonetheless, both the growth of the disasters (in magnitude and number) in the future and the random nature of the disasters are neglected. An appropriate way to incorporate the growth and randomness of the disasters is to model them in the form of non-homogenous stochastic processes. However, this needs an extensive study on forecasting the trend in the occurrence rate and magnitude of the disasters all around the world, which itself requires quite detailed data about the disasters happened during a relatively long period globally.

As for future work, after gathering and processing the required data, we will apply the above model to a case of 16 disasters in the period between 2005 and 2010 in the South-east Asia, South-Asia and Pacific regions. Because of the limited size of the real-world problem in hand, some features of the model can be deactivated. RLUs are not considered and there is only one regional terminal in Singapore which is visited by two liner shipping routes. The two routes visit 16 ports in total. One route is served by 4 vessels and the other one by one vessel. Each disaster has only one distribution point. Demand for disaster relief items is given per week. For the sake of modelling, it is assumed that all the demand in a week is aggregated on the last day of the week. Furthermore, out of the 16 ports visited on the shipping routes, only 6 have capacities available at the terminals. In addition, transport costs and transport times to the distribution points are only available for these ports. Moreover, each disaster location can be supplied by only one of these ports. It makes it possible to reduce the number of ports and to merge distribution points into the ports. The possibility of direct shipment from Singapore to the ports by the affiliate shipping line is still under question. In addition, there is only one disaster relief item which itself is a package of multiple items. Each package is stored and shipped in pallets. Finally, it is assumed that there are no two overlapping disasters that makes it possible to
formulate the operational decisions for each disaster separately and independently. All in all, the size of the model will be as small as just 875 variables and 1272 functional constraints. Therefore, since the model is a pure linear programming, the complexity and size of the model is not likely to be a problem in the process of solving.

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