A Network Transshipment Model for Planning Humanitarian Relief Operations after a Natural Disaster

Alistair Clark*
Department of Mathematical Sciences, University of the West of England, Bristol, BS16 1QY, UK.
Tel: +44 (0) 117 328 3134, Fax: +44 (0) 117 328 2734, Email: Alistair.Clark@uwe.ac.uk

Bernadette Culkin
Worcestershire, UK

Abstract

Every year, natural disasters and humanitarian crises affect approximately 200 million people, requiring the quick movement of goods and people to ease the human suffering and to return the population to some sense of normality. With contributions to humanitarian relief programmes falling short of what is required, programme managers need to become more cost-efficient and 'do more with less'. The field of operational research (OR) has developed many models to help the commercial sector examine current practices and find ways of becoming more cost efficient. However, much of this good practice has not transferred to the humanitarian field.

This paper develops a mathematical transshipment multi-commodity supply-chain network model for use within humanitarian relief operations. A small data set, based on real life data from the South Asian Earthquake of October 2005, is used to validate the model solutions compared to the real life situation. Several variants of the model are developed to add realism and flexibility over a number of possible scenarios. From the variant solutions several recommendations are made to provide guidance on planning for humanitarian relief operations.

Keywords: Planning, Logistics, Humanitarian Relief, Linear programming, Developing countries

*Corresponding author

1. Introduction

Every year, natural disasters and humanitarian crises affect approximately 200 million people, often temporarily displacing up to five million people [1]. Responding rapidly to these situations relies on the quick movement of goods and people to ease the human suffering and to return the population to some sense of normality.

A disaster, which can take a variety of forms, is described in [2] as ‘a disruption that physically affects a system as a whole and threatens its priorities and goals.’ However, the occurrence of a disaster does not necessarily mean that humanitarian assistance is required. Many disasters occur throughout the year without becoming a crisis. It is neither the size nor magnitude of the disaster that constitutes a crisis, but rather the need for intervention. If the disaster can be dealt with using existing routines then the situation is an emergency rather than a crisis [3]. A crisis evolves into a disaster when ‘it challenges the traditional values shared by the organization the incumbent response mechanisms become saturated and overwhelmed and external help is required’ [3]. Such foreign intervention of food, shelter and services by other governments and non-government organisations (NGOs) is known as relief or humanitarian assistance [1][4][5].

When a disaster occurs, the right goods and people must be sent to the right place, at the right time and in the right quantity [6]. This movement of goods and people accounts for 80% of any disaster relief operation and is often the most expensive part of any relief operation, making it a crucial factor in determining whether the humanitarian effort has been a success or a failure [1][2].

However, each year contributions of resources have fallen short of what is required [7], leading to humanitarian organisations ‘managing programmes more efficiently, doing more with less’ [5]. Cost efficiency has been a particular focus within the commercial sector for a number of years, achieved by making improvements to supply chains through the examination of ‘cross-functional solutions to address some of the barriers that inhibit improvements’ [8]. However, much of this good practice has not crossed over to the humanitarian sector where organizations are 15 to 20 years behind their private sector counterparts in terms of supply chain development [1][2].

Indeed, as one researcher puts it, 'it is paradoxical that a sector which has such extreme requirements in terms of timeliness, affordability and oversight is so underdeveloped. It is precisely this paradox that creates what we see as a great opportunity for advancement of the field and of the humanitarian mission.' [1].

Operational Research (OR), known as Operations Research in the USA, has contributed widely to the commercial sector by developing models to help plan logistics and transportation operations. However the humanitarian sector has been effectively ignored [9]. A recent post-1980 literature survey [10] of OR research and disaster management operations found just 109 articles relating specifically to the use of OR in disaster management, of which 31 were related to natural disasters and just 1 to humanitarian situations.

Yet the aim of humanitarian relief operations is 'to mitigate the urgent needs of a population with sustainable reduction of their vulnerability in the shortest amount of time and with the least amount of resources' [3], a challenge that is ideal for OR approaches such as mathematical optimisation and discrete-event simulation. The *Association of European Operational Research Societies* has also recognised the growing need to 'develop new methodologies or new variants of old ones, such as emergency logistics' [11], devoting its Management Science Strategic Innovation Prize in 2006 to this area. The British OR Society's 2006 annual Blackett Lecture was also devoted to humanitarian aid logistics [2].

As a contribution in that direction, this paper develops a transshipment network flow model to assist policy makers and planners to design an effective supply chain so that goods and service reach those in need as quickly as possible. The paper is organised as follows: Section 2 defines the humanitarian principles and discusses the planning required for effective supply chain management. Section 3 then considers the models that have been developed for use in humanitarian relief operations. Section 4 goes on to develop an initial network flow model. Several variants of this model are proposed and tested with South Asian data in Section 5. The modelling and optimisation outcomes are discussed from a strategic planning perspective. Section 6 concludes by discussing some general implications for planners of supply chains in humanitarian relief operations.

2. Planning For Humanitarian Relief Operations

Planning for relief operations needs to abide by the humanitarian principles which are fundamental to the operations of humanitarian organisations [2]. Three principles define humanitarianism: humanity, impartiality and neutrality. These state, in short, that suffering will be alleviated wherever it is found, giving priority to the most urgent needs and without discrimination [2][3].

These principles are described in the Code of Conduct for the International Federation of Red Cross and Red Crescent Societies (IFRC) [6], developed in 1994 to define a 'standard of behaviour' expected of NGOs working in disaster-affected countries. Following this, a group of organisations drew up a humanitarian charter in 1997, together with minimum standards to be attained during any relief operation which came to be known as the Sphere Project [12]. These principles guide the work of NGOs and their planning activities.

Planning, or preparedness, outlines a set of actions to be taken in the event of a disaster occurring [10]. It is essential to ensure proper co-ordination and anticipate problems that may occur in the supply chain at an early stage [2][13][14][15][16][17]. Put simply, 'preparedness is essential for a timely, competent and cost-effective emergency response' [17].

Planning for efficient humanitarian supply chains can be seen as a part of disaster recovery planning, defined by the United Nations International Strategy for Disaster Reduction as a set of 'actions, arrangements and procedures taken in anticipation of an emergency to ensure a rapid, effective and appropriate response that may save lives and livelihoods' [18]. The World Conference on Disaster Reduction in January 2005 called for governments to prepare for effective response and recovery by 'identifying and allocating existing resources from the establishment, development and emergency budgets for disaster and risk management to greater effect in the realization of sustained risk reduction' [19]. This is endorsed by NGOs who state in their Code of

Conduct that ‘governments should seek to provide a coordinated disaster information and planning service’ [20].

Many authors, e.g. [13], report that there is frequently a lack of planning in humanitarian supply chains, resulting in inefficiencies. Some authors believe that planning is difficult during the initial stages of the humanitarian response because each disaster is unique [4][17]. However, the Pan-American Health Organisation (PAHO) [21] disputes this point, stating that most disasters and their arising needs are usually predictable and so, by studying past humanitarian assistance programmes, accurate forecasts can be made [17], allowing ‘regions at risk to prepare themselves and for relief agencies to prepare their efforts’ [4][22]. In this way, an international humanitarian organisation was able to devise a top ten list of commodities required in most emergencies and arrange pre-purchase agreements with suppliers [23].

Rather than planning for cost-effective programmes, [17] describes the objective of humanitarian relief operation in its initial stages as being able to ‘improvise and set up a supply chain which can deliver at all, rather than contemplating optimal and cost-efficient solutions.’ However, [2] affirms that ‘a successful response to a disaster is not improvised’. This view is also endorsed by the PAHO who state that ‘the erroneous idea that logistics may be improvised at the moment of a disaster depending on needs “indicated by the situation” must be eliminated’ [21].

Two types of planning are identified in [24], namely, strategic and tactical.

1. ***Strategic Planning*** can be thought of as long term planning. It identifies available resources and allows policy-makers and planners to assess the strengths and weaknesses of a system based on a number of likely disaster scenarios.
2. ***Tactical/Operational Planning*** is short term planning and plans current daily or weekly operations. In the humanitarian sector this would occur when a disaster strikes and humanitarian aid is needed.

Strategic planning is common within the commercial sector. For example, the Kellogg Company inputs estimated costs and demand forecasts into their strategic model in order to optimally source products, allowing them to establish financial budgets, space for inventory and transportation requirements [25]. The models are also used to test alternative scenarios of a particular problem. Proctor and Gamble have also used such models to look at the impact of closing particular plants [26]. The use of strategic models, as in the commercial sector, can aid in identifying necessary resources and budgets.

Strategic planning practice can be used within the humanitarian sector through the use of data from past operations which can provide important ‘post-event learning’ [1] and are important in establishing effective responses to relief operations [27]. One reason why these types of strategies have not yet filtered into the humanitarian sector could be due to lack of financing as NGOs can find funds for relief but not for planning for relief [2].

3. Models Developed by other Researchers

Many studies into disaster management make use of mathematical programming and incorporate well established models such as inventory-allocation models [28], vehicle routing models [29], location-distribution models [30], multi-modal network models [29][31][32] and inventory-control models [33]. A variety of objective functions have been used, the most common of which is minimising the cost of the operation [31][32]. However, planning operations based on costs alone may conflict with the IFRC Code of Conduct [34], which states that aid should be distributed based on need.

The IFRC Code of Conduct is adhered to by [29] who sets the objective function to minimise the amount of unsatisfied demand in their model. Unsatisfied demand is also included in the objective function by [30] together with a priority weighting for each commodity. The model developed by [28] minimises ‘the amount of pains and starving’, but there is no information about how this is calculated. However, cost cannot be totally ignored because humanitarian organisations are becoming increasingly accountable to their donors on how funds are spent [2] and are required to plan more cost-effective programmes due to a shortfall in funding contributions

[17]. This is acknowledged in [31] who not only minimising the costs of the operation but also include a penalty cost for unmet demand.

All the authors above acknowledge that their models can be used to plan for humanitarian relief operations. However, no author makes recommendations for use in preparing for a disaster. Instead, the focus is on inputting data and analysing the results from that particular data set.

One of the difficulties in planning for humanitarian relief operations is that information changes quickly, particularly at the beginning of operations, a reality that must be reflected in any model that is developed. The model in [29] incorporates this by allowing new plans to be developed at given time intervals once updated information has been received. The model in [31] is an attempt at planning where supply and arc capacities are determined in the pre-event stage for each earthquake scenario. This information is then extracted for the actual event.

It is not clear whether these models are flexible enough to use in other kinds of disasters. The model in [29] focuses specifically on logistics planning after a natural disaster, but the model is only tested on a relief operation after an earthquake, and gives no indication of whether it is suitable in other natural disasters. The models in [31] and [32] also give little indication of the generality. This is particularly pertinent for [32] given that their model is tested on artificially generated data. The model in [31] was developed based on a number of earthquake scenarios, but again no indication is given about whether it is applicable to other types of disaster.

Inventory management receives little attention in the literature. The model presented in [33] ‘determines optimal order quantities and reorder points for a long-term emergency relief response’. However, this type of model is far too detailed for strategic use which should only give an indication of inventory and capacity levels during the initial phase of the relief operation.

4. A Network Transshipment model for Emergency Relief

We now develop a basic transshipment model for exploratory strategic planning. A humanitarian supply chain can be thought of as starting at multiple suppliers, then passing through various transshipment points and finally arriving at the multiple recipients.

Figure 1 shows a humanitarian supply chain as a network transshipment model in which items are 'pulled' through the supply chain to meet the demands of the recipient. The quantity of items sent along the chain is dependent upon the demand at the final destination.

The model is strategic, rather than operational, and aims to identify whether there are sufficient resources, suppliers, modes of transport, inventory and storage capacity along the supply chain. It includes all the necessary nodes within the supply chain as defined in the conceptual model. Suppliers, warehouses, airports, seaports and rail terminals and recipients are all nodes along the supply chain with possible intermediate demand for certain items.

Users of the model can flexibly define supply and demand parameters at each node as well as capacity levels for flows along each arc. The model can represent a variety of resources and constraints such as the type and number of transport vehicles available or limits on the number of items sent to each warehouse. The use of a network model also allows restrictions on arcs to model the impacts of natural disasters on the supply chain such as impassable roads.

To specify and formulate the model more precisely, consider the following index sets:

S	suppliers
W	warehouses
R	recipients (people)
A	airports
F	seaports

B	rail terminals
I	items
E	types of vehicles available
K	node $S \cup W \cup R \cup A \cup F \cup B$ of the supply chain
G	intermediate nodes $S \cup W \cup A \cup F \cup B$
L	links between successive nodes

The index t represents a day within the planning horizon. Thus t = 1, ..., 10 means a ten-day horizon with decisions at the start of each day, including the current one (for which t = 1). Non-negative values of t represent the past, so that, for example, t = 0 would be the day before the current one.

The following parameters contain all the known information that planners should (ideally) know**.**

I_{ki}^{0}	current initial inventory at node k of item i (*i*.e., at the end of day 0)
D_{kit}	demand at node k for item i on day t
U_{ki}^{0}	current unsatisfied demand at node k for item i
VC_{v}	maximum capacity that each vehicle v can carry in metric tonnes
VA_{kvt}	Integer number of vehicles available at node k of a given vehicle type v on day t
L_{kjv}	lead time from node k to node j using a given vehicle type v
T_{kjvit}^{0}	number of units already sent from node k to node j, using a given vehicle type v, of item i at past times $t=-L_{kjv},\ldots,0$
F_{kjv}	fixed transport cost to include driver, fuel, maintenance etc. of using each vehicle type v between node k and node j
W_{i}	weight of each item i
C_{k}	capacity limits of each node k

The decisions to be taken correspond to the following variables:

T_{kjvit}	number of units sent from node k to node j, using a given vehicle type v, of each item i on day t
V_{kjvt}	integer number of vehicles sent from node k to node j on day t

The outcomes of these decisions are the following variables:

I_{kit} inventory at node *k* of item *i* at the end of day *t*

U_{kit} unsatisfied demand (backlog) at node *k* for item *i* at the end of day *t*

The model, being strategic, is designed to plan and analyse flows through the supply chain in advance of a natural disaster occurring, exploring possible scenarios. The decision variables give information about the amount T_{kjvit} of items transported from one node to another and the number of vehicles V_{kjvt} needed to do so. The inventory outcome variable I_{kit} allows planners to investigate the amount of storage required for the supply chain to operate effectively and efficiently. However, the unsatisfied demand outcome variable U_{kit} is probably the most important as it provides information on how many recipients will still be waiting for each item at the end of each day in the planning horizon.

Any humanitarian operation has at its heart the requirement to ease the suffering of others, and so the objective function of this model is to minimise *Need*, defined as the number of recipients still requiring quantities of items accumulated over time. However, cost cannot be completely ignored and so needs to be minimized and included in the objective function. This leads to the use of a multi-objective function in expression (1) below that not only minimises need but also transportation and inventory costs. However, the humanitarian organisations' Code of Conduct requires that aid must be delivered based on need and not cost [12][20]. To follow this Code the objectives have been pre-emptively weighted placing much greater priority on minimising need before transportation and inventory costs:

$$\text{Minimise} \quad \sum_{kit} U_{kit} + 0.001 \sum_{kjvt} F_{kjv} V_{kjvt} + 0.01 \sum_{kit} I_{kit} + \sum_{kjvt} V_{kjvt} \qquad (1)$$

The weight values of 1, 0.001, 0.01 and 1 in expression (1) are somewhat arbitrary, but the user must ensure that the magnitude of weightings between each of the components reflects the importance of that particular component in the policy of the organization. For this paper, we wished the items to be delivered to recipients as quickly as possible, hence the high weighting given to this component in relation to the other components.

Another factor that must be considered when specifying these weightings are the units of measurement of each component. At first glance it may appear that there is a greater weighting given to inventory than transport. However, the magnitude of the transportation costs means that its weighting has to be scaled down in order for transportation costs to approximately equal inventory costs. The danger with using weightings is that if there was a small transportation cost and a large inventory then these weightings may be inappropriate leading to the inventory component having a greater influence than the transportation costs weighting. The weightings have been verified so that this problem should not occur.

The final component $\sum_{kjvt} V_{kjvt}$ of the objective function also minimises the number of vehicles used. It has been added because transportation costs from suppliers are assumed to be paid for by the supplier, and so the number of vehicles used are not minimised by the fixed costs component $\sum_{kjvt} F_{kjv} V_{kjvt}$ in the objective function. If policy makers knew the cost for these journeys then this component could be removed from the objective function.

In a network flow model, supply must balance demand, inventories, and backlogs over time. Constraint (2) ensures that no more items are sent than are received and/or taken from the local inventory:

$$\sum_{jv} T_{jkvi,t-L_{jkv}} + I_{ki,t-1} - U_{ki,t-1} = \sum_{jv} T_{kjvit} + I_{kit} - U_{kit} + D_{kit}$$

for all nodes *k*, items *i* and days *t* (2)

Constraint (2) states that, on any given day and at any given node, the items arriving from previous nodes, together with the items inherited from the previous day's ending inventory, less the unmet demand from the previous day, should equal in quantity the items sent to the next nodes, plus the demand and the amount put into inventory, less any unsatisfied demand.

In the model, unsatisfied demand U_{kit} can be thought of as backlog. The model does not allow backlogs to occur at intermediate nodes because it is only at the final destination (where recipients are based) that planners would need to know whether there is still unsatisfied demand. Thus unsatisfied demand at intermediate nodes is fixed to be zero.

The use of lead time in constraint (2) highlights one of the main differences between this and other models developed for humanitarian operations after a natural disaster. Lead time is an important consideration as it affects the decisions made about sourcing supplies and consequently how long recipients are deprived of help. It will influence decisions about the minimum inventory of items to keep in local warehouses or pre-agreed purchase agreements to deal with initial demand.

Constraint (3) specifies the amount of each item currently held in inventory at each node, i.e., at the end of day 0:

$$I_{ki0} = I_{ki}^{0} \qquad \text{for all nodes } k\text{, and items } i \tag{3}$$

Each time the model is re-run during the course of the operation, the values of parameter I_{ki}^{0} would be updated to reflect the items in inventory at the time of planning. Similarly constraint (4) defines the current unsatisfied demand U at day 0:

$$U_{ki0} = U_{ki}^{0} \qquad \text{for all nodes } k\text{, and items } i \tag{4}$$

Initially, unsatisfied demand U_{ki}^{0} at day 0 is set at zero because it is assumed that the recipients had no need for any extra items before the natural disaster occurred, i.e., demand was being dealt with by existing systems. However, when using the models during relief operations, unsatisfied demand would be the number of recipients still requiring items at the current point in time.

Constraint (5) defines the amount of each item sent between nodes before the disaster has occurred:

$$T_{kjvit} = T^0_{kjvit} \quad \text{for all nodes } k \text{ \& } j\text{, vehicles } v\text{, items i, and days } t \tag{5}$$

The parameter T^0_{kjvit} has a default value of 0 as it is assumed that it is not known that a disaster is imminent and therefore items were not pre-ordered. If the natural disaster is expected then operations planners may have pre-ordered certain items which can then be entered into the model using T^0_{kjvit}. The same applies, as in constraint (2), if the model is re-run during a humanitarian relief operation then the number of items that have not yet arrived but are in the supply chain pipeline.

Constraint (6) ensures that there are enough vehicles to transport items between nodes:

$$V_{kjvt} \geq \frac{0.001 \sum_i T_{kjvit} W_i}{VC_v} \quad \text{for all nodes } k \text{ \& } j\text{, vehicles } v\text{, and days } t \tag{6}$$

The coefficient 0.001 converts the item weights in kilograms to metric tonnes, the units of vehicle capacity.

Constraint (7) ensures that the weight of all inventory items is within the node capacity limits, again multiplying by 0.001 to convert from kilograms to metric tonnes:

$$0.001 \sum_i I_{kit} W_i \leq C_k \quad \text{for all nodes } k\text{, items } i\text{, and days } t \tag{7}$$

5. Computational Analysis and Model Refinement

The basic model was tested and further developed over a 10-day planning horizon with data representing 25 suppliers, 6 warehouses, 8 recipients, 8 airports/heliports, 1 seaport, 6 rail terminals, 5 items, and 4 vehicle types. A larger instance was then implemented with 49 suppliers, 6 warehouses, 13 recipients, 8 airports/heliports, 1 seaport, 6 rail terminals, 5 items, and 4 vehicle types. The data was adapted from that on the UNJLC website for the Pakistan Earthquake in 2005.

The model was implemented using AMPL [35] and solved using Cplex 9.1 [36] on a Sun V208 Dual Opteron 252 processor running under Linux with a processing speed of 2.6 GHz and 4GB of RAM. Almost all the model refinements below took less than 10 seconds to optimally solve, as discussed in more detail later in the paper.

5.1 Analysis with the Uncapacitated Model

If there are no capacity limits, then all supplies are dispatched to recipients in the disaster zone on day 1. All supplies are sent to the airport that has the shortest lead times and cheapest transportation costs as the objective function requires the model to reduce unsatisfied demand in the shortest amount of time, at minimum cost and with the the least inventory.

When deciding where to send items, the model considers which recipients are closest to the point of entry, i.e., which have the shortest lead times. If there is no difference in the lead time of two or more recipients then the model considers which of these has cheaper transportation costs.

Helicopters are used to transport items to heliports. Even though they are more expensive, helicopters are chosen because they can get items to where they are needed quickly thus satisfying the objective that unsatisfied demand should be minimised in the shortest amount of time. The recipients with the cheapest helicopter rates are chosen to receive items. Trucks are then used to transport items from heliports to warehouses and onward to recipients.

Those recipients without access to heliports are in danger of not receiving items because these need to be delivered by truck, a journey which has a longer lead time than the same journey by helicopter. Consequently the time taken to minimise unsatisfied demand increases. In addition, these recipients are also further away from the initial points of entry and so have larger transportation costs, increasing the value of the objective function. Special attention might need to be given to this group of recipients to ensure that they are given consideration when distributing aid.

The model does not take into account a problem that is identified in many situation reports, namely airport congestion. Is there enough space for all aeroplanes to land? Are there sufficient resources to deal with the volume of items being delivered? If not, then this will delay the arrival of aeroplanes on subsequent days and so prolong the time taken to deliver items, extending time needed to meet (or minimise) unsatisfied demand. To be realistic the model should be adapted to include a limit on the number of aeroplanes that can arrive at each airport on any given day.

5.2 Airport Arrival Capacity

To allow planners to investigate the impact of imposing limits on the number of aeroplanes arriving at each airport, a parameter AC_{jvt} is added to the model in an additional constraint (8) limiting the number of aeroplanes that can arrive each day.

$$\sum_{kjv} V_{kj,t-L_{kjv}} \leq AC_{jvt} \quad \text{for all nodes } j\text{, vehicles } v\text{, and days } t \tag{8}$$

Constraint (8) states that the total number of vehicles $V_{kj,t-L_{kvt}}$, sent t-L_{kjv} days ago from nodes k to j to arrive on day t, is less than or equal to the capacity AC_{jvt} at node j for each vehicle type v on a given day t. Indexing the airport capacity parameter over t allows planners to change the limits on a given day to take account of the number of staff available to deal with arriving items, space for aeroplanes, weather, etc, at each airport.

When airport capacity is limited, the number of days over which airports are used increases, because there are not enough spaces at each airport for the planes to land and so the model staggers the delivery of items. This leads to an increase in the amount of time in which recipients are waiting for items.

Items initially arrive at the airport closest to the disaster zone until it has reached its capacity. At this point, arrivals are switched to the airport that has the next shortest lead times and cheapest transportation costs, and so on. The total number of planes increases, due to the transfer of items by air from airports further away than those closest to the disaster zone. Items are transferred by plane rather than by road due to the objective function, which requires that unsatisfied demand should be minimised in the shortest amount of time. The model chooses the route and vehicle with the shortest lead times which results in items being transferred by aeroplane to the airport closest to the disaster zone where helicopters and trucks are then used to transport items to their final destination.

5.3 Limited Number of Vehicles

So far, there is an unlimited supply of vehicles. Although this provides useful information on where vehicles are needed and the ideal number required, it is not realistic. Adding constraint (9) below allows planners to examine the impact on the objective function of a limited availability VA_{kvt} of vehicles.

$$\sum_{j} V_{kjvt} \leq VA_{kvt} \qquad \text{for all nodes } k\text{, vehicles } v\text{, and days } t \qquad (9)$$

Indexing by day t allows planners to flexibly specify the number of vehicles available over time so as to model, for example, NGOs donating extra vehicles. Note that the location of vehicles at nodes is not modelled – such information has to be explicitly provided on a day-by-day basis via the values of the parameter VA_{kvt}.

5.4 Limited Helicopters at Each Stage

Limiting the number of helicopters available has no effect on the arrival of items into the disaster zone. All items are still sent by suppliers on day 1, arriving at the airport closest to the disaster zone.

The model initially uses helicopters to transfer items to those recipients with cheaper transportation costs. When all helicopters have been used, the model then has to consider alternative forms of transport which still minimise unsatisfied demand in the shortest amount of time. This leads the model to choose trucks and to send these to the place with the cheapest transportation costs for trucks. Transferring remaining items by truck ensures that there are no items left in the inventory, fulfilling the third component of the objective function which states that inventory should be minimised.

However, the time taken to deliver items increases, compared to the uncapacitated model, as items sent by road have longer lead times than if sent by helicopter.

5.5 Helicopters and Road Access

Delivery by road when helicopters are unavailable works well when there is no disruption to the road network. However, should this happen, as occurs frequently after earthquakes, then delivery of items may be affected.

Items continue to be sent by helicopter to the recipient with the cheapest transportation costs, in line with the objective function of minimising unsatisfied demand in the shortest amount of time and at minimum cost. When all helicopters available have been used, the model has to look for the next quickest mode of transport available that will still minimise unsatisfied demand as quickly as possible, namely trucks. The model then considers which recipient has the shortest lead time and cheapest transportation cost. If this recipient cannot be reached, then the model looks at the next shortest lead times and cheapest routes, and so on.

Planners may wish to restrict the use of helicopters to serve those recipients where there is no road access or introduce a new mode of transport, such as an airlift, to drop items directly to recipients.

When the availability of helicopters is limited, then all helicopters at the initial point of entry are used. The remaining helicopters at other heliports are not used which is a waste of a valuable resource which would not occur in the real world. The model needs to be adapted so that better use is made of this valuable resource.

5.6 Pooling Vehicles

Instead of allocating vehicles equally amongst all nodes, they can be pooled to allow a more effective use of resources. An additional constraint (10) is needed.

$$\sum_{kj} V_{kjvt} \leq VP_{vt} \qquad \text{for all vehicles } v\text{, and days } t \qquad (10)$$

where the new parameter VP_{vt} specifies the number of vehicles of type v in the pool on day t. Again, indexing the vehicle pool parameter over t allows planners to add additional vehicles to the pool should they become available.

5.7 Pooling Helicopters

Pooling resources actually increases transportation costs, due to the greater use of helicopters than when not pooled. This is due to the fact that helicopters journeys cost twice as much as trucks, an increase that has a great effect on transportation costs.

Pooling helicopters allows them to be allocated where they are best used, i.e., at the initial point of entry to deal with the incoming supplies. In a similar way to the previous model, the items are sent to those recipients with short lead times and cheaper transportation routes and therefore satisfies the objective function which states that unsatisfied demand should be minimised in the shortest amount of time with respect to transportation costs.

When all helicopters in the pool are used, items are sent by road to the recipient with shortest lead times and cheapest trucking rates. Items could be stored in inventory for delivery next day but there is a component in the objective function that states that inventory should be minimised. In addition, storing items in inventory would not reduce the time taken to minimise unsatisfied demand nor minimise transportation costs, therefore increasing the objective function.

Pooling helicopters allows a greater number of items to be delivered and therefore unsatisfied demand is minimised more quickly, compared to when vehicles are not pooled.

5.8 Limited Trucks at Each Stage

A limited availability number of trucks at each node causes the use of a greater number of airports to receive items, even though capacity is not reached at each airport. The reason for this is because of a problem further down the supply chain.

The objective function requires that items should be delivered as quickly as possible in order to minimise unsatisfied demand in the shortest amount of time. This results in items being sent to the airport closest to the disaster zone. Items are initially transferred by helicopter to those recipients with the cheapest transportation costs. However, delivery stalls when there are no more trucks available to transport items from heliport to warehouse, causing an increase in the time taken to deliver items.

One may think that items could be delivered to the heliport and stored there until they are ready to be transferred by truck but the next component in the objective function states that inventory should be minimised. Thus, rather than have items stored in inventory, items are sent to recipients by road, to be delivered the following day. So when after asmany items as possible are delivered by helicopter, the model then uses all its trucks to transfer deliver items to recipients. When all these trucks have been used, suppliers send items to the next airport so that the trucks there can be used to deliver items to recipients.

Items are delivered to a greater number of places than when transport is not limited. Some of these recipients are further away from the initial point of entry, and consequently have higher transportation costs which contribute to increased transportation costs.

5.9 Pooling Trucks

The pooling of trucks allows the model to allocate them to where they are most needed. Once again, items are sent to recipients with the cheapest transportation costs and shortest lead times. The model solution shows that items are initially transported by helicopter to recipients with cheaper transportation costs. However, transportation then switches to road which, initially, appears quite surprising as there are an unlimited amount of helicopters available to transport these items with a lead time of zero. However, if items were transferred by helicopter, then there are not enough vehicles available to transfer items from the heliport to the warehouse and then onto recipient. At this point, items would need to be stored in the inventory. But this does not happen because the minimisation of inventory in the objective function causes items to be then sent to the recipient with the next cheapest trucking route, therefore minimising the transportation costs component of the objective function.

There is a difference in the time taken to deliver items due to the fact that initial delivery to the disaster zone is delayed so as to minimise the inventory component of the objective function.

5.10 Emergency Contingency Stocks

Even with the use of emergency contingency stocks, the number of aeroplanes arriving each day does not differ from the uncapacitated model. This is not surprising as the objective function states that unsatisfied demand should be minimised in the shortest amount of time and so all items are sent as quickly as possible to the airport closest to the disaster zone. There are an unlimited number of helicopters and trucks available to transport items to warehouses, so inventory will be minimised.

The addition of emergency contingency stocks into the supply chain causes an increase in the transportation costs (due to the large increase in the number of trucks used to transport the emergency stocks from warehouses to recipients). In addition, unsatisfied demand initially decreases sharply, but then follows a similar pattern to the uncapacitated model as more items enter the disaster zone from external suppliers.

The initial unsatisfied demand decreases because all emergency contingency stocks are sent to the closest recipient on day 1. This is because the objective function states that unsatisfied demand should be minimised in the shortest amount of time with respect to transportation costs. This journey has zero lead time and, as items are delivered by truck, transportation costs are relatively cheap.

Items from external suppliers are sent to those recipients that have short lead times and cheap transportation costs, as in the uncapacitated model. This is to satisfy the objective function which states that unsatisfied demand should be minimised in the shortest amount of time with respect to transportation costs.

Once again, there are recipients who do not receive any items. These recipients are at a considerable disadvantage to other recipients for a number of reasons. Firstly, they are furthest way from the initial point of entry and so have larger transportation costs. Secondly, they do not have a heliport nearby so they have larger lead times as items have to be delivered by truck. Finally, they do not have a warehouse nearby and so initial demand is not minimised. The combination of all these factors leads to these recipients not receiving items.

In all the models examined so far, the decision of where items are delivered is based on shortest lead times and cheapest transportation costs. However, delivering items based on speed and cost may violate the NGOs' Code of Conduct [34] which states that humanitarian aid should be delivered based on need. Thus the model should be adapted to include a parameter identifying relative need and then prioritise aid to where it is most needed.

5.11 Prioritising Greatest Need

Prioritising need ensures that those in greatest need receive items first. The objective function (11) includes a weighted average of unsatisfied demand so those recipients with a greater weighting P_k will have a less unsatisfied demand than those deemed to be of lower priority.

$$\text{Minimise} \quad \sum_{kit} P_k U_{kit} + 0.001 \sum_{kjvt} F_{kjv} V_{kjvt} + 0.01 \sum_{kit} I_{kit} + \sum_{kjvt} V_{kjvt} \qquad (11)$$

The weightings for P_k range from 10 (for the location of the greatest need) down to 1 (indicating the lowest need).

The number of aeroplanes landing is the same as in the unprioritised uncapacitated model. This is to be expected as there are no constraints on how many aeroplanes allowed to land at each airport nor on the number of vehicles available to transport items from airports.

However, transportation costs can increase, depending on how the priority weighting P_k has been allocated. Those recipients with a higher priority status tend to be further away from the initial point of entry. These recipients have higher transportation costs and, because they do not have a heliport nearby, items need to be transported by road. The model solution shows that there is an increase in the usage of all forms of transport in order to reach recipients, contributing to increased transportation costs.

5.12 Minimum Delivery to each Recipient

Another way of ensuring a fairer distribution of food is to enforce a distribution policy whereby a minimum amount M_{ij} of each item i is delivered to each node j is incorporated into a new constraint:

$$\sum_{kv} T_{kjvi} \geq M_{ji} \qquad \text{for all nodes } j \text{ and items } i \qquad (12)$$

Indexing M_{ij} by end-node j allows planners to set minimum delivery levels for each recipient based on a number of factors such as number of people affected, particular needs of each recipient, and so on.

Again, the number of aeroplanes arriving is the same as in the original uncapacitated model, the reason being that items will arrive as quickly as possible so that unsatisfied demand can be minimised in the shortest amount of time.

When a minimum delivery policy is introduced, transportation costs again increase slightly compared to the original uncapacitated model, as some formerly neglected recipients have larger transportation costs. The number of helicopters is reduced because some of these new recipients do not have a heliport nearby and so their items are delivered by road, for example, Abbottabad. The original helicopter-aided recipients of these items receive less than previously, thus reducing the need for helicopters.

All recipients receive the minimum number M_{ij} of items, as declared in the data set. The remaining items are sent by helicopter to those recipients with the shortest lead times and cheaper transportation costs, as the objective function requires that unsatisfied demand should be minimised in the shortest amount of time with respect to transportation costs. If demand has been satisfied then any remaining items are sent by helicopter to the recipient with the next cheapest transportation costs. Items are sent to other recipients via heliports, as this is the quickest way of getting items closest to recipients and allows unsatisfied demand to be minimised more quickly.

It is possible to combine the use of a priority weighting P_k and minimum delivery amount M_{ij} so that all recipients receive a minimum number of items but then priority is given to those recipients with a higher priority weighting.

5.13 Reducing Unused Vehicle Capacity

In all the models examined so far, there have been situations when the number of items transported has been very small, leading to a great deal of unused space in vehicles. This is not a cost-effective way of delivering items which, in addition, may cause upset to those recipients who are in desperate need of goods if only 10 items arrive for over 100,000 people. Even though unsatisfied demand is minimised in the shortest amount of time, it is not a policy that would be endorsed by most organisations who would want resources to be used to maximum effect. One way of overcoming this is to reduce the amount of slack that is left in each vehicle. Thus more items will be put onto each vehicle enabling much more cost effective operations.

Constraint (13) calculates the amount VS_{kjvt} of vehicle slack:

$$VS_{kjvt} = V_{kjvt} VC_v - 0.001 \sum_i T_{kjvit} W_i \geq 0$$

for all nodes k & j, vehicles v, and days t (13)

Slack is then minimised in the revised objective function (14):

$$\text{Minimise} \sum_{kit} U_{kit} P_k + 0.001 \sum_{kjvt} F_{kjv} V_{kjvt} + 0.01 \sum_{kit} I_{kit} + \sum_{kjvt} V_{kjvt} + \sum_{kjv} VS_{kjvt} \quad (14)$$

When vehicle slack is minimised, there is no effect on the higher priority components of the objective function. The total number of items delivered to each recipient in the amount of time taken to deliver these items remains the same. However, as desired, the number of deliveries of less than 100 items is reduced, as are the number of vehicles used and transportation costs. This further reduces the value of the objective function as transportation costs are reduced, therefore providing a much more cost effective operation.

Varying the relative weights of the inventory, transportation and vehicle-slack components in the objective function allows different polices to be explored, and the consequent impact on the time taken to satisfy demand. However, a more direct and comprehensive way of investigating the impact of different policies, would be to directly introduce constraints on, for example, the permitted amount of vehicle slack, or other components of the objective function. This type of multi-criteria decision making would need to be undertaken interactively with planners, making use of multi-objective optimisation methods that explore the efficient frontier of Pareto-optimal decisions [37], for example, the eta-constraint technique [38].

5.14 Computational times

With the smaller data set, the models had between 10,500 and 11,600 integer variables. All but two of the model refinements above took less than 10 seconds to optimally solve, with half taking under 1 second. However, the truck pooling truck model took 57.7 seconds to solve, probably due to the small number of trucks available, resulting in a tightly constrained model. The capacitated landing model was also tightly constrained with few aeroplanes being allowed to land at each airport.

The fast solution times make the model highly suitable for multiple runs during an interactive session with decision-making end-users to explore different policies.

However, under the larger data set, no optimal solution was provably found after 4 hours for capacitated-trucks model. The long solution time is due to the very small number of trucks available to transport all items to recipients, making it tightly constrained. The addition of extra suppliers and recipients has increased the complexity of the model to find an optimal solution. Under these circumstances, computation needs to be stopped after some predetermined amount of time, and the incumbent solution used or some heuristic other method used.

6. Recommendations and Conclusions.

This paper develops a mathematical transshipment multi-commodity supply-chain network model to aid policy makers plan for effective humanitarian relief operations after an earthquake. A small data set, based on real life data from the South Asian Earthquake of October 2005, is used to validate the model solutions compared to the real life situation. The model aids the planning process by allowing policy makers to test a number of scenarios so that a better understanding of the strengths and weaknesses of the supply chain can be developed.

The model can be initially used as an uncapacitated model to provide useful information about budget requirements, numbers and types of vehicles required, capacity limits at initial points of entry and at warehouses, time taken to satisfy demand, whether the number of existing suppliers is satisfactory to meet the needs of a given scenario, etc. Several variants of the model are developed to add realism and flexibility over a number of possible scenarios thus allowing policy makers to examine the consequences of their ‘real-life’ situation such as limited availability of vehicles, restricted capacity at initial points of entry and warehouses, road closures etc.

The multi-criteria nature of the objective function also obliges planners to consider and clarify their priorities – indeed this is one of the most useful purposes of the model. The organisation should carefully consider its priorities as these can affect the cost of the humanitarian relief operation. Is minimising unsatisfied demand in the shortest amount of time more important than minimising transportation costs? What action should be taken if some recipients do not receive items? How much capacity can be unused in each mode of transport or should vehicles be filled to capacity? These discussions are then useful in determining the weightings that should be given to each of the components in the objective function.

Based on the analysis above, general guidance on the use of the model can be synthesised. Table 1 lists a number of problem scenarios that planners may be faced with, together with recommendations on how to use the model to overcome each problem.

The recommendations in Table 1 concern the allocation of resources and the kind of parameters that need to change and in which direction. This is helpful guidance for policy makers and strategic planners to consider and act upon before a disaster occurs. However, the quantitative and optimising characteristics of model also make it very useful for tactical operations, enabling field planners to flexibly redirect transportation and material resources on a daily basis, if reliable and timely data is available. If some of data is of doubtful quality or needs to be very roughly estimated, then the models' outputs will need to be treated accordingly. Nevertheless, such outputs will help to compare the consequences of different courses of action.

One of the major advantages with using this model is the use of the AMPL modelling language [35]. When used with solvers on the NEOS server [39], AMPL can be used with minimal financial outlay which, given the difficulties in funding planning activities [2], is a positive step. Access to the NEOS server is free to the public. The user only needs to upload the model and data set to the NEOS server which then solves the problem and emails the solution back to the user. However, one of the difficulties with this approach is that it relies on the availability of internet connections within the disaster zone. The availability of telecommunications after a natural disaster can be unreliable and therefore organisations may not wish to rely on finding a solution through a publicly available solver. However, efforts are being made to encourage governments to plan for and have arrangements in place for effective telecommunications access in emergency situations [40]. Moreover AMPL and associated solvers are available commercially for stand-alone use on PCs.

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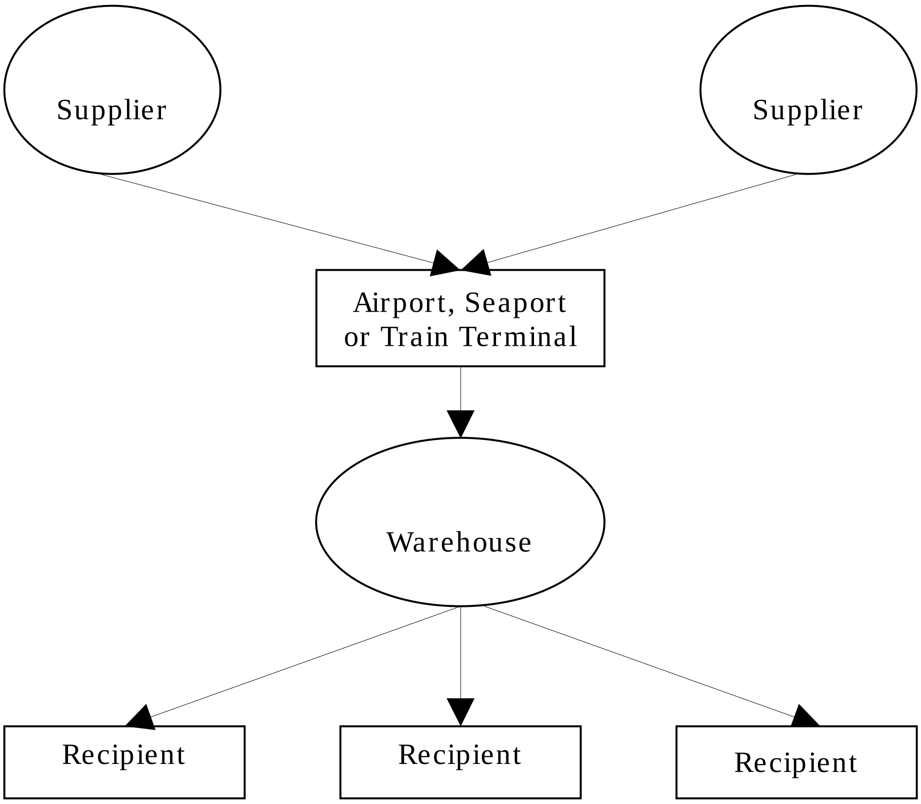

Figure 1 - A humanitarian supply chain

Scenario	**Recommendation**
Low budget	▪ Increase weighting on transportation cost component in objective function. ▪ Minimise vehicle slack. ▪ Reduce the number of helicopters used.
Limited Storage	▪ Stagger arrival of supplies from external suppliers. ▪ Send items to warehouses by truck to make use of storage in transit.
Recipients neglected	▪ Introduce a priority status. ▪ Introduce a minimum delivery policy. ▪ Consider placing emergency contingency stocks close to these areas.
Small number of helicopters and trucks available	▪ Pool resources to make maximum use of resource.
Need to reduce the amount of time taken to minimise unsatisfied demand	▪ Increase the number of helicopters available at the initial point of entry. ▪ Increase the number of trucks available at heliports and warehouses. ▪ Increase the number of aeroplanes allowed to land at airports. ▪ Consider the use of suppliers close to the disaster zone.
Limited Road Access	▪ Restrict the use of helicopters to those recipients that have no road access. ▪ Introduce airlifts as a new mode of transport to these recipients.

Table 1 – Recommendations for effective humanitarian relief operations

<u>Captions for Figures and Tables</u>

Figure 1 - A humanitarian supply chain

Table 2 – Recommendations for effective humanitarian relief operations