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Multiple-buyer procurement auctions framework for humanitarian supply chain management

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Abstract

Purpose – The purpose of this paper is to address the inefficiency in resource allocation for disaster relief procurement operations. It presents a holistic and reconfigurable procurement auctions-based framework which includes the announcement construction, bid construction and bid evaluation phases.

Design/methodology/approach – The holistic framework is developed in a way that auctioneers and bidders compete amongst each other in multiple rounds of the procurement auction. Humanitarian organization in disaster locations are considered as auctioneers (buyers) and suppliers are considered as bidders.

Findings – Unique system parameters (e.g. announcement options, priority of items, bidder strategies, etc.) are introduced to represent the disaster relief environment in a practical way. The framework is verified by simulation and optimization techniques using the system characteristics of the disaster relief environment as an input. Based on the parameters and their values, behavioural changes of auctioneers and suppliers are observed.

Originality/value – Combining the three phases of procurement auctions is unique both in the auction literature and in the disaster relief research, and it helps the humanitarian organizations supply the immediate and long-term requirements in the disaster location more efficiently.

Keywords Procurement, Auctions, Resource allocation, Disasters, Supply chain management, Simulation

Paper type Research paper

Introduction

Natural disasters (e.g. floods, hurricanes, earthquakes, etc.) have always been a challenge for mankind and, even in this highly civilized era of human history the aftermath of natural disasters still comprises many issues. The property damage from Hurricane Katrina in 2005 alone was estimated about $96 billion (White House, 2006). In 2004, more than 15,000 lives were lost as the result of tsunamis in Indonesia, India, Sri Lanka and Thailand. About 1,000 were left injured or reported missing, and

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100 of 1,000 were left homeless in these countries. More examples can be given from other places of the world, but the crucial question regarding these figures is how the world community responds to disasters. Unfortunately, non-governmental organizations (NGOs), local governments and the United Nations do not perform disaster relief operations in an efficient and standard way that can overcome all of the consequences of a disaster.

In the aftermath of natural disasters, vital resources (e.g. food, water, tents, clothing, medicine, etc.) are usually not readily available to the victims of the natural disasters. Although it is usually a logistical challenge to provide these resources to the victims because of the infrastructural damage and the chaotic environment after the strike, some of this challenge can be addressed by effective resource allocation. Allocating the available resources more efficiently is the principal objective of disaster-relief organizations and NGOs during disaster-relief operations (Medina-Borja *et al.*, 2007). In the context of disaster relief, inefficiency in resource allocation can be defined as being unable to deliver the resources to the disaster location in the right quantity and at the right time. Acquiring the right amount of requested supplies is crucial to responding properly to disasters. Timely response is necessary to decrease the fatalities and to preserve perishable food and medical supplies.

The purpose of this paper is to examine methods to increase the efficiency of resource allocation procedures within disaster relief operations. Alternative methods to supply the immediate and long-term requirements of disaster locations are proposed. Although nothing can be done to stop the natural disasters, the means to serve millions of people affected from natural disasters can be improved. A key requirement is to utilize all available resources in locations other than the disaster location. Some potential methods that should be considered for improving resource allocations include: offering similar items that will work in place of the required item (e.g. substitution options) and supplying quantities that are less than the requested quantity (e.g. partial demand fulfilment options). Since timely response is critical, there should also be procedures to address the urgency of requirements (e.g. priority of items). Humanitarian organizations in disaster locations should also consider methods to acquire a minimum amount of items (e.g. require a minimum threshold level).

This paper describes an optimization-based framework for addressing these options and is organized as follows. A literature review of humanitarian supply chain management (SCM) is given in the next section. Following the literature review, the proposed procurement auction-based framework will be explained. Then, an experimental study is given to evaluate the system parameters introduced for the resource allocation problem. Outcomes and insights gained from the study are given in the conclusion section.

Literature review

Allocating the available resources at the right time and in the right quantity is an inherent part of the humanitarian SCM. Humanitarian SCM and humanitarian logistics are used interchangeably in this study as well as in the literature (Beamon, 2004; van Wassenhove, 2006; Kovacs and Spens, 2007). In their literature survey of humanitarian logistics in disaster-relief operations, Kovacs and Spens (2007) indicate that this field did not receive much attention from academic journals. Practitioner journals address the problems in humanitarian logistics, but they do not usually provide quantitative analysis or solution methodologies to these problems (Kovacs and Spens, 2007).

Although not prevalent, humanitarian SCM has been studied in different focus areas within the operations research/management science field. The logistics area deals with the routing of vehicles, the assignment of items to vehicles and scheduling of these vehicles (Barbarosoglu and Arda, 2004; Ozdamar *et al.*, 2004; Yi and Ozdamar, 2007), whereas the inventory pre-positioning area deals with the warehouse selection problem, safety stock and inventory policy determination of emergency supplies (Beamon and Kotleba, 2006a, b). On the other hand, the resource utilization and allocation area deals with defining procedures to satisfy the resource needs in the disaster location (Fiedrich *et al.*, 2000; Gong and Batta, 2007; Qiao *et al.*, 2007).

In order to understand the scope of humanitarian SCM, disaster relief activities should be understood in detail. Major activities in disaster relief operations related to the current study can be given as assessment, appeals management and procurement (Thomas, 2003). Assessment happens within the first 24 hours after the disaster strikes and professionals from humanitarian organizations are deployed to the disaster locations and estimate the supply requirements in the area. Within the first 36 hours after the disaster, appeals are released to humanitarian organizations, governments and international NGOs. Appeals are defined by the type and quantity of relief supplies. In-kind donations need to be prioritized, sorted, counted and compared with the current demand. Cash donations lead to procurement activities that in turn delay the delivery to the disaster location, but do not have the burden of in-kind donations. Procurement operations are vital for disaster relief operations, due to the fact that the pre-positioned or usable inventories of suppliers may not be enough for the disaster relief operation. The first 72 hours are vital and supplies are transported to the disaster location at all costs. After the first urgent period, suppliers are mostly localized and a more stable supply flow is maintained for three months' time (van Wassenhove, 2006). For an extended list of disaster relief activities, the reader is referred to Thomas (2003), Pettit and Beresford (2005), Altay and Green (2006), van Wassenhove (2006) and Kovacs and Spens (2007).

The following definition of humanitarian logistics is very close to private sector logistics definition:

> Humanitarian logistics is defined as the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for the purpose of alleviating the suffering of vulnerable people (Thomas and Kopczak, 2005).

Although each has different characteristics, the solutions in one sector might be used to some extent in the other. Private sector logistics is about 15 years ahead of the logistics in disaster relief (van Wassenhove, 2006). Therefore, it is important to understand humanitarian SCM by comparing it to its well-known commercial counterpart. This comparison is given in Table I (adapted from Beamon, 2004; van Wassenhove, 2006).

It can be seen in Table I that there is a clear need of procurement activity in humanitarian supply chains because of the cash donations and the fact that on hand inventories are usually not sufficient at the onset of a disaster. Many private companies have used procurement auctions for a long time to determine from which suppliers to satisfy their resources (Rothkopf and Whinston, 2007; Elmaghraby and Keskinocak, 2006). Inspired from the procurement auctions in private companies,

Topic	Commercial SCM	Humanitarian SCM
Main objective	Maximize profit	Save lives and help beneficiaries
Demand pattern	Fairly stable and can be predicted with forecasting techniques	Irregular with respect to quantity, time and place. Demand is estimated within the first hours of response
Supply pattern	Mostly predictable	Cash is donated for procurement. Unsolicited donations and in-kind donations need sorting, prioritizing to decrease bottlenecks
Flow type	Commercial products	Resources like evacuation vehicles, people, shelter, food, hygiene kits, etc.
Lead time	Mostly predetermined	Approximately zero lead time, demand is needed immediately
Delivery network structure	Established techniques to find the number and locations of warehouses, distribution centres	*Ad hoc* distribution facilities or demand nodes, dynamic network structure
Inventory control	Safety stocks for certain service levels can be found easily when demand and supply pattern is given	Unpredictable demand pattern makes inventory control challenging. Pre-positioned inventories are usually insufficient
Technology and information systems	Highly developed technology is used with commercial software packages	Less technology is used, few software packages that can record and track logistics data. Data network is non-existent
Performance measurement method	Based on standard supply chain metrics	Time to respond the disaster, fill rate, percentage of demand supplied fully, meeting donor expectation
Equipments and vehicles	Ordinary trucks, vehicles and fork-lifts	Robust equipment are needed to be mounted and demounted easily
Human resources	Commercial SCM is now a respected career path (Thomas, 2003)	High employee-turnover, based on voluntary staff, harsh physical and psychological environment
Stakeholders	Shareholders, customers and suppliers	Donors, governments, military, NGOs, beneficiaries, United Nations, etc.

Table I. Comparison of commercial and humanitarian SCM

an auction-based procurement framework is proposed here for humanitarian supply chains.

An auction is a mechanism, which outlines procedures to establish resource allocation based on bids submitted by participants (McAfee and McMillan, 1987). Two parties are defined for a specific auction: auctioneers and bidders. Procurement auctions occur when the auctioneer supplies its resources with the given bids at the end of an auction. Procurement auctions are usually cited as one-to-many auctions, where one buyer announces the demand and several suppliers bid on those announcements (Rothkopf and Whinston, 2007). In this study, the suppliers are determined in a framework where multiple auctioneers and multiple bidders exist. Therefore, the type of the auction detailed in this paper is many-to-many. Here, auctioneer parties are the humanitarian organizations that are requesting resources in disaster locations and the bidder parties are suppliers, where auctioneers compete for the limited resources that bidders have on hand.

It should be noted here that we assume that the suppliers are acting on humanitarian grounds and they are trying their best to supply the requirements of the humanitarian organizations. Therefore, the procurement auction in this study mainly works as an effective distributed mechanism in order to increase the efficiency of resource allocation. A centralized formulation is not considered, because the necessary information about the suppliers is dispersed and might not be available to the auctioneer.

The Fritz Institute is a leading non-profit organization working in this area. The Fritz Institute's goal is to facilitate an effective disaster response and recovery especially by targeting improvements in the humanitarian SCM field. The Fritz Institute's (2007) humanitarian logistics software (HELIOS) was launched in September and some NGOs (e.g. World Vision International and Oxfam, etc.) have started to implement HELIOS for pilot disaster relief operations. HELIOS has a procurement module, which includes purchase requisition, request for quotation, bid insertion and comparative bids analysis activities. The framework proposed in this paper can be applied to develop this procurement module.

Another humanitarian organization that can be cited as a real world example for the motivation of this study is Aidmatrix Foundation, Inc. It is a non-profit organization which provides SCM solutions to distribute more than $1.5 billion in aid annually affecting the lives of more than 65 million people. The International Federation of Red Cross, Federal Emergency Management Agency (FEMA) and North Atlantic Treaty Organization Euro-Atlantic Disaster Response Coordination Centre are three of the partners that use Aidmatrix Network® in their humanitarian relief requirements (Aidmatrix Foundation, 2009). Aidmatrix Network® is important to show the practicality of the problem detailed in this study, because it is used by large humanitarian organizations and it has several components similar to the framework detailed in this paper. The software modules pertinent to this study are in-kind donations management, procurement, needs management and online auction modules. These similar modules will be explained where needed.

As a real world example for a government institution using online procurement auctions, FEMA can be given. FEMA uses FedBid™ as an online procurement auction platform to procure its humanitarian supplies (FedBid, 2007). Aidmatrix Network® uses online auctions to redistribute the donations within a network of NGOs. In the online auction module of Aidmatrix Network®, the idea is to send the unsolicited donations to the place where they are needed with a sealed-bid silent auction opened by the present owner of the donation.

The presented framework here is a simulation-based procurement-auction model that uses integer programming (IP) formulations to construct and evaluate bids. Announcement construction, bid construction and bid evaluation are three phases of the framework that correspond, respectively, to the appeals management process, suppliers' bid quotation and supplier selection activities in a disaster relief operation. Announcement construction and bid evaluation phases are managed by the humanitarian organizations in disaster locations and the bid-construction phase is managed by the suppliers. Given that the majority of the literature focuses on the bid evaluation phase (i.e. the winner determination problem), this work also addresses the less studied phases before the winner determination phase (de Vries and Vohra, 2004; Elmaghraby and Keskinocak, 2006). These are the announcement construction and bid construction phases. The quality of the outcome from the auction relies heavily upon these earlier phases (Aissaoui *et al.*, 2007). This work explores the system parameters that need to be considered for a successful auction in all three phases. Although bid-construction phase is studied for the transportation procurement (Lee *et al.*, 2007) and for iterative combinatorial auctions (Kwon *et al.*, 2005), there have not been many studies focusing on a holistic framework covering these phases from start to finish for an auction (Abrache *et al.*, 2001). This study aims to address this literature gap by connecting the aforementioned phases.

Procurement auctions framework

Given that local resources are vital in the first few days after a disaster strikes, they should be utilized efficiently to supply the needs of the victims immediately. Additionally, procurement activities should be performed according to the specifics of disaster relief operations in the long run. The framework proposed for disaster relief operations here fits well both into the immediate response with local resources and also the long-term procurement activities from local and global suppliers. The main idea is to introduce some auction design parameters and decision-making logic that would facilitate the procurement activities.

The procurement auctions considered in this paper have multiple auctioneers and multiple bidders. The bidder parties can be identified as warehouses, suppliers, or manufacturers of the auctioned items in a disaster relief environment, whereas the auctioneer parties represent the NGOs, government institutions, or any humanitarian organization in disaster locations that send appeals for the items. The auctioneer here represents a buyer entity that is authorized to procure the appeals list for that humanitarian organization. The same buyer entity can procure the items that are needed for other disaster locations, but in this case the announcement would have different characteristics (e.g. ease of logistics, priority of items, etc.). These entities can also be regarded as different humanitarian organizations operating in that same disaster location focusing on different type of items. Decision variables are the quantity and type of items to be procured from bidders at the end of an auctioning period. The presented framework is for a two-echelon supply chain, where all bidders have an external supplier replenishing their inventories by an (s, S) policy. An (s, S) policy is assumed, because a variation of this policy was applied in Kenya (Beamon and Kotleba, 2006b). The auction process is shown in Figure 1.

As seen in Figure 1, in the announcement-construction phase, the auctioneer accumulates incoming demands and releases announcements based-on a predefined count threshold for priority of items (i.e. a certain number of highest priority items). Demands for different items arrive to auctioneers as appeals for relief supplies. These demands are then bundled according to the announcement construction criterion. When there are enough demands to form an announcement, it is announced. The auctioneer accumulates demands to benefit from the economies of scale in the procurement process. The bid-construction phase receives an announcement, compares demanded items with on hand inventory quantities, and their associated values. The value of an item corresponds to its age and condition. Using this information, bidders (suppliers) determine the quantities and mix of their bids with the aim of minimizing the current asset value of offered items. In the bid evaluation phase, bid quantities and their associated asset values are maximized by a general multidimensional knapsack

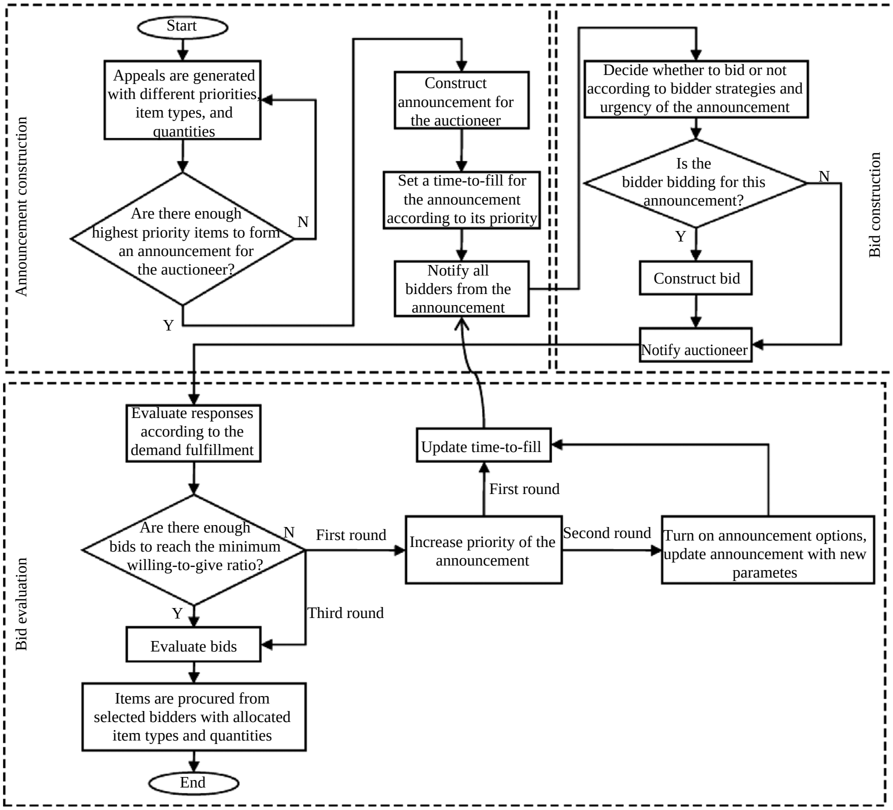

Figure 1.
Procurement auctions framework

problem (MDKP). Details of the framework will be explained in separate sections. The following considerations are made in the auction process:

- When an auction is finalized, the procured items from the bidder to the auctioneer are considered to be shipped and consumed.
- Without loss of generality, there is only one substitute for each item and two or more order substitutes (i.e. substitute of a substitute) are not allowed. This implies that original and substitute items are paired as each other's substitutes.
- An announcement cannot have the original item and the substitute item at the same time.

The auctioneer is responsible for setting the stage for the auction. An auctioneer can offer two announcement options in the announcement-construction phase. These are substitution and partial fulfilment options. These options are proposed in order to fulfill the demand of the disaster locations as much as it is possible with the current inventories of bidders. Although unsolicited in-kind donations are preferred over cash donations by business firms (Binder and Witte, 2007), they often cause the supplies to wait in the warehouses, perishing and bulking as unclaimed (Thomas and Fritz, 2006). Unsolicited donations are such a problem that some humanitarian organizations have been obliged to employ staff just to wipe out these unwanted or expired supplies (Murray, 2005). If the substitution option is preferred by the humanitarian organizations in disaster locations, then these unsolicited donations will get a chance to be used instead of causing stocking costs. Substitute item options are given to the bidder to give the opportunity to bid on the item even if it does not have the original quantity. In the FedBid™ platform (FedBid, 2009), a substitution option is given in four scales: exact match only, brand name or equal, meet or exceed, or a similar line item. The partial fulfilment option enables better usage of supplier inventories, and the value of the item gives a means to humanitarian organizations to evaluate the supplies. In the in-kind donations module of Aidmatrix Network® (Aidmatrix Foundation, 2009), humanitarian organizations in disaster locations are given the option to partially accept the offers of the supplier, which shows that the partial fulfillment option in this study is realistic.

The priority of items is included in the framework to improve the linkage between the humanitarian organizations and suppliers. Three levels of priority are used in the proposed framework. The first level indicates urgent-immediate distribution, the second level indicates low-priority distribution and the third level indicates non-priority items. The prioritization of supplies has been recommended (Davidson, 2006) and applied in disaster relief operations (van Wassenhove and Tomasini, 2003). For example, the priority of the items is represented with low, medium and high priority scale in the needs management module of Aidmatrix Network (FEMA, 2009).

The ease of logistics concept attempts to take into account of the differences among suppliers in terms of convenience in geographical or topographical access to the disaster location. During disasters, essential infrastructure like highways, roads and bridges are usually destroyed. A network formulation is not developed in this framework, because distance might not be the only reason facilitating the logistics operations. Instead, the ease of logistics criterion is designed to help humanitarian organizations to differentiate among different suppliers in the bid evaluation phase. The ease of logistics parameter is considered in three levels with integer from [1, 3] interval. The suppliers having better (i.e. higher) ease of logistics are favoured in the bid evaluation. Although suppliers are prioritized with an integer scale from [0-3] interval in the HELIOS software (Fritz Institute, 2007), it is not used as a means to assess the ease of access to the disaster location.

In the announcement-construction phase, appeals for items are declared with item types, quantities and priorities. Each item type has a priority, an integer from the interval [1, 3] (with one being the highest priority). When a certain quantity threshold is reached for the highest priority items, the decision for partial fulfilment and substitution options is taken and the announcement is constructed. In the procurement module of Aidmatrix Network® (Aidmatrix Foundation, 2009), consolidation of orders is given as an option, which shows that the bundling of items is a viable option. Time-to-fill for the announcement is defined as the waiting time of the announcement before receiving any response from bidders. Time-to-fill corresponds to "respond-by dates" in the needs management module of Aidmatrix Network® (FEMA, 2009). An upper bound for time-to-fill was selected as 24 time units (e.g. hours, etc.), because the assessment usually happens within the first 24 hours after the disaster strikes (Thomas, 2003). The weighted priority (WP) of the announcement is calculated with [sum of products of item priorities and quantities/sum of product quantities]. It defines the announcement's urgency by taking out quantity effect. Then, the WP of the announcement is used in extrapolating from [1, 3] priority interval to [1, 24] time unit interval using [(time-to-fill − 1)/(24-1) = (WP − 1)/(3-1)]. Note that higher priority announcements have a shorter time-to-fill. Urgency of an announcement represents the severity of the requirements in the disaster location. A sample announcement is given in Table II for six item types. The count threshold is 200 for this example announcement. The WP is 1.913 (calculated with 1,271/665) and the announcement has 11.497 time units before receiving any response from bidders. When an announcement is constructed, bidders are notified for bid construction, which leads to the bid-construction phase.

Bid-construction phase

In the bid-construction phase, bidders need to decide whether to bid or not on the announcement. This decision is based on the urgency of the announcement and the bidding strategy that the bidder follows. Strategy threshold represents the limit of auctioneers for letting bidders to follow their bidder strategies. If the announcement is urgent (i.e. the priority of the announcement is less than the strategy threshold), the bidder by-passes its bidding strategy and constructs bid for the announcement. Otherwise, it checks whether its bidding strategy picks the upcoming announcement. If the announcement is chosen, then the bidder constructs the bid; otherwise, the bidder notifies the auctioneer with a null bid. Bidders make the comparison among announcements with three different strategies:

(1) Bid to the announcement if it has the longest waiting time in the announcement queue.

(2) Bid to the announcement if it has the highest fill rate (i.e. supplied amount/requested amount) with original item types.

(3) Bid to the announcement if it is the most urgent (i.e. the lowest WP).

These strategies are applied only when there are enough announcements (three announcements are taken without loss of generality) in bidder's agenda to compare. The first strategy aims to decrease the waiting time of announcements in the queue. The second strategy aims to better utilize on hand inventories and the third strategy gives importance to the priority of the items.

After a bidder decides to bid on an announcement, it uses an IP formulation to construct its bid. The decision in bid construction is whether to use substitute items or not while fulfilling the announcement with original items. A bidder may have choices of

Item type	Quantity	Priority	Substitution	Partial fulfillment	WP
1	229	2	1	1	458
3	88	2	1	0	176
6	153	1	1	1	153
8	90	3	1	0	270
9	55	3	0	1	165
10	50	1	0	0	50
Total	665				1,272

Table II. Sample announcement for a 200 threshold on count priority satisfying the demand with only original items, only substitute items, or a mix of those depending on its inventory on hand. The objective function used in bid construction is formulated as: $\sum_{j}^{m}(X_jV_j + Y_jW_j)$, where X_j is the original quantity bid, Y_j is the substitute quantity bid, V_j and W_j are the original and substitute values of the bidders' inventory for item j of the announcement having m items. Value is a function of the sales price, the condition and the age of the item in the supplier's inventory. Value of each item in its inventory is known by the bidder a priori. The challenge here is whether to include substitutes and how much to include when it is allowed by the auctioneer party. The bids are divisible and all-or-nothing bids are not accepted, therefore suppliers are considered as willing to give the quantity that is allocated by the auctioneer at the same value as they offered for the whole quantity (Wurman *et al.*, 1998; Schvartzman and Wellman, 2007). In the following formulation, if-then constraints and inventory availability parameters are critical. If-then constraints are needed for the partial demand fulfilment and the substitution options. The inventory availability parameter aims to determine the inventory on hand. The index of items in an announcement in the IP formulation is represented by ($j = 1, \ldots m$). The parameters and decision variables are given in Table III.

The objective function is given as [$\text{Min}\sum_{j}^{m}(X_jV_j + Y_jW_j)$]. The constraints of the IP formulation are as follows:

$$X_j + S_jY_j \geq Q_j - Mz_j \quad \forall j \tag{1}$$

$$Y_j \leq \text{MS}_j \quad \forall j \tag{2}$$

$$X_j \leq I_j \quad \forall_j \tag{3}$$

$$Y_j \leq H_j \quad \forall_j \tag{4}$$

Parameter	Definition
Q_j	Original demand quantity for item type j
I_j	Original quantity of type j in bidder's inventory
H_j	Substitute quantity of type j in bidder's inventory
V_j	Value of original type j in bidder's inventory
W_j	Value of substitute type j in bidder's inventory
P_j	$\begin{cases} 1, \text{ if partial demand fulfillment is allowed for type } j \\ 0, \text{ otherwise} \end{cases}$
S_j	$\begin{cases} 1, \text{ if substitute type is allowed for type } j \\ 0, \text{ otherwise} \end{cases}$
z_j	$\begin{cases} 0, \text{ if inventory of bidder is greater than announced quantity for type } j \\ 0, \text{ otherwise} \end{cases}$
M	Big-M (i.e. a sufficiently large integer)
Decision variables	
X_j	Original quantity bid by the retailer
Y_j	Substitute quantity bid by the retailer

Table III. Parameters and decision variables in bid-construction phase

$$X_j \geq P_j I_j - \mathrm{M}(1 - z_j) \quad \forall j \tag{5}$$

$$Y_j \geq S_j P_j H_j - \mathrm{M}(1 - z_j) \quad \forall j \tag{6}$$

$$X_j \geq 0 \text{ and integer} \quad \forall j \tag{7}$$

$$Y_j \geq 0 \text{ and integer} \quad \forall j \tag{8}$$

Using the parameters given in the announcement and inventory on hand, z_j is calculated. z_j represents the availability of the bidder for the announcement. It is calculated using ($I_j + S_j H_j \geq Q_j$) for each item in the announcement. If this inequality is valid, this means that the bidder has enough inventory to satisfy this item in the announcement. Then z_j is equal to 0. If it is not valid, then z_j is set to 1. The objective function represents the bid value, which the bidder offers for the announcement under consideration. It is minimized to make use of the aged items as soon as possible. Decision variables are the quantities of original and substitute items in the bid. The first two constraints are the announcement fulfilment constraints. In equation (1), the first term represents the original quantity and the second term is present only when substitutes are allowed. The right-hand-side is the original quantity in the announcement. If there is not enough inventory (i.e. $z_j = 1$), then this constraint is redundant by the use of the Big-M. Equation (2) forces substitute bids to be 0 when substitution is not allowed. Equations (3) and (4) prohibit the bidder from bidding more than the on hand inventory. Equations (5) and (6) oblige bidders to give whatever they have as a bid if they do not have enough inventories to fully satisfy the announcement. Equations (7) and (8) are the integer constraints for the decision variables.

Bid evaluation phase

In the bid evaluation phase, the auctioneer collects responses from bidders and decides whether or not to send the announcement back to bidders for another round. Multi-round auctioning usually means the revision of the bid from suppliers (Bourbeau *et al.*, 2005); on the other hand, the framework in this paper introduces modification of announcements to get a higher fill rate in the upcoming rounds. In our framework, the willing-to-give ratio is important. The willing-to-give ratio is defined as [(total bid quantity)/(announcement quantity)]. This ratio is calculated for each item using all the bids. When there are enough bids to reach the predetermined willing-to-give ratio for all item types, then auctioneer evaluates the bids. If there are not enough bids, then the priority of the announcement is increased by a priority increase rate, time-to-fill is updated (i.e. decreased) and the announcement is sent back to the bidders for a second round. In the second round, if the willing-to-give ratio is still not reached, then the substitution and partial fulfilment options are turned on for the item types where they were not allowed before. Then, the priority of the announcement is increased, time-to-fill is updated and the announcement is sent back to the bidders for a third round. If the willing-to-give ratio is still not reached, then the auctioneer evaluates the bids and becomes content with the available bids.

The bid evaluation phase chooses the suppliers to fulfil the announcement. The auctioneer might fulfil the announcement by only original items, only substitute items, or a mix of those depending on the bids received and the location of the bidders.

The objective function used in bid evaluation is formulated as: $\sum_j^n \sum_j^m \alpha_i(A_{ij}V_{ij}+B_{ij}W_{ij})$, where A_{ij} is the original quantity of item j allocated to bidder i, B_{ij} is the substitute quantity of item j allocated to bidder i, and V_{ij} and W_{ij} are the original and substitute values of the bidder i's inventory for item j in an announcement having m items. Note that V_{ij} and W_{ij} are exogenous for the auctioneer and declared by the bidder in the bid-construction phase. Here, α_i represents the ease of logistics parameter for bidder i. The following formulation is a variation of the general MDKP (Akcay *et al.*, 2007). The index of items in an announcement in the IP formulation is represented by $(j = 1, \ldots m)$ and the index of bidders is represented by $(i = 1, \ldots n)$.

The objective function is given as $[Max \sum_j^n \sum_j^m \alpha_i(A_{ij}V_{ij}+B_{ij}W_{ij})]$. The constraints of the IP formulation are as follows:

$$\sum\nolimits_j^n (A_{ij}+B_{ij}) \leq Q_j \quad \forall j \tag{9}$$

$$A_{ij} \leq C_{ij} \quad \forall i,j \tag{10}$$

$$B_{ij} \leq D_{ij} \quad \forall i,j \tag{11}$$

$$A_{ij} \geq 0 \text{ and integer} \quad \forall i,j \tag{12}$$

$$B_{ij} \geq 0 \text{ and integer} \quad \forall i,j \tag{13}$$

The objective function represents the value that the auctioneer is willing to pay to the bidders. It is maximized in order to prefer the newest and the most items as possible. A value notion is introduced instead of a pure price model, because when price is the only criterion for bid evaluation, incumbent suppliers are reluctant to enter into procurement auctions (White *et al.*, 2004; Jap, 2007). Moreover, when price is the only measure for resource allocation, the qualitative measures of product and the capabilities of the suppliers are not considered (Rothkopf and Whinston, 2007). In our framework, qualitative measures of the product are considered within the age, condition and location (i.e. ease of logistics) of the product. The capabilities of suppliers are increased and diversified by partial fulfilment and substitution options. Decision variables are A_{ij} and B_{ij}, corresponding, respectively, to the original quantity of item j allocated to bidder i and the substitute quantity of item j allocated to bidder i. Equation (9) is the announcement fulfilment constraint. Equations (10) and (11) prohibit the auctioneer from allocating more than the bid quantities. Here, C_{ij} and D_{ij} correspond, respectively, to the original quantity of item j bid by bidder i and the substitute quantity of item j bid by bidder i in the bid-construction phase. Equations (12) and (13) are integer constraints for the decision variables.

Experimental study

In this section, the proposed procurement auctions-based framework is evaluated with respect to different design parameters. A simulation model was used to generate different problem instances and to combine the three phases of the framework. The simulation model is coded using the Java Simulation Library (Rossetti, 2008) with CPLEX 10.1™ called to solve the IP formulations during the simulation runs.

All experiments were conducted on a PC with an Intel™ Pentium™ 4 2.8 GHz CPU and 2 GB RAM. The results of two sets of experiments are analyzed and presented here: the first set of experiments illustrates the effects of the environmental factors and the second set of experiments details the effects of different auction parameters with four special scenarios. The environmental and auction design parameters are shown in Figure 2.

In Figure 2, environmental factors are shown as:

- demand quantity distribution;
- the ease of logistics;
- value of the item;
- inventory on hand; and
- lead time.

Auctioneer-related parameters are given as willing-to-give ratio, strategy threshold, count threshold and priority increase rate. Bidder-related parameter is given as bidding strategy. In the following two sections environmental factors and auction design parameters are explained.

Environmental factors

The location and timing of a disaster determine some environmental factors which can be changed neither by the auctioneers nor by the bidders. These environmental factors affect the result of the procurement auctions, but are not an inherent part of the auction design. In an attempt to stabilize the environmental factors for the scenario analysis, a 2^5 full factorial design of experiments was performed with three bidders and one auctioneer. This auctioneer can be regarded as a single humanitarian organization. One high and one low level was chosen from Table IV. In Table IV, 33 per cent of bidders represent one bidder and 66 per cent of bidders represent two bidders. Lead time represents the number of hours to ship from lead time demand filler to the bidder's warehouse. For instance, one bidder with $U(12,72)$ represents a shorter lead time. Demands for different item types were generated using a Poisson distribution with a

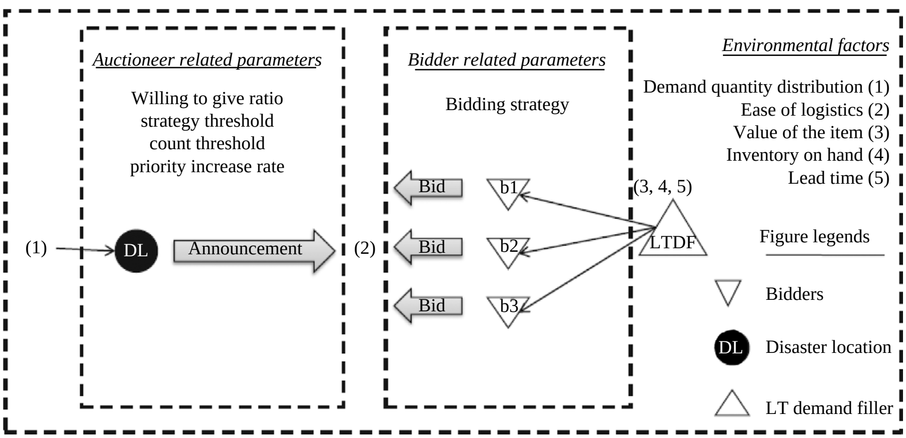

Figure 2.
Experimental design factors

Factor	Level Low	High
Demand quantity distribution	$U(1{,}50)$	$U(100{,}150)$
Ease of logistics	33% of the bidders – 3	33% of the bidders – 1
	67% of the bidders – 1	67% of the bidders – 3
Value of the item	33% of the bidders – 100	33% of the bidders – 50
	67% of the bidders – 50	67% of the bidders – 100
Inventory on hand	33% of the bidders – 70	33% of the bidders – 30
	67% of the bidders – 30	67% of the bidders – 70
Lead time	33% of the bidders – $U(12{,}72)$	33% of the bidders – $U(72{,}120)$
	67% of the bidders – $U(72{,}120)$	67% of the bidders – $U(12{,}72)$

Table IV. Environmental factors and their levels

mean of 1 demand/time-unit. Each item type is equally likely to be demanded out of ten item types. About 1,000 individual demands are generated with 30 replications. The quantity of each demand is a random variable, which follows the demand quantity distribution. Each incoming demand quantity is added to its same item type in the bundle and the count threshold (200) is checked. If the threshold is met, then this bundle, which includes quantities for different item types, is announced. The demand quantity distribution depends on the severity of the damage in the disaster location. In Table IV, severe damage of the disaster location is represented by high demand quantity distribution (i.e. $U(100{,}150)$). Ease of logistics is a constant factor relative to disaster locations and bidders, which is determined after the disaster strikes. For instance, a bidder with an ease of logistics factor of three would be favoured in the bid evaluation. Value of the item, inventory on hand and lead time are determined by contractual terms between external lead time demand fillers and bidders. The S-value represents the order up to level and the s-value represents the reorder point, which is taken as ten for all bidders.

One of the performance measures in humanitarian logistics is the quantity that is supplied out of the amount requested (Davidson, 2006). This metric is defined as the fill rate. A practical example for the fill rate can be given from a disaster relief operation after South Asia Earthquake on 9 October 2005. The fill rate (i.e. appeal coverage) was 63 per cent after the first week, 47 per cent after the second week, 74 per cent after a month, 91 per cent after two months and 93 per cent after three months (Davidson, 2006). "Percent of needs met" is the term used for fill rate in the needs management module of Aidmatrix Network® (Aidmatrix Foundation, 2009). Allocation share of bidders is another performance measure, which defines the distribution of supplied items among bidders. When the results of the full factorial design are analyzed, the value of the item and ease of logistics factors have no effect on the fill rate. Other quantity-related factors have an effect on fill rate. Inventory on hand and ease of logistics affect the bidder shares, where higher inventory on hand and higher ease of logistics increase the bidder's share. For the scenario analysis, middle levels from Table IV were selected and remained unchanged during the remaining experiments. Demand quantity distribution was selected as $U(50{,}100)$ for all disaster locations. The value of the item in a bidders' inventory is taken as 75, inventory on hand was set to 100 and ease of logistics was set to two for all bidders. The fill rate of the auctioneer with these middle levels is 0.59.

Auction design parameters

Auctioneer-related parameters give flexibility to the auctioneers to adapt themselves to the changing settings of different disasters and different locations. Willing-to-give ratio determines the eagerness of the auctioneer for demand satisfaction. Since resources are limited in a disaster relief environment, there might be cases where auctioneers need to be satisfied with a certain amount. This concept is termed willing-to-give because it shows the willingness of the bidders to bid on an announcement. The strategy threshold is a safety factor for disaster locations where the below threshold levels by-pass bidder strategies in urgent announcements and oblige bidders to bid on the announcement. Count threshold determines the number of highest priority items and the timing of an announcement. Priority increase rate determines the rate to increase the priority between multiple rounds. We assume that the tolerance of the auctioneer to wait decreases with increasing number of rounds. Bidding strategy gives flexibility to bidders whether to bid or not. Table V summarizes the special scenarios to analyze these auction parameters.

The experiments in Table V are performed with three auctioneers and nine bidders. Only the target design parameters are altered in each scenario. After the target design parameter is analyzed, it remained unchanged in later scenarios. The first scenario is the base case for the multiple auctioneers setting. In the second scenario, bidding strategies are introduced. The third scenario introduces multiple rounds and the fourth scenario evaluates bidding strategies and multiple rounds together. The fill rate, the allocation share among bidders and the announcement queue characteristics are used as the performance factors (Beamon and Balcik, 2008). An announcement queue holds all the announcements that an auctioneer has requested.

The objective of the first scenario is to examine the effect of multiple auctioneers and count threshold on fill rate. Neither bidders nor the auctioneers have decision-making logic; bidders bid to every announcement and auctioneers get whatever they are given. This scenario is like a single round sealed-bid auction. The results are given in Table VI. It can be concluded that total number of announcements, number of announcements in the announcement queue and fill rate decreases with increasing count threshold levels. With one auctioneer and three bidders, the fill rate was 0.59 compared to the 0.71 fill rate with three auctioneers and nine bidders in experiment one. This increase can be by explained by the pooling of different bidder inventories. A count threshold was selected as 400 for future scenarios with a fill rate of 0.61.

The second scenario examines the effect of bidder decision making, bidder strategies and strategy threshold. Three out of nine bidders all behave according to one bidding strategy. In this analysis, the strategy threshold is altered. This scenario is like a single round sealed-bid auction with increased governance on the bidder side. The results are given in Table VII. Urgency increases by decreasing levels of WP and bidder strategies are by-passed for an urgent announcement. Since $E[\mathrm{WP}] = 2$, probabilistically fewer number of announcements fall into below threshold levels. It can be seen that lower levels for strategy threshold give bidders more freedom of not bidding, therefore fill rate decreases. The third bidding strategy emphasizes announcements with higher WP; consequently bidders seven to nine have the highest shares in the allocation. Bidders using the second bidding strategy outperform the bidders with the first bidding strategy, because the second bidding strategy picks the announcements with higher fill rate. The announcement queue shows similar characteristics in this scenario when

Table V. Four scenarios to evaluate different auction design parameters

Scenario	Bidders	Auctioneers	Performance measure	Target design parameter
1	No decision on whether to bid or not Construct bid to every announcement	Evaluate all the bids. Single Round	Fill rate announcement queue	Base case for multiple disaster locations Count threshold
2	Decide to bid or not Three bidders-strategy 1 Three bidders-strategy 2 Three bidders-strategy 3	Evaluate all the bids Single round Count threshold same for all auctioneers (400)	Fill rate Allocation share among bidders Announcement queue	Effect of bidder decision making and bidding strategies Strategy threshold
3	No decision on whether to bid or not Construct bid to every announcement	Decide to evaluate bids Multiple rounds Count threshold same for all (400) Strategy threshold same for all (1.7)	Fill rate Announcement queue	Effect of auctioneer decision making Effect of multiple rounds Willing to give ratio
4	Decide to bid or not Three bidders-strategy 1 Three bidders-strategy 2 Three bidders-strategy 3	Decide to evaluate bids Multiple rounds Count threshold same for all (400) Strategy threshold same for all (1.7) Wiling-to-give same for all (0.7)	Fill rate Allocation share among bidders Announcement queue	Effect of auctioneer decision making and bidder decision making combined Effect of multiple rounds Priority increase rate

Experiment	Auctioneer	Count threshold	Fill rate	Total number of announcements	Average time an announcement spends in queue	Average number of announcements in queue
1	1	200	0.71	104.67	11.20	1.17
	2	200	0.71	104.67	11.18	1.16
	3	200	0.71	104.67	11.24	1.17
2	1	200	0.73	104.67	11.20	1.17
	2	400	0.61	55.93	11.76	0.65
	3	600	0.51	38.37	12.06	0.46
3	1	400	0.61	56.63	11.82	0.67
	2	400	0.61	55.93	11.76	0.65
	3	400	0.61	56.00	11.82	0.66

Table VI.
First scenario results

Experiment	Auctioneer	Strategy threshold	Fill rate	Sum of bidders one to three share	Sum of bidders four to six share	Sum of bidders seven to nine share
1	1	1.5	0.04	0.07	0.22	0.71
	2	1.5	0.05			
	3	1.5	0.04			
2	1	1.5	0.04	0.14	0.26	0.14
	2	1.7	0.12			
	3	1.9	0.30			
3	1	1.7	0.10	0.12	0.24	0.64
	2	1.7	0.12			
	3	1.7	0.12			

Table VII.
Second scenario results

compared with the first scenario having the 400 count threshold level. A strategy threshold of 1.7 was selected for the last two scenarios for all auctioneers.

The third scenario examines the effect of multiple rounds, auctioneer decision making and willing-to-give ratio. In this scenario, bidders do not have bidding strategies. During multiple rounds of auctioning, the auctioneer alters the parameters of the announcement to reach higher fill rates. In each round, when the willing-to-give ratio is not reached, for the items having $WP > 2$, priority is increased by the priority increase rate. For instance, an item with 2.2 WP would have 2.1 WP after one round of auction with a 0.1 priority increase rate. In the third scenario, the priority increase rate is taken as 0.1 for all auctioneers. The results are given in Table VIII. Fill rates jumped substantially to closer values to 1.0. Since the willing-to-give ratio is related to bidder strategies, it shows a slight effect on fill rates. If the willing-to-give ratio is increased, fill rates slightly decrease. Altering the willing-to-give ratio changes the number of announcements resolved in each round. If the willing-to-give ratio is increased, it pushes the announcements back to the later rounds. The number of resolved announcements in the second round is the least, which shows that announcement options do not change the decision of sending the announcement back to the bidders. The average time that an announcement spends in the queue and the average number of announcements in the queue almost doubled. It can be concluded that auctioneers wait more in order to reach the higher fill rates in later rounds. The willing-to-give ratio was set to 0.7 for the last scenario.

Experiement	Auctioneer	Willing-to-give ratio	Fill rate	Average time an announcements spends in queue	Average number of announcements in queue	Total number of announcements	Number of resolved announcements	First round resolved	Second round resolved	Third round resolved
1	1	0.5	0.9992	22.63	1.27	56.63	54.80	9.87	0.53	44.40
	2	0.6	0.9994	22.38	1.24	55.93	54.17	9.27	0.47	44.43
	3	0.7	0.9996	22.56	1.25	56.00	54.43	8.03	0.60	45.80
2	1	0.6	0.9994	22.66	1.27	56.63	54.80	9.50	0.70	44.60
	2	0.6	0.9996	22.43	1.24	55.93	54.17	9.23	0.43	44.50
	3	0.6	0.9996	22.62	1.25	56.00	54.43	8.23	0.30	45.90
3	1	0.7	0.9994	22.64	1.27	56.63	54.80	9.37	0.57	44.87
	2	0.7	0.9999	22.39	1.24	55.93	54.17	8.93	0.40	44.83
	3	0.7	0.9998	22.65	1.26	56.00	54.43	8.03	0.53	45.87

Table VIII.
Third scenario results

The fourth scenario examines the combined effects of bidder and auctioneer decision making in multiple rounds with priority increase rate. This scenario includes all the design parameters that are proposed. Priority increase rate works together with strategy threshold to by-pass the bidder strategies. The results are given in Table IX. If priority is increased by 0.5 between rounds, then bidder strategies are by passed and bidders are obliged to bid, which leads to higher fill rates. If priority is increased by 0.1 between rounds, then bidders might decide not to bid, which decreases fill rate. If the priority increase rate is smaller, more announcements are pushed to later rounds to be resolved. When auctioneers use different priority increase rates as 0.1, 0.1 and 0.5, respectively, the third auctioneer with 0.5 does not reach to the high fill rate when they all use 0.5. If the auctioneers use 0.5, 0.5 and 0.1, respectively, the third auctioneer with 0.1 does not have a fill rate as low as when they all use 0.1. The higher priority increase rate makes announcements spend less time in the queue and enable higher fill rates to be reached. The bidder shares change significantly. Lower priority increase rate makes first bidding strategy more powerful, whereas, bidders with the second bidding strategy get more shares with a higher priority increase rate.

In order to compare different scenarios in terms of fill rate, the experiments on which the later scenarios built were selected. The third experiment from the first, second and third scenarios, and the first experiment from the last scenario were examined. The average fill rates of auctioneers and the announcement queue characteristics are shown in Table X. The first scenario reaches a 0.61 fill rate, whereas in the second scenario, fill rate decreases substantially, because most of the bidders choose not to bid and auctioneers do not have a means to compel them to bid. These two scenarios have the least time spent and number in announcement queue. The third scenario introduces auctioneer decision making in multiple rounds, and if the auctioneer is not satisfied with what has been bid, it sends the announcement back to the bidders. This allows more time for the bidders to replenish their inventory and gives priority to the second and third round announcements in the announcement queue. As a result, announcements spend more time in the queue, but reach the highest fill rate. This result might be unrealistic, because bidders do not have the decision to bid or not. In the fourth scenario, although the time an announcement spends in the queue increases, it reaches a higher fill rate than the first and the second scenario.

Discussion

Since humanitarian supply chains have unique characteristics when compared to corporate supply chains, the environment should be understood before assessing the contribution of a framework. Therefore, in the first phase of experimental study, environmental factors were conceived and they are kept as constants in the second phase. This approach enabled an examination of the auction design parameters proposed in this paper within reasonable environmental conditions. Each scenario focused on a different parameter to represent the effect of that particular parameter.

The framework includes some design parameters which can easily be implemented in disaster relief operations. It is shown in the experimental study that the priority of items and WP of a bundle affect the fill rate of an announcement. Bundling of items has not been studied in the auction literature as much as the single indivisible item case (Klemperer, 2004), therefore bundling of items in the framework is a contribution to the

Table IX.
Fourth scenario results

Experiment	Auctioneer	Priority increase rate	Fill rate	Average time the announcements spends in queue	Average number of announcements in queue	Total number of announcements	Number of resolved announcements	First round resolved	Second round resolved	Third round resolved	Sum of bidders one to three share	Sum of bidders four to six share	Sum of bidders seven to nine share
1	1	0.1	0.803	33.13	1.85	56.63	54.80	3.43	0.47	50.77	0.71	0.22	0.07
	2	0.1	0.829	32.85	1.81	55.93	54.17	3.93	0.50	49.70			
	3	0.1	0.796	33.04	1.82	56.00	54.43	3.63	0.57	50.17			
2	1	0.5	0.970	28.34	1.58	56.63	54.90	3.80	2.70	48.40	0.38	0.43	0.18
	2	0.5	0.971	28.11	1.55	55.93	54.47	4.23	2.77	47.47			
	3	0.5	0.968	28.43	1.57	56.00	54.63	3.83	2.00	48.80			
3	1	0.1	0.856	33.13	1.85	56.63	54.67	3.47	0.47	50.73	0.59	0.30	0.11
	2	0.1	0.876	32.86	1.81	55.93	54.10	3.67	0.77	49.67			
	3	0.5	0.875	28.54	1.58	56.00	54.67	3.50	2.30	48.87			
4	1	0.5	0.923	28.51	1.59	56.63	54.90	3.27	3.07	48.57	0.49	0.36	0.15
	2	0.5	0.924	28.36	1.56	55.93	54.47	3.63	2.67	48.17			
	3	0.1	0.915	33.09	1.83	56.00	54.37	3.43	0.53	50.40			

auction literature. The ease of logistics and announcement options can be used in software like HELIOS to reach higher efficiency in resource allocation. Bidder and auctioneer decision making introduces competition among bidders and among auctioneers, which is the practical case in procurement operations.

The framework is not intended to find the market-clearing price using each party's valuations of each item type; rather, we focus on the item type and quantity allocation from the sellers to the buyers. The exploratory research (Kovacs and Spens, 2007) serves the purpose of conceiving the specifics of disaster relief logistics. The framework proposed in this paper is a quantitative and holistic model that can be used to address the specific needs of disaster relief logistics.

The network-flow models (Ozdamar *et al.*, 2004; Yi and Ozdamar, 2007; Barbarosoglu and Arda, 2004) are narrowly focused and usually deal with the vehicle routing and allocation of specific resources, whereas our proposed framework is holistic (from demand creation to the fulfilment of the demand) as well as modelling the procurement activity with an auction. Resource allocation problems are typically solved in the literature (Fiedrich *et al.*, 2000; Gong and Batta, 2007; Qiao *et al.*, 2007) for equipment, vehicles and reusable supplies. The framework here provides alternative methods for consumable supplies; therefore, it does not have the scheduling components that are found in other models.

Conclusion

A simulation-based procurement-auction framework is presented in this paper to address the inefficiencies of humanitarian supply chains. In humanitarian supply chains, humanitarian organizations in multiple disaster locations appeal for relief items at the same time in an area where supplier resources are limited. The specific design characteristics of disaster relief procurement activities are incorporated into the announcement construction, bid construction and bid evaluation phases of the framework. Humanitarian organizations in disaster locations are considered as auctioneers and suppliers are considered as bidders. Auctioneers compete to one another in multiple rounds of the procurement auction. The holistic framework in three phases is unique not only in procurement auction literature, but also in disaster relief logistics. The value notion plays a balanced role in the framework, since the bid-construction phase minimizes the value, but the bid evaluation phase maximizes the value. The use of the value notion helps suppliers to make use of the old items more effectively in the bid-construction phase and helps the disaster location to get better conditioned items in the bid evaluation phase.

Humanitarian organizations in disaster locations are given the right to reject the bids when they do not fulfil a certain portion of the appeal list. When humanitarian organizations are not satisfied, they send a revised announcement to the suppliers. Humanitarian organizations in disaster locations have substitution and partial

Table X.
Comparison of four scenarios

Scenarios	Fill rate	Time in Q	Number in Q
First	0.61	11.80	0.66
Second	0.11	11.80	0.66
Third	1.00	22.56	1.26
Fourth	0.81	33.01	1.83

fulfilment options while sending the announcement. Together with quantity, item type and priority information; the announcement options give a complete representation of the appeals list. Multiple rounds auctions usually require bids to be updated in each round, but the framework in this paper allows auctioneer humanitarian organizations to revise the announcements. Priority of announcement is connected to the waiting time of an announcement. Multiple round auctioning helped humanitarian organizations to increase their fill rate.

Suppliers are better evaluated with the ease of logistics parameter, which gives importance to the suppliers that have easy access to the disaster location. Suppliers are given the right to use bidding strategies when the announcement is not urgent. The balance with urgency in disaster relief operations and supplier preferences are accomplished with some threshold levels. Some bidding strategies performed well in certain settings, which leads to the conclusion that these strategies should be disaster specific.

As a future work, shipping and vehicle routing decisions can be incorporated into the framework with lead times from suppliers to the disaster locations. Combinatorial valuation of different bundles might also be a good extension of the current work. Different inventory replenishment policies for bidders can be used to trigger supplies from the supplier. A substitution factor might be used to convert original items into substitute items to come up with a policy different than one-to-one replenishment. Finally, data and information from a recent disaster relief effort could be collected in order to attempt to "replay" the disaster procurement process within the framework to better assess how the framework would have an effect on a real disaster situation.

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