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RESEARCH PAPER

A Robust Contract-Based Hybrid Procurement Model with Supplier Incentives for Humanitarian Supply Chains under Uncertainty

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Abstract

Typically, humanitarian agencies (HAs) tend to preposition relief supplies before potential disasters to increase resource availability in the post-disaster phase. However, prepositioning imposes high costs on relief chains. On the other hand, although postponing relief supply procurement to the post-disaster phase may avoid prepositioning costs, it comes with significant supply risks. This study utilizes buyback, option, and quantity discount contracts which enables HAs to adopt a hybrid strategy for providing relief supplies, ensuring maximum post-disaster supply availability. In this paper, a robust bi-objective two-stage stochastic programming model is proposed for supplier selection and the procurement of critical and non-critical relief supplies. The model also emphasizes suppliers' profits to incentivize their participation in the relief chain. In this study, a combination of robust stochastic programming and robust convex programming is employed to manage uncertainty. The model is applied to a case study, and multiple sensitivity analyses are performed. The results demonstrate that, compared with the situation in which hybrid contracts are not utilized, the proposed model reduces the HA's cost by 38.4% and expected shortages by 22.6%, while increasing suppliers' profits by 41.8%.

Keywords: Humanitarian Supply Chain, Procurement Strategies, Buyback, Option Contract, Robust Stochastic Optimization.

1. Introduction

Humanitarian agencies (HAs) strive to mitigate disaster risks through pre-disaster operations to ensure preparedness for the post-disaster phase. Key operations include relief supply procurement, warehousing, and distribution. Inadequate pre-disaster planning is almost certain to exacerbate the inevitable post-disaster chaos. More precisely, a lack of timely relief supplies increases human suffering and loss of life. Therefore, it is vital to establish an efficient and effective humanitarian supply chain (HSC) capable of sourcing and delivering relief supplies from suitable providers to affected areas. it is necessary for HAs to implement rigorous supplier selection and procurement processes that benefit both the agency and its suppliers. On the other hand, relief supplies can be classified into two groups of critical and non-critical. The first group includes emergency and sensitive items such as food and medicine, while the second includes more general items with long-term shelf-lives such as tents and blankets. Non-critical relief

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supplies are not time-sensitive, can be stored for future disasters, and typically involve low storage costs. Conversely, critical supplies are extremely time-sensitive, need to be available quickly, often require specific storage conditions, and face urgent and uncertain demand.

Under a buyback contract, the HA and its suppliers establish an agreement in which suppliers manufacture and deliver relief supplies to the HA for prepositioning in warehouses. Within a typical buyback contract, if the stocked inventory exceeds actual demand, the HA can return the unused stock to its supplier for an agreed-upon *buyback* price [1]. The supplier, in turn, can obtain a salvage value by selling the returned stock in a secondary market. This mechanism allows the HA to mitigate the financial risk of unused inventory and keep costs to a minimum.

In an option contract, the HA reserves a portion of the supplier's capacity at a unit option price in the pre-disaster phase. In post-disaster, when demand is realized, the HA may exercise this option at a predefined exercise price. Under this arrangement, the HA does not procure or store inventory in advance but retains the right to place orders post-disaster [2]. A key advantage of option contracts is their ability to prevent overstocking. If, however, demand exceeds the reserved quantity, the HA may place additional orders at an adjusted price [3]. The characteristics of non-critical relief supplies render them well-suited to buyback contracts and thus allow the HA to maintain a sufficient inventory for the response phase and return unused items at a buyback price if necessary. Conversely, critical relief supplies are more compatible with the option contract. This is because the HA does not have to preposition these supplies and can thereby avoid the costs and specific conditions of storing these time-sensitive, high-maintenance items. In other words, the HA can postpone the procurement of critical supplies to the post-disaster phase.

Since the quantity of demand in future disasters cannot be predicted, there may be instances where suppliers' capacity will be insufficient to meet the surging demand. In such cases, prepositioned non-critical supplies, reserved quantities of critical items, and post-disaster procurements may prove inadequate. Engaging backup suppliers in the post-disaster phase can address this shortfall and enhance the overall resilience of the HSC. A promising solution for the HA may be to sign quantity discount (QD) contracts with backup suppliers for post-disaster procurement. Under this type of contract, backup suppliers offer lower unit prices for larger order quantities.

2. Literature Review

Given the background of the study, this section is devoted to reviewing the most prominent recent works in two key areas: (1) supplier selection and relief supply prepositioning models, and (2) application of supply contracts in HSCs.

2.1. Supplier Selection and Relief Supply Prepositioning Models

Although the literature on this topic is extensive, this review focuses on studies most relevant to the present research. Falasca and Zobel [4] proposed a TSSP model for relief procurement under a fixed budget, addressing both pre- and post-disaster phases. Bozorgi-Amiri et al. [5] introduced a multi-objective programming model that integrated supplier selection and procurement decisions with other relief operations, while accounting for uncertainty in parameters such as demand, supply, and costs. Galindo and Batta [6] worked on facility location and relief supply prepositioning, considering the possibility that supply sources might be disrupted. Balcik and Ak [7] introduced a novel approach for integrating supply agreement frameworks into supplier selection and prepositioning operations. They employed a QD contract to facilitate the procurement of relief supplies and their prepositioning in warehouses. Pradhananga et al. [8] formulated a model encompassing resource allocation and distribution planning while accounting for procurement decisions in both pre- and post-disaster phases.

Tofighi et al. [9] developed a hybrid model combining stochastic and possibilistic programming approaches for facility location, prepositioning, and distribution planning across both phases. Safaei et al. [10] proposed a bi-level programming approach to identify suitable suppliers, determine prepositioning strategies, and optimize distribution networks, while considering supply and demand as uncertain parameters. Hu and Dong [11] addressed supplier selection and prepositioning by introducing quantity-based payment mechanisms and delivery times for both phases. Shokr et al. [12] proposed a robust bi-level programming model that utilized QD contracts and incorporated third-party logistics providers (3PLPs) for post-disaster transportation. Building on this, Shokr et al. [13] presented a robust TSSP model that supported collaboration among HAs in group procurement, prepositioning, and joint distribution planning. Aghajani et al. [14] developed an integrated procurement-warehousing decision model using a TSSP framework. The researchers employed a combination of quantity flexibility and option contracts for procuring relief supplies from both primary and backup suppliers. Additionally, they used rental warehouses to cope with capacity limitations in prepositioning.

2.2. Supply Contracts in Humanitarian Logistics

In recent years, the development of procurement contracts within the context of humanitarian logistics has gained increasing attention. For example, Balcik and Ak [7] proposed a TSSP model that incorporated a quantity discount contract between an HA and multiple suppliers for relief supply procurement. Torabi et al. [15] proposed a TSSP model to integrate procurement and prepositioning decisions across pre- and post-disaster phases using a quantity flexibility contract.

Option contracts represent another notable procurement mechanism, having garnered significant scholarly interest. Hu et al. [16] proposed a put option contract aimed at reducing inventory risks and enhancing supplier profitability. Aghajani et al. [3] also adopted an option contract to integrate supplier selection and prepositioning decisions in an HSC. Kord and Samouei [17] applied a quantity flexibility contract in a procurement model in which an internal supplier might outsource production to external suppliers to accelerate operations. Wang et al. [18] developed an optimization model featuring an option contract for supplier selection and prepositioning under uncertainty and demand ambiguity. Hu et al. [19] proposed a supplier selection model based on an option contract which incorporated both all-unit and incremental QDs. Shokr et al. [20] proposed a fourth-party humanitarian logistics model for making collaboration between multiple HAs, utilizing QD contract to purchase relief supplies from suppliers.

Remarkably, although buyback contracts have proven advantageous in humanitarian logistics Wang et al. [1], they appear to have been largely overlooked in existing optimization models for relief procurement. Based on the literature review, the major contributions of this research can be outlined as follows:

- Proposing a hybrid procurement strategy involving buyback, option, and QD contracts for relief supply procurement;
- Applying distinct supply contracts to critical and non-critical relief supplies;
- Promoting equity, in addition to profitability, among suppliers;
- Developing a TSSP model that accounts for deep uncertainty in parameters while ensuring solution and model robustness; and
- Validating the proposed model through a case study inspired by an actual disaster scenario

3. Problem Description and Model Formulation

The HSC discussed in this study consists of several suppliers, central warehouses, and demand points. The HA procures essential relief supplies from suppliers during the pre-disaster phase and either stocks them in central warehouses or reserves certain quantities to ensure availability during the response phase. To facilitate coordination between the HA and suppliers, three mechanisms are adopted: buyback, option, and QD contracts. The classification and operational details of these contracts are outlined below.

The suppliers are categorized into two groups: primary and backup. Primary suppliers are those with which the HA establishes agreements pre-disaster to secure a continuous supply of both critical and non-critical relief commodities. In case of capacity limitations of primary suppliers, backup suppliers are activated post-disaster. Backup suppliers are not involved in any pre-disaster procurement operations and are therefore excluded from buyback and option contracts. Instead, they are engaged through QD contracts, which solely apply to post-disaster purchases.

As previously discussed, relief supplies can be broadly classified into critical and non-critical items. Non-critical relief supplies are typically durable and are highly likely to face uncertain demand. These items can be prepositioned during the preparedness phase to allow the HA to store them in secure and accessible locations to mitigate shortage risks during the response phase. In contrast, critical relief supplies are often needed urgently, expensive, and perishable, making their prepositioning costly and/or impractical. Given these characteristics, the buyback contract is best suited for non-critical supplies, while the option contract is preferable for critical supplies.

Under a buyback contract, procurement decisions are made pre-disaster. This allows the HA and primary suppliers to negotiate terms and agree on a fixed unit price for orders. The primary suppliers should then deliver the supplies to the HA's central warehouses. In the post-disaster phase, if actual demand exceeds the prepositioned inventory, the HA may place additional orders for supplies at a higher price. On the other hand, if demand falls short of projections, the HA may return excess inventory to the suppliers in exchange for a buyback price, with the suppliers potentially earning salvage value from the returned goods. It is worth noting that, in commercial settings, buy-back contracts mitigate demand uncertainty by reducing the risk of overstocking for retailers. Similarly, in humanitarian logistics, although non-critical and durable items such as tents and blankets do not expire, there is substantial uncertainty regarding both the timing and volume of demand associated with specific disaster events [1]. This uncertainty gives rise to a different type of risk. First, excess inventory held by a single HA ties up limited storage capacity and financial resources. Second, surplus items may not be immediately required, yet maintaining them at forward operating bases can impose significant logistical and operational costs. Moreover, although items such as tents and blankets are non-perishable, they are highly volume-intensive, consume considerable storage space, and incur substantial handling costs. Consequently, excess stock held by an HA can become financially burdensome in the absence of mechanisms for transferring or reallocating inventory.

The buyback contract is modeled in a way to represent the availability of a risk-sharing and reverse-flow mechanism, which aligns with the strategic planning level of the proposed model. In practice, the HAs frequently rely on pre-negotiated framework agreements or standardized contract templates, where such parameters are exogenously defined and not dynamically optimized during response phase. Furthermore, for non-critical commodities, the dominant concerns are storage capacity, handling costs, and inventory risk across multiple disaster events rather than physical deterioration or strict time-based return limits. These aspects are implicitly captured through inventory holding costs and capacity constraints in the model.

In contrast, under an option contract, the HA places pre-disaster orders for critical relief supplies with primary suppliers. To be precise, the HA pays a unit option price for reserving a specified quantity of supplies. The suppliers, in turn, are required to manufacture and store the reserved items at their own facilities. In the event of an actual disaster, the HA may exercise the option and pay a predefined price per unit to have the supplies shipped to its warehouses. If the realized demand exceeds the reserved quantity, the HA can exercise all options and place additional orders at a higher – i.e. retail – price. The advantage for the HA is that, if the post-disaster demand turns out to be lower than anticipated, only a portion of the reserved quantity is exercised, allowing the HA to avoid unnecessary costs. This contractual structure motivates primary suppliers of critical relief supplies to become active participants in the HSC.

It is important to also establish favorable conditions for supplier participation. The supply contracts discussed thus far not only promote coordination but also ensure a win-win situation between the HA and suppliers. Still, in order to actualize this collaboration and persuade the suppliers to become part of the HSC, the HA must guarantee them both profits and equity. In such conditions, suppliers are motivated by the prospect of maximizing their revenue, while the HA is committed to treating all suppliers fairly during the post-disaster procurement process. Under these conditions, suppliers should demonstrate greater willingness to integrate into the HSC.

The structure and analytical framework of this study are based on the following basic assumptions:

- Buyback and option contracts are negotiated exclusively with primary suppliers during the preparedness phase.
- The HA can place orders with backup suppliers during the response phase, operating under a QD contract.
- Backup suppliers may be engaged post-disaster to supply both critical and non-critical relief commodities.
- Suppliers may possess excess inventory in the post-disaster phase, which they have manufactured pre-disaster as part of their business-as-usual operations.
- The suppliers are responsible for delivering the ordered relief supplies to the HA's central warehouses.
- All suppliers aim to maximize their profits.
- The HA is responsible for distributing relief supplies to demand points during the response phase.
- The HA operates on a limited procurement budget in both the pre- and post-disaster phases

Sets and Indices:

I	Set of HO warehouses, indexed by $i \in I$
R	Set of relief supplies, indexed by $r \in RI = \{CR, NCR\}$. *CR* and *NCR* stand for critical relief items and non-critical relief items, respectively.
J	Set of suppliers, indexed by $j \in J = \{PS, BS\}$. *PS* and *BS* stand for primary suppliers and backup suppliers, respectively.
L	Set of demand points, indexed by $l \in L$
C	Set of purchasing levels for backup suppliers, indexed by $c \in C$
S	Set of scenarios, indexed by $s \in S$

Parameters:

oc_i	Fixed cost of establishing warehouse *i*
bc_{rj}	Fixed cost of concluding a buyback contract with supplier *j* for non-critical relief commodity *r*
oc_{rj}	Fixed cost of concluding an option contract with supplier *j* for critical relief commodity *r*
h_{ri}	Unit holding cost of relief commodity *r* in warehouse *i*
sc_i	Storage capacity of warehouse *i* for relief supplies

p_{rj}	Unit cost of purchasing non-critical relief commodities at wholesale price from primary supplier *j* under buyback contract
ap_{rjis}	Unit cost of purchasing non-critical relief commodities from primary supplier *j* for warehouse *i* under buyback contract in scenario *s*
ϑ_{rj}	Buyback price of non-critical relief commodity *r* obtainable from supplier *j*
op_{rj}	Unit option price of critical relief commodity *r* for supplier *j*
ep_{rj}	Unit exercise price of critical relief commodity *r* for supplier *j*
aep_{rjs}	Unit exercise price for additional amounts of critical relief commodity *r* by supplier *j* in scenario *s*
φ_{rj}	Capacity of supplier *j* for pre-disaster supply of relief commodity *r*
pc_{rj}	Unit production cost of relief commodity *r* for supplier *j*
sv_{rj}	Salvage value of non-critical relief commodity *r* for supplier *j*
η_{rjs}	Surplus inventory of supplier *j* for supplying relief commodity *r* in scenario *s*
v_r	Unit volume of relief commodity *r*
d_{rls}	Demand for relief commodity *r* at demand point *l* in scenario *s*
dc_{rils}	Unit distribution cost of relief commodity *r* from warehouse *i* to demand point *l* in scenario *s*
$[lb_{rjc}, ub_{rjc}]$	Lower- and upper-bound prices offered by backup supplier *j* for supplying relief commodity *r* at purchasing level *c* under QD contract
π_{rjcs}	Unit cost of purchasing relief commodity *r* from backup supplier *j* at purchasing level *c* in scenario *s*
pr_s	Occurrence probability of scenario *s*
Φ	Pre-disaster procurement budget of the HA
ψ^s	Available post-disaster procurement budget of the HA in scenario *s*
α	Minimum procurement fraction from each primary supplier for each order to ensure equitable order distribution

<u>Decision Variables:</u>

σ_i	A binary variable that equals 1 if warehouse *i* is established for holding relief supplies; otherwise, 0.
x_{rj}	A binary variable that equals 1 if primary supplier *j* ($j \in PS$) is selected for supplying non-critical relief commodity *r* ($r \in NCR$) under buyback contract; otherwise, 0.
y_{rj}	A binary variable that equals 1 if primary supplier *j* ($j \in PS$) is selected for supplying critical relief commodity *r* ($r \in CR$) via option contract; otherwise, 0.
θ_{rjc}	A binary variable that equals 1 if purchasing level *c* is selected from backup supplier *j* for post-disaster purchase of relief commodity *r* under QD contract; otherwise, 0.
q^1_{rji}	Quantity of non-critical relief commodity *r* ordered from primary supplier *j* based on buyback contract for delivery to warehouse *i*
q^2_{rjis}	Additional quantity of non-critical relief commodity *r* to be purchased post-disaster based on buyback contract from primary supplier *j* for warehouse *i* in scenario *s*
Δ_{rjis}	Unused inventory of non-critical relief commodity *r* in warehouse *i* supplied by primary supplier *j* in scenario *s*
z^1_{rj}	Quantity of critical relief commodity *r* reserved pre-disaster from primary supplier *j* via option contract
z^2_{rjis}	Quantity of critical relief commodity *r* exercised from primary supplier *j* via option contract to be delivered post-disaster to warehouse *i* in scenario *s*
z^3_{rjis}	Additional quantity of relief commodity *r* exercised from primary supplier *j* via option contract to be delivered post-disaster to warehouse *i* in scenario *s*
qb_{rjcis}	Quantity of relief commodity *r* ordered from backup supplier *j* at purchasing level *c* to be delivered post-disaster to warehouse *i* in scenario *s* under QD contract
w_{rjils}	Quantity of relief commodity *r* supplied by primary supplier *j* to be distributed post-disaster from warehouse *i* to demand point *l* in scenario *s*
u_{rjils}	Quantity of relief commodity *r* supplied by backup supplier *j* to be distributed post-disaster from warehouse *i* to demand point *l* in scenario *s*

Without loss of generality, it is assumed that for the buyback contract, $R_{rj} > p_{rj} > pc_{rj} > sv_{rj}$ where R_{rj} is the retail price. $R_{rj} > p_{rj}$ ensures that the HA is sufficiently motivated to procure non-critical relief supplies under the buyback contract from the designated suppliers. As for the option contract, we have $WH_{rj} < op_{rj} + ep_{rj} < aep_{rjs}$ where WH_{rj} is the wholesale price. $WH_{rj} < op_{rj} + ep_{rj}$ ensures that the price is high enough to be attractive to suppliers and $op_{rj} + ep_{rj} < aep_{rjs}$ guarantees that the quantity of supplies procured pre-disaster is low enough to attract the HA.

The HA's objective function can thus be formulated as follows:

$$\min f_1 = EC + FC + IC + OC + \sum_s pr_s \left(PPC_s + PQD_s + DC_s + PC_s - BBR_s \right) \tag{1}$$

The cost components are detailed as follows:

(a) Fixed costs of establishing warehouses:

$$EC = \sum_i oc_i \sigma_i$$

(b) Fixed contractual costs:

$$FC = \sum_{r \in NCR} \sum_{j \in PS} bc_{rj} x_{rj} + \sum_{r \in CR} \sum_{j \in PS} oc_{rj} y_{rj}$$

(c) Prepositioning costs under the buyback contract:

$$IC = \sum_{r \in NCR} \sum_{j \in PS} \sum_i (p_{rj} + h_{ri}) \times q^1_{rji}$$

(d) Option contract cost related to reserving critical relief supplies:

$$OC = \sum_{r \in CR} \sum_{j \in PS} op_{rj} z^1_{rj}$$

(e) Post-disaster procurement costs under the buyback and option contracts:

$$PPC_s = \sum_{r \in NCR} \sum_{j \in PS} \sum_i ap_{rjis} q^2_{rjis} + \sum_{r \in CR} \sum_{j \in PS} \sum_i ep_{rj} z^2_{rjis} + \sum_{r \in CR} \sum_{j \in PS} \sum_i aep_{rjs} z^3_{rjis} \quad \forall s$$

(f) Post-disaster procurement costs from backup suppliers under the QD contract:

$$PQD_s = \sum_r \sum_i \sum_{j \in BS} \sum_c \pi_{rjcs} qb_{rijcs} \quad \forall s$$

(g) Relief supply distribution cost:

$$DC_s = \sum_r \sum_j \sum_i \sum_l dc_{rils} \left(w_{rjils} + u_{rjils} \right) \quad \forall s$$

(h) Penalty cost imposed due to shortages:

$$PC_s = \sum_r \sum_l PU_{rls} \Pi_{rls} \qquad \forall s$$

(i) HA's revenue from the buyback contract:

$$BBR_s = \sum_{r \in NCR} \sum_{j \in PS} \sum_i \vartheta_{rj} \times \Delta_{rjis} \qquad \forall s$$

The suppliers' objective function can be presented as follows:

$$\max f_2 = FC + IC + OC - GC + \sum_s pr_s \left(PPC_s + SV_s - BBR_s \right) \tag{2}$$

Where the terms include:

(j) Production costs:

$$GC = \sum_{r \in NCR} \sum_{j \in PS} pc_{rj} q_{rji}^1 + \sum_{r \in CR} \sum_{j \in PS} pc_{rj} z_{rj}^1$$

(k) Salvage value of unused non-critical relief supplies under the buyback contract:

$$SV_s = \sum_{r \in NCR} \sum_{j \in PS} \sum_i sv_{rj} \times \Delta_{rjis} \qquad \forall s$$

$$\sum_i q_{rji}^1 \le \varphi_{rj} x_{rj} \qquad \forall r \in NCR, j \in PS \tag{3}$$

$$z_{rj}^1 \le \varphi_{rj} y_{rj} \qquad \forall r \in CR, j \in MS \tag{4}$$

Constraints (3) and (4) relate to the selection of suppliers and their capacity to supply non-critical relief supplies. Notably, the buyback contract is activated through a binary decision variable indicating its availability. Nevertheless, its operational and economic impacts are modeled endogenously. Specifically, the model includes a decision variable representing the unused inventory of non-critical relief commodities (Δ_{rjis}). The returned quantity and the associated buyback revenue are directly determined from this variable within the optimization framework. Thus, the binary variable captures contract availability, while surplus inventory levels and financial flows are optimally determined under uncertainty (see Constraints (8)-(9))

$$\sum_{r \in NCR} \sum_{j \in PS} v_r q_{rji}^1 \le sc_i \sigma_i \qquad \forall i \tag{5}$$

Constraint (5) limits the volume of prepositioned relief supplies according to the capacity of the available warehouses.

$$\sum_{r\in NCR}\sum_{j\in PS}\sum_{i} p_{rj} q_{rji}^{1} + \sum_{r\in CR}\sum_{j\in PS} op_{rj} z_{rj}^{1} \le \Phi \tag{6}$$

Constraint (6) states that the costs associated with prepositioning non-critical relief supplies or reserving critical ones pre-disaster must not exceed the HA's procurement budget.

$$\sum_{i}\sum_{j\in PS} w_{rjils} + \sum_{i}\sum_{j\in BS} u_{rjils} = d_{rls} \qquad \forall r,l,s \tag{7}$$

Constraint (7) pertains to demand, ensuring that the relief supplies procured from primary and backup suppliers are distributed to demand points in the response phase.

$$\sum_{l} w_{rjils} + \Delta_{rjis} = q_{rji}^{1} + q_{rjis}^{2} \qquad \forall i, j\in PS, r\in NCR, s \tag{8}$$

$$\Delta_{rjis} \le q_{rji}^{1} \qquad \forall i, j\in PS, r\in NCR, s \tag{9}$$

Constraint (8) sets the flow balance of non-critical relief supplies, ensuring that the quantity distributed to demand points does not exceed the sum of prepositioned stock and additional supplies procured post-disaster from primary suppliers. This constraint also calculates the unused prepositioned inventory remaining at warehouses. Constraint (9) ensures that the unused inventory does not exceed the quantity prepositioned supplies.

$$\sum_{i} q_{rjis}^{2} \le \eta_{rjs} \qquad \forall r\in NCR, j\in PS, s \tag{10}$$

Constraint (10) states that post-disaster procurement of additional non-critical relief supplies from primary suppliers must not exceed their supply capacity.

$$\sum_{c} \theta_{rjc} \le 1 \quad \forall r, j\in BS \tag{11}$$

$$lb_{rjc}\theta_{rjc} \le \sum_{i} qb_{rjcis} \le ub_{rjc}\theta_{rjc} \qquad \forall r, j\in BS, c, s \tag{12}$$

Constraints (11) and (12) pertain to post-disaster procurement from backup suppliers for both critical and non-critical relief supplies. Since these are governed by QD contracts, Constraint (11) ensures that a specific procurement level is respected, and Constraint (12) guarantees that the quantity of procured supplies falls within the selected level's lower and upper bounds.

$$\sum_{i} z_{rjis}^{2} \le z_{rj}^{1} \qquad \forall r\in CR, j\in PS, s \tag{13}$$

$$\sum_{i} z_{rjis}^{3} \le \eta_{rjs} y_{rj} \qquad \forall r\in CR, j\in PS, s \tag{14}$$

Constraints (13) and (14) deal with exercising the option contract with primary suppliers to procure critical relief supplies post-disaster. Constraint (13) ensures that the exercised quantity does not exceed the reserved quantity, and Constraint (14) ensures that any additional quantity of supplies needed by the HA does not exceed the supplier's capacity.

$$\sum_l w_{rjils} \le z^2_{rjis} + z^3_{rjis} \quad \forall i, j \in PS, r \in CR, s \tag{15}$$

Constraint (15) specifies that the post-disaster distribution flow of critical relief supplies must not exceed the sum of the quantity already exercised and any additional quantities purchased from primary suppliers.

$$\sum_l u_{rjils} \le \sum_c qb_{rjcis} \qquad \forall i, j \in BS, r, s \tag{16}$$

Constraint (16) ensures that the distribution flow for relief supplies purchased from backup suppliers are lower than their quantity.

$$\sum_l w_{rjils} \le M \times \sigma_i \quad \forall i, j \in PS, r \in CR, s \tag{17}$$

Constraint (17) ensures that the flow of critical relief supplies from each warehouse to demand points can be established once the warehouse is already opened pre-disaster. Notably, this constraint applies to the flow of relief items purchased from primary suppliers.

$$\sum_l u_{rjils} \le M \times \sigma_i \qquad \forall i, j \in BS, r, s \tag{18}$$

Constraint (18) guarantees that the flow of non-critical and critical relief supplies from each warehouse to demand points, purchased through backup suppliers, can be established once the warehouse is already opened pre-disaster.

$$\left(\begin{array}{l} \sum_{r \in NCR} \sum_{j \in MS} \sum_i ap_{rjis} q^2_{rjis} + \sum_{r \in CR} \sum_{j \in MS} \sum_i ep_{rj} z^2_{rjis} + \\ \sum_{r \in CR} \sum_{j \in MS} \sum_i aep_{rjs} z^3_{rjis} + \sum_r \sum_i \sum_{j \in BS} \sum_c \pi_{rjcs} qb_{rjcis} \end{array} \right) \le \psi_s \qquad \forall s \tag{19}$$

Constraint (19) limits the total post-disaster procurement cost. To be specific, this constraint ensures that costs for all relief supplies – critical, non-critical, and those from backup suppliers – remain within the HA's post-disaster procurement budget.

$$\sum_i q^1_{rji} + \sum_i q^2_{rjis} \ge \alpha \sum_l \left(d_{rls} - \Pi_{rls} \right) \quad \forall r \in NCR, j \in PS, s \tag{20}$$

$$\sum_i z^2_{rjis} + \sum_i z^3_{rjis} \ge \alpha \sum_l \left(d_{rls} - \Pi_{rls} \right) \quad \forall r \in CR, j \in PS, s \tag{21}$$

Constraints (20) and (21) promote equity among suppliers by ensuring that each primary supplier covers some of the demand.

$$\begin{array}{l} \sigma_i, x_{rj}, y_{rj}, \theta_{rjc} \in \{0,1\} \quad \forall i, r, j, c \\ q^1_{rji}, q^2_{rjis}, \Delta_{rjis}, z^1_{rj}, z^2_{rjis}, z^3_{rjis}, qb_{rjcis}, w_{rjils}, u_{rjils} \ge 0 \quad \forall i, r, j, l, c, s \end{array} \tag{22}$$

Constraint (22) states the feasibility conditions are decision variables.

Since the model is formulated as a bi-objective optimization problem, it must be converted into a single-objective model. This is achieved by applying the weighted sum method, where each objective function is normalized by its range differences and measurement units. Therefore, we have:

$$\min g = \lambda_1\left(\frac{f_1 - f_1^{\min}}{f_1^{\max} - f_1^{\min}}\right) + \lambda_2\left(\frac{f_2^{\max} - f_2}{f_2^{\max} - f_2^{\min}}\right) \tag{23}$$

s.t: Constraints (3-23)

Notably, $f_i^{\min}$ and $f_i^{\max}$ represent the minimum and maximum values of the *i*th objective function, respectively. Also, λ_i denotes the priority of *i*th objective function where $\lambda_i \in [0,1]$ and $\sum_i \lambda_i = 1$.

4. Solution Procedure

This section addresses the model's approach to uncertainty. As the proposed model is based on TSSP, a scenario-based robust optimization technique is adopted to ensure robustness in the demand constraint. Additionally, the *unit additional procurement price for non-critical relief supplies* and the *unit additional exercise price for critical relief supplies* are the problem's uncertain parameters in the post-disaster phase. These two parameters are best expressed as intervals to indicating deep uncertainty and an efficient method is presented to cope with this type of uncertainty.

4.1. Modelling Demand Uncertainty

Constraint (7) in the proposed model contains a scenario-dependent demand parameter, and it is essential for the model to be robust regarding this constraint. To this end, the robust optimization framework developed by Mulvey et al. [21] is adopted. This approach ensures both solution robustness and model robustness. Solution robustness implies that the selected solution remains nearly optimal across all scenarios; while model robustness ensures that the solution remains nearly feasible across all scenarios.

To formulate the scenario-based robust version of the proposed model, the following general stochastic models are defined:

$$\min \sigma(x, y_1, ..., y_s) + \tau\rho(\upsilon_1, \upsilon_2, ..., \upsilon_s) \tag{24}$$

s.t:

$$Ax = b \tag{25}$$

$$C_s x + D_s y_s + \upsilon_s = e_s \quad \forall s \tag{26}$$

$$x, y_s, \upsilon_s \geq 0 \quad \forall s \tag{27}$$

Where *S* denotes a set of discrete demand scenarios for uncertain demands. The subset (C_s, D_s, e_s) represents the uncertain parameters in scenario *s*. The first and second terms of Objective Function (24) account for solution robustness and model robustness, respectively. The infeasibility of the model is denoted by υ_s, a variable that represents unmet demand in the proposed model. Furthermore, $\rho(\upsilon_1, \upsilon_2, ..., \upsilon_s)$ is the penalty function for controlling model infeasibility. Leung et al. [22] defines solution robustness as the sum of the mean value of the objective function and ω times the weighted term for absolute deviation of the objective function:

$$\sigma(x,y)=\sum_{s\in S}pr_s\xi_s+\omega\sum_{s\in S}pr_s\left|\xi_s-\sum_{s'\in S}pr_{s'}\xi_{s'}\right| \tag{28}$$

where ξ_s denotes Objective Function (28) in scenario *s*. At this point, the non-linear Relation (28) should be linearized as follows:

$$Min\sum_{s\in S}pr_s\xi_s+\omega\sum_{s\in S}pr_s\left[\left(\xi_s-\sum_{s'\in S}pr_{s'}\xi_{s'}\right)+2o_s\right] \tag{29}$$

$$\left(\xi_s-\sum_{s'\in S}pr_{s'}\xi_{s'}\right)+o_s\geq 0 \quad \forall s \tag{30}$$

$$o_s\geq 0 \qquad \forall s \tag{31}$$

By introducing the sufficiently large parameter τ for model robustness, the final robust optimization model is formulated as follows:

$$Min\sum_{s\in S}pr_s\xi_s+\omega\sum_{s\in S}pr_s\left[\left(\xi_s-\sum_{s'\in S}pr_{s'}\xi_{s'}\right)+2o_s\right]+\tau\sum_{s\in s}\sum_{r}\sum_{l}pr_s\Pi_{rls} \tag{32}$$

s.t:

$$\sum_i\sum_j w_{rjils}+\sum_i\sum_j u_{rjils}+\Pi_{rls}=d_{rls} \qquad \forall r,l,s \tag{33}$$

Constraints (3-6), (8-22), (30-31)

where τ denotes the unit penalty cost for shortages.

4.2. Modelling Post-Disaster Procurement Prices: Robust Convex Programming

As the HA negotiates buyback and option contracts with suppliers, some parameters are certain and others uncertain. The unit procurement cost of non-critical relief supplies, the unit option price, and the unit exercise price for critical relief supplies are the problem's certain parameters, set by the HA and suppliers pre-disaster as the basis of their contract agreements. On the other hand, the unit additional procurement cost of non-critical relief supplies and the unit additional exercise price for critical relief supplies are uncertain, with varying degrees of uncertainty according to disaster severity. Reliable historical data to estimate the probability distribution functions is unavailable. Thus, based on expert opinions, the two uncertain parameters are defined as intervals whose values fall within a symmetric range. In this paper, the method proposed by Bertsimas and Sim [23] is adopted to model the two above-mentioned uncertain parameters.

Constraint (19) in the original model involves these uncertain parameters. Specifically, the variables ap_{rjis} and aep_{rjs} represent the problem's uncertain parameters and are modeled as the following symmetric intervals:

$$\left(\begin{array}{l}\sum_{r\in NCR}\sum_{j\in PS}\sum_{i}ap_{rjis}q_{rjis}^2+\sum_{r\in CR}\sum_{j\in PS}\sum_{i}ep_{rj}z_{rjis}^2+\\ \sum_{r\in CR}\sum_{j\in PS}\sum_{i}aep_{rjs}z_{rjis}^3+\sum_{r}\sum_{i}\sum_{j\in BS}\sum_{c}\pi_{rjcs}qb_{rjcis}\end{array}\right)\leq\psi_s \qquad \forall s \tag{34}$$

The unit additional procurement cost of non-critical relief supplies and the unit additional exercise price for critical relief supplies take values in $[ap_{rjis} - \hat{ap}_{rjis}, ap_{rjis} + \hat{ap}_{rjis}]$ and $[aep_{rjs} - \dot{a}ep_{rjs}, aep_{rjs} + \dot{a}ep_{rjs}]$, respectively, whose nominal values are ap_{rjis} and aep_{rjs}. Furthermore, $\hat{ap}_{rjis}$ and $\dot{a}ep_{rjs}$ are the two parameters' maximum deviation from nominal value, respectively. Here, Γ_{rjis}^{ap} and Γ_{rjs}^{aep} represent the budgets of uncertainty in the *i*th row and can take values in the $[0, \left|J_{rji}^{ap}\right|]$ and $[0, \left|J_{rj}^{aep}\right|]$ intervals, where $\left|J_{rji}^{ap}\right|$ and $\left|J_{rj}^{aep}\right|$ represent the maximum number of uncertain parameters in Constraint (34). Therefore, we can reformulate Constraint (34) as follows:

$$\left(\begin{array}{l} \sum_{r \in NCR} \sum_{j \in PS} \sum_{i} ap_{rjis} q_{rjis}^{2} + \beta(q_{rjis}^{2}, \Gamma_{s}^{ap}) + \sum_{r \in CR} \sum_{j \in PS} \sum_{i} ep_{rj} z_{rjis}^{2} + \\ \sum_{r \in CR} \sum_{j \in PS} \sum_{i} aep_{rjs} z_{rjis}^{3} + \beta(z_{rjis}^{3}, \Gamma_{s}^{aep}) + \sum_{r} \sum_{i} \sum_{j \in BS} \sum_{c} \pi_{rjcs} qb_{rjcis} \end{array} \right) \le \psi_{s} \quad \forall s \tag{35}$$

where $\beta(.)$ is a protection function that may be expressed as follows:

$$\beta(q_{rjis}^{2}, \Gamma_{s}^{ap}) = \max_{\{S_s \cup \{t_s\} | S_s \subseteq J_s, |S_s| = \lfloor \Gamma_s \rfloor, t_s \in J_s \backslash S_s\}} \left\{ \sum_{r \in NCR} \sum_{j \in PS} \sum_{i} ap_{rjis} q_{rjis}^{2} + \left(\Gamma_{s}^{ap} - \lfloor \Gamma_{s}^{ap} \rfloor \right) ap_{rjist_s} q_{rjis}^{2} \right\} \tag{36}$$

$$\beta(z_{rjis}^{3}, \Gamma_{s}^{aep}) = \max_{\{S_s \cup \{t_s\} | S_s \subseteq J_s, |S_s| = \lfloor \Gamma_s \rfloor, t_s \in J_s \backslash S_s\}} \left\{ \sum_{r \in CR} \sum_{j \in PS} \sum_{i} aep_{rjs} z_{rjis}^{3} + \left(\Gamma_{rjs}^{aep} - \lfloor \Gamma_{rjs}^{aep} \rfloor \right) aep_{rjst_s} z_{rjis}^{3} \right\} \tag{37}$$

where (36) is equal to the following model:

$$\begin{array}{ll} \beta(q_{rjis}^{2*}, \Gamma_{s}^{ap}) = \max & \sum_{r} \sum_{j} \sum_{i} ap_{rjis} q_{rjis}^{2*} r_{rjis} \\ s.t: & \sum_{r} \sum_{j} \sum_{i} r_{rjis} \le \Gamma_{s}^{ap} \quad (w_{s}^{ap}) \\ & 0 \le r_{rjis} \le 1 \quad \forall r, j, i \quad (g_{rjis}^{ap}) \end{array} \tag{38}$$

The duality of (38) is as follows:

$$\begin{array}{l} \min \; w_{s}^{ap} \Gamma_{s}^{ap} + \sum_{r} \sum_{j} \sum_{i} g_{rjis}^{ap} \\ s.t: w_{s}^{ap} + g_{rjis}^{ap} \ge ap_{rjis} q_{rjis}^{2*} \quad \forall r, j, i, s \\ \quad w_{s}^{ap}, g_{rjis}^{ap} \ge 0 \quad \forall r, j, i, s \end{array} \tag{39}$$

The same procedure can be done for relation (37). Thus, the robust counterpart of Constraint (35) is as follows:

$$\left(\begin{array}{l} \sum_{r \in NCR} \sum_{j \in PS} \sum_{i} ap_{rjis} q_{rjis}^{2} + w_{s}^{ap} \Gamma_{s}^{ap} + \sum_{r} \sum_{j} \sum_{i} g_{rjis}^{ap} \\ \sum_{r \in CR} \sum_{j \in PS} \sum_{i} ep_{rj} z_{rjis}^{2} + \sum_{r} \sum_{i} \sum_{j \in BS} \sum_{c} \pi_{rjcs} qb_{rjcis} \\ \sum_{r \in CR} \sum_{j \in PS} \sum_{i} aep_{rjs} z_{rjis}^{3} + w_{s}^{aep} \Gamma_{s}^{aep} + \sum_{r} \sum_{j} g_{rjs}^{aep} \end{array} \right) \le \psi_{s} \quad \forall s \tag{40}$$

$$w_s^{ap}\Gamma_s^{ap} + g_{rjis}^{ap} \geq ap_{rjis} q_{rjis}^2 \quad \forall r, j, i, s \tag{41}$$

$$w_s^{aep}\Gamma_s^{aep} + g_{rjs}^{aep} \geq aep_{rjs} z_{rjis}^3 \quad \forall r, j, i, s \tag{42}$$

$$w_s^{ap}, w_s^{aep}, g_{rjis}^{ap}, g_{rjs}^{aep} \geq 0 \quad \forall r, j, i, s \tag{43}$$

5. Case Description

Hormozgan, a province in southern Iran consisting of 13 counties, holds significant economic and demographic importance. Surrounded by four active fault lines, the region is geographically vulnerable, with each fault considered to possess the potential to trigger an earthquake. With a population of nearly 1.8 million, any high-magnitude earthquake in this area could result in catastrophic consequences. Historical data point to Hormozgan as one of the most disaster-prone provinces in Iran, having experienced frequent moderate earthquakes over the past decade.

The case study involves five types of relief commodities: water, canned foods, blankets, tents, and hygiene kits. The objective is to plan for meeting the demand for these supplies during the first five days following a potential disaster. It is assumed that each person requires three liters of water and two canned foods per day. Additionally, over the five-day period, each person needs one hygiene kit and two blankets, while each tent is shared by four individuals.

Based on the province's 1,788,949 population, the total demand under the worst-case scenario is detailed in Table 1. Demand in each county is assumed to be proportional to its population. Three disaster scenarios are considered, corresponding to earthquakes of magnitudes 6.5, 7.0, and 7.5 on the Richter scale, with associated probabilities of 0.2, 0.4, and 0.4, respectively. The demand for relief supplies is both location- and scenario-dependent. To be specific, demand scales with disaster severity and is multiplied by 0.7, 0.85, and 1 for the 6.5, 7.0, and 7.5 magnitude scenarios, respectively. Therefore, scenario-based demand is computed as $d_{rls} = TD_r \times Pro_l \times coef_s$, where $coef_s$ is the severity coefficient and Pro_l is the proportion of the population of each demand point.

Table 1. Demand for relief supplies under the worst-case scenario

Relief commodities	**Total demand (TD_r)**
Blanket	1,788,949
Tent	447,237
Water	26,834,235
Canned Food	17,889,490
Hygiene kit	1,788,949

Three primary and two backup suppliers from both inside and outside the province are engaged for supplying the required relief supplies. The unit prices for each supply item (p_{rj}, op_{rj}, ep_{rj}) are reported in Table 2, generated using a uniform distribution.

Table 2. Prices of relief supplies

Relief commodities	**Unit purchasing cost (p_{rj})**	**Unit option price (op_{rj})**	**Unit exercise price (ep_{rj})**
Blanket	U(20,30)	-	-
Tent	U(180,220)	-	-
Water	-	U(0.13,1.70)	U(2,2.3)
Canned Food	-	U(0.35,0.50)	U(5,6)
Hygiene kit	-	U(0.72,0.90)	U(10.45,12)

5.1 Case study results

The outcomes of the case study, derived from solving the proposed model, are presented in this section. Table 3 reports the optimal cost values associated with the HA and suppliers. Evidently, the majority of the HA's pre-disaster costs stem from the procurement and prepositioning of tents and shelters under the buyback contract. Given the scenario-based structure of the model, post-disaster costs are reported as expected optimal values. Notably, the option contract results in lower pre-disaster costs than the buyback contract, as it enables the HA to only reserve – and not preposition – critical supplies at a lower initial cost. Conversely, in the post-disaster phase, the highest procurement cost stems from exercising the option contract. This is because the HA is contractually has the right to exercise the reserved quantities of critical supplies, despite already maintaining adequate stocks of non-critical items through prepositioning. In other words, the HA places greater emphasis on prepositioning non-critical supplies under the buyback contract, while critical supplies are mainly managed through the option contract. Additionally, returning unused inventory under the buyback contract generates a significant revenue and thereby encourages the HA to confidently preposition non-critical supplies. As Table 3 indicates, establishing warehouses and securing contracts with suppliers incur substantial pre-disaster costs for the HSC.

Table 3. Cost structure of the case study

Objective structure	Cost ($)
HA's expected total cost	2.68E+08
Pre-disaster procurement cost under buyback contract	8.86E+07
Pre-disaster procurement cost under option contract	1.14E+07
Expected post-disaster procurement cost under buyback contract	8.36E+05
Expected post-disaster procurement cost under option contract	1.48E+06
Expected post-disaster procurement cost under QD contract with backup suppliers	2.24E+05
Expected buyback revenue	1.67E+07
Expected additional pre-disaster costs	8.87E+07
Expected additional post-disaster costs	9.35E+07
Suppliers' expected profit	1.48E+08
Expected pre-disaster profit	4.17E+06
Expected post-disaster profit	1.44E+08

The suppliers' profits are also reported in Table 3. As can be seen, post-disaster profits exceed pre-disaster profits. This outcome can be largely attributed to the option contract, which ensures that the main payment for critical relief supplies is made post-disaster, boosting supplier profitability.

Table 4 and Table 5 present the optimal decisions for non-critical and critical relief supplies, respectively. As Table 4 shows, the number of blankets prepositioned in warehouses is sufficient to meet demand, resulting in zero expected shortage and the HA returns the unused inventory. This indicates that the prepositioned quantity exceeded demand under all scenarios and the HA was able to return the surplus for a buyback price. In contrast, the prepositioned number of tents proves insufficient, which means additional tents should be procured from the primary and backup suppliers. Consequently, no tent remains unused, and the buyback quantity is zero.

Table 4. Results of the model for non-critical relief supplies

Relief commodity	Prepositioning level	Expected post-disaster procurement from primary suppliers	Expected post-disaster procurement from backup suppliers	Expected shortage	Expected buyback quantity
Blankets	1.81E+06	0	0	0	2.19E+05
Tents	8.37E+04	1.67E+04	499	2.95E+05	0

Table 5 outlines the optimal decisions for critical relief supplies. The results indicate that water bottles can be adequately supplied by the primary suppliers, with no shortages observed. However, the reserved quantities and later procurements of canned foods and hygiene kits from both primary and backup suppliers fall short of meeting demand. It is therefore advisable to increase the number of relevant suppliers or negotiate for greater supply capacities.

Table 5. Results of the model for critical relief supplies

Relief commodity	Reserved quantity	Expected exercised quantity	Expected additional exercised quantity	Expected post-disaster procurement from backup suppliers	Expected shortage
Water Bottles	2.70E+07	2.53E+07	0	892	0
Canned foods	1.53E+07	1.33E+07	1.10E+04	1.55E+06	6.11E+06
Hygiene kits	1.51E+06	1.51E+06	1.00E+04	7.40E+05	1.06E+06

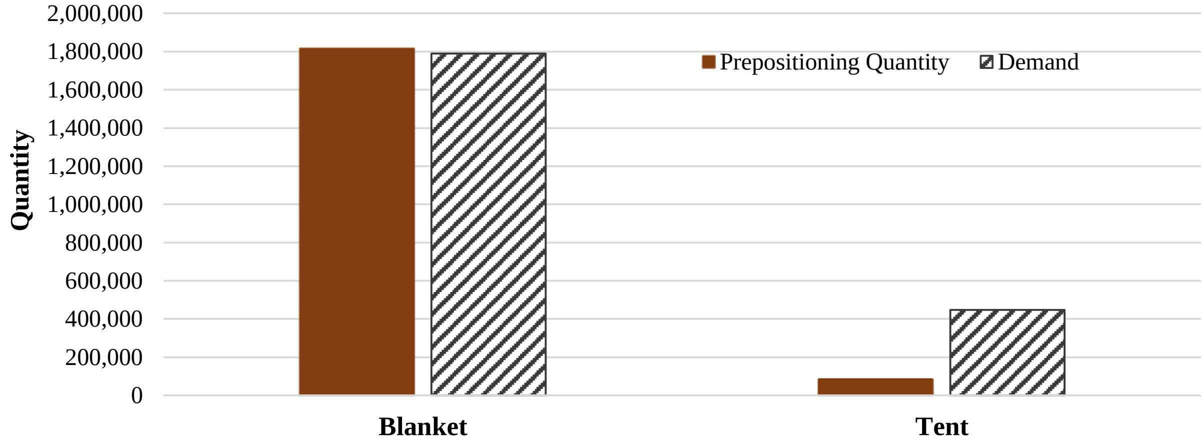

Figure 1. Comparison of demand and prepositioning quantities for non-critical relief supplies

Figure 1 compares the prepositioned quantities of non-critical relief supplies, procured under the buyback contract, with demand. Since the case study involves three scenarios, the high-severity scenario (i.e. Scenario #3) is reported in Figure 1 and Figure 2. The results indicate that blankets are procured and stocked in large numbers, approximately equal to their demand. This means that, for this item, the HA preferred to rely on a prepositioning strategy instead of post-disaster procurements. On the other hand, tents are prepositioned in small numbers, and their demand is much greater than the inventory procured and stocked pre-disaster. Therefore, the HA preferred to postpone supplying tents until the post-disaster phase through additional purchases from primary suppliers or by placing orders with backup suppliers.

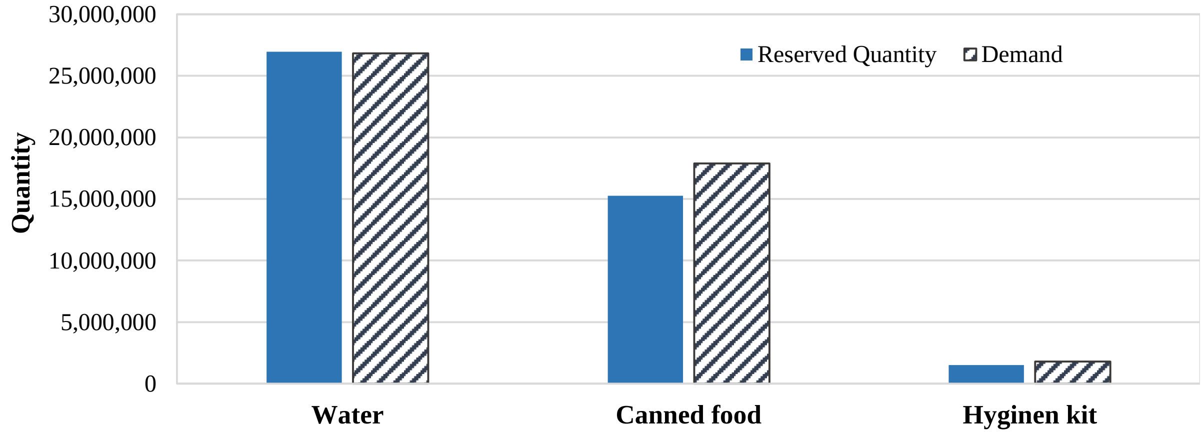

Figure 2. Comparison of demand and prepositioned quantities for critical relief supplies

Figure 2 reports the comparison between the reserved quantity of critical relief supplies ordered from primary suppliers under the option contract and their respective demands. Water seems to have been reserved approximately as much as the demand; however, canned foods and hygiene kits were reserved in quantities that fell short of their demands. Moreover, Table 5 shows that the exercised quantity of canned foods and hygiene kits was not sufficient to meet the post-disaster demand and the HA had to procure additional quantities at higher unit prices. The HA also had to procure more supplies from backup suppliers post-disaster to meet demand; however, shortages still occurred for these two items. It can thus be concluded that, in order to prevent shortages, the HA would need to either expand the suppliers' capacities to increase the reserved quantities, or increase the number of primary and backup suppliers.

Figure 3 presents the exercised quantities of critical relief supplies from primary suppliers under the option contract under each scenario. As expected, the high-severity Scenario #3 demands more quantities exercised. Compared to Table 5, water bottles reserved under the option contract appear to be sufficient and no additional procurement is required. However, canned foods and hygiene kits face shortages as the reserved, exercised, and additionally exercised quantities fall short of meeting demand. The HA should thus either increase reserved quantities by expanding the number of primary or backup suppliers or secure suppliers that possess higher capacity levels.

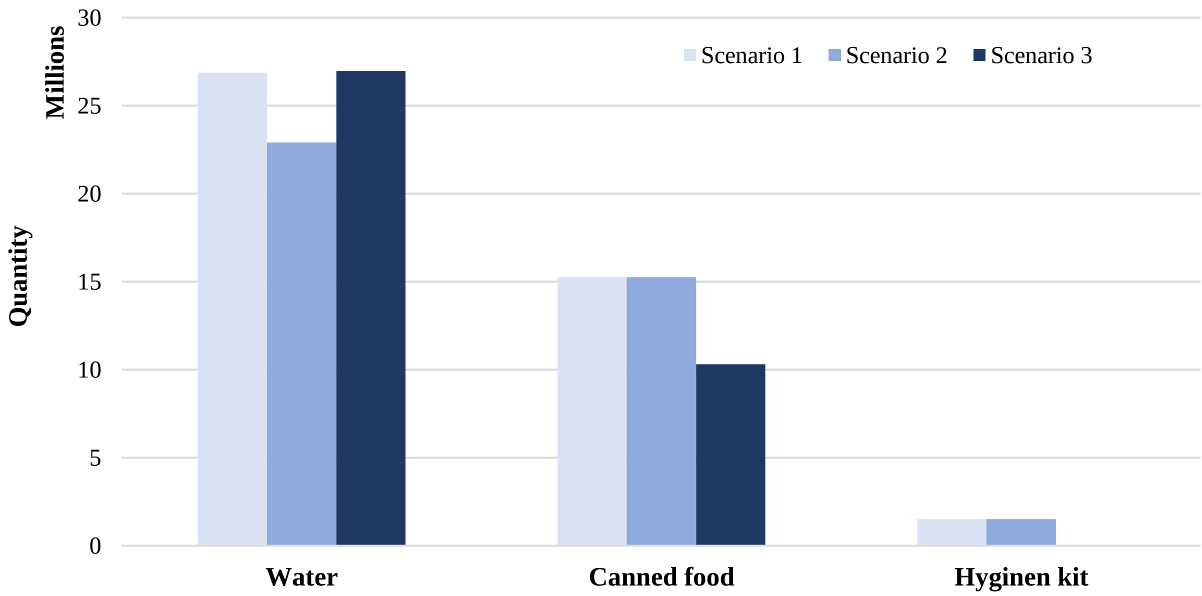

Figure 3. Exercised quantities of critical relief supplies under each scenario

Sensitivity Analyses

This section presents several sensitivity analyses to examine how variations in key parameters affect the model's behavior and the decision-making process. Figure 4 demonstrates the impact of the post-disaster procurement budget on costs associated with the buyback and option contracts. As this budget decreases, option contract costs also decline, while buyback contract costs increase. Option contract costs include the expenses incurred by reserving and exercising critical relief supplies from primary suppliers in both the pre- and post-disaster phases. In contrast, buyback contract costs include the expenses incurred by procuring non-critical relief supplies over the same phases. When the post-disaster procurement budget is reduced, the HA becomes less capable of placing orders to exercise reserved quantities post-disaster. Consequently, the HA compensates by increasing the pre-disaster prepositioning of non-critical relief supplies to mitigate potential shortages given its limited post-disaster budget for procuring additional items from the suppliers.

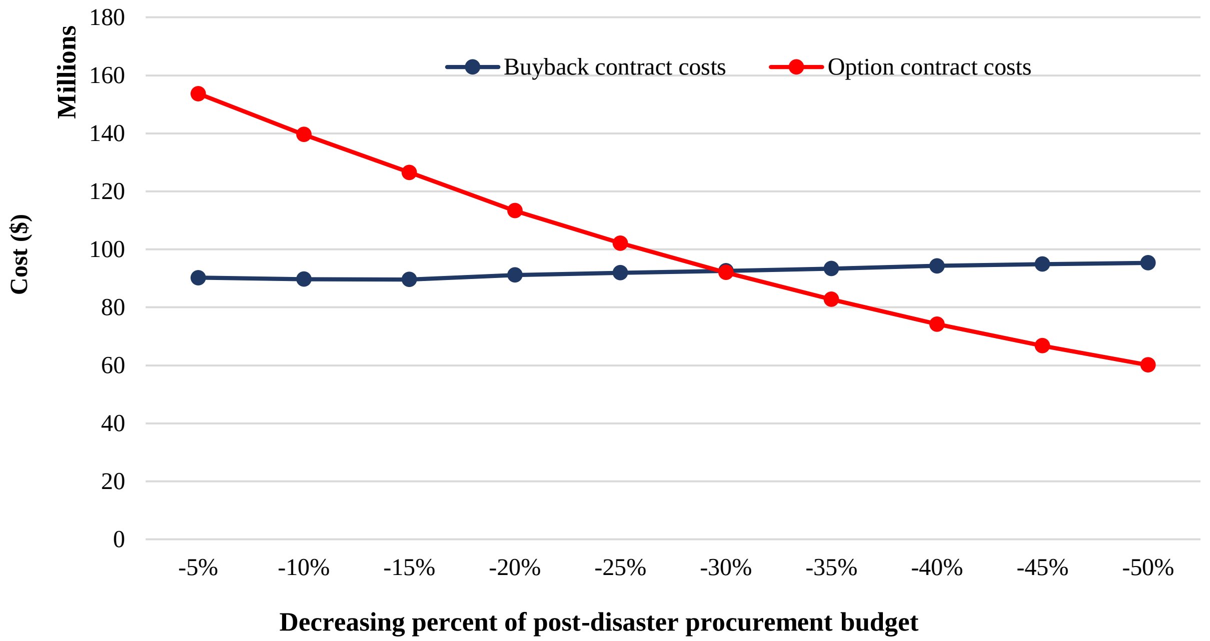

Figure 4. Costs of buyback and option contracts under varying post-disaster procurement budgets

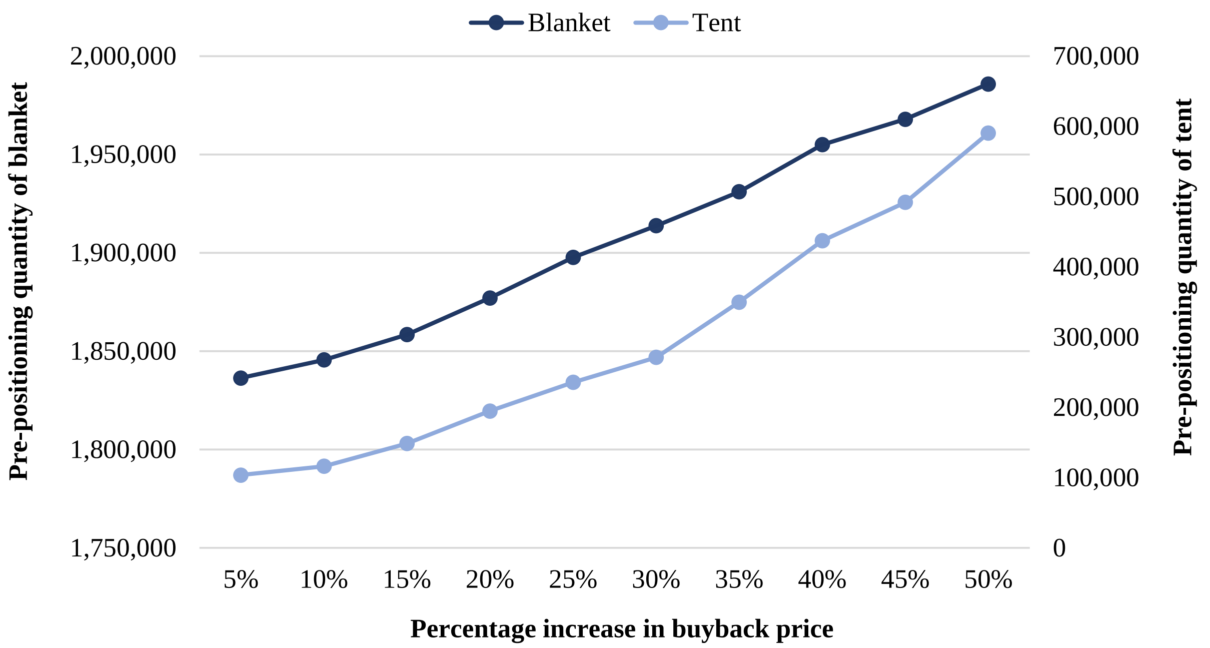

Figure 5. Effect of buyback price on prepositioning strategy

Figure 5 presents the relationship between buyback prices and prepositioning quantities of non-critical relief supplies. The case study was solved across several iterations, with the buyback price increasing by 5% in each iteration. A direct correlation observed among the iterations is that higher buyback prices lead to increased prepositioning quantities. The increase is particularly pronounced for tents compared to blankets. When compared with Figure 1, it is evident that the HA initially prepositioned only a small number of tents. However, as the buyback price rises, the HA procures and stocks significantly more tents. For instance, a 50% increase in the buyback price results in the number of prepositioned tents to rise by 5.7 times the original amount. In contrast, a 50% increase in the buyback price leads to only a 1.08-times rise in the number of prepositioned blankets. This is because, as Figure 1 revealed, the HA has already prepositioned an adequate number of blankets in the initial state and is therefore reluctant to increase its stock any further.

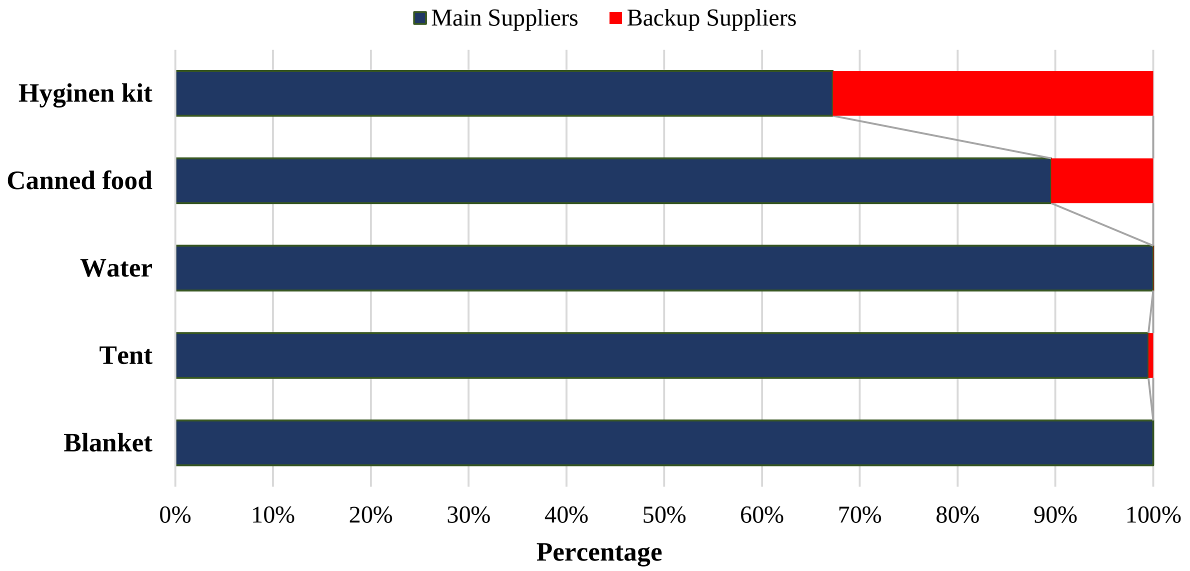

Figure 6. Share of primary and backup suppliers from supplying relief supplies

Figure 6 illustrates the share of critical and non-critical relief supplies sourced from primary and backup suppliers. The results indicate that hygiene kits and canned foods are the two relief items for which the HA relies on backup suppliers during the post-disaster phase, and procures them under the quantity discount contract. Previous results revealed that the reserved quantities of these two items were insufficient; consequently, the HA must place additional orders with backup suppliers. In contrast, when it comes to water (critical), tents (non-critical), and blankets (non-critical), only minimal help is needed from backup suppliers. This suggests that the buyback and option contracts with primary suppliers have successfully provided the HA with adequate quantities of these three items.

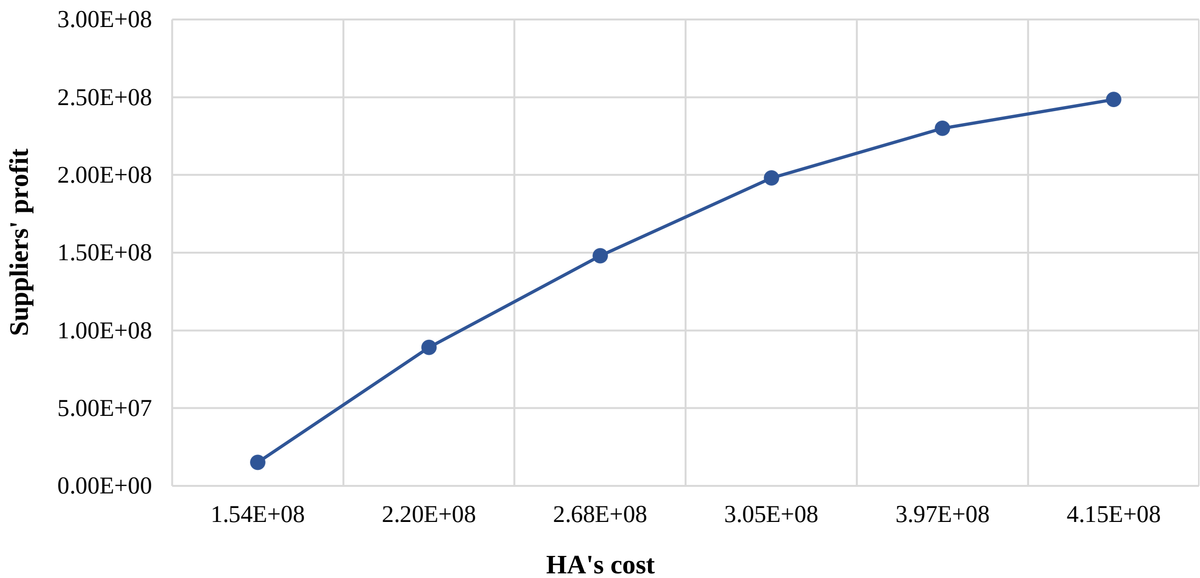

Figure 7. Pareto frontier illustrating the trade-off between the HA's cost and suppliers' profit

Since the proposed model is bi-objective, a Pareto frontier analysis is conducted to illustrate the trade-off between the HA's cost and suppliers' profit. To this end, the bi-objective model is transformed into a single-objective formulation using the weighted sum method, in which different values of the weighting parameter λ_1 ($\lambda_2 = 1 - \lambda_1$) are considered. Each weight combination yields an efficient solution, which is depicted on the Pareto frontier in Figure 7.

The results clearly reveal a trade-off between the HA's cost and suppliers' profit. Solutions that minimize the HA's cost tend to reduce suppliers' profit, potentially undermining their willingness to participate in uncertain and disruption-prone humanitarian contexts. Conversely, solutions that increase suppliers' profit lead to higher HA costs but provide stronger financial incentives for supplier participation. Notably, the intermediate region of the Pareto frontier indicates that relatively modest increases in the HA's cost can result in substantial gains in suppliers' profit. Therefore, by selecting a solution from this intermediate region, the HA can encourage supplier participation through economic incentives rather than relying on assumed cooperation.

To demonstrate the synergistic effect of the proposed hybrid procurement model, several analyses were conducted, and the results are reported in Table 6. For this purpose, three situations are considered. The first situation corresponds to the proposed approach, in which the HSC benefits from option, buy-back, and QD contracts, and is equivalent to the original model presented in this study. The second situation considers the presence of option and buy-back contracts while eliminating the QD contract; consequently, the HA is unable to procure relief commodities from backup suppliers. To model this situation, the decision variables associated with QD contracts and backup suppliers are removed from the original formulation. The third situation assumes that no contractual arrangements are used in the procurement of relief commodities. Accordingly, a reduced version of the proposed model is formulated by eliminating all contract-related decision variables.

Table 6. Analyzing the synergetic effect of multiple contracts

Situation	The HA's expected Cost	The Suppliers' expected profit	Expected Shortage
Situation 1	2.68E+08	1.48E+08	7.39E+06
Situation 2	3.05E+08	1.23 E+08	7.85E+06
Situation 3	3.71E+08	۰.۸۶E+08	9.06E+06

As shown in Table 6, eliminating the QD contract, thereby preventing the procurement of relief commodities from backup suppliers, has a direct impact on the HA's cost, suppliers' profits, and shortage levels. Specifically, the HA's cost increases by 13.8%, suppliers' profits decrease by 16.8%, and shortages increase by 6.2%. Moreover, the third situation further demonstrates a deterioration in all performance metrics. Compared with the first situation, the HA's expected cost increases by 38.4%, suppliers' expected profits decrease by 41.8%, and expected shortages increase by 22.6%. These results clearly indicate that the proposed hybrid procurement model, which incorporates multiple contractual arrangements for purchasing relief commodities in both pre- and post-disaster phases, enhances the cost efficiency and responsiveness of the HSC, as reflected by reduced costs and shortages. Furthermore, since the proposed model leads to lower HA costs while increasing suppliers' profits, this contract-based approach facilitates a win-win partnership between the HA and the suppliers. On the other meaning, suppliers participation is driven by economic incentives rather than assumed cooperation, as the results indicate an increase in expected profit.

6. Conclusion and Future Research Directions

To address the risk of not having timely access to critical and non-critical relief supplies, as well as to avoid incurring high prepositioning costs, this study proposes a hybrid strategy in which the HA adopts a prepositioning approach for non-critical relief supplies and a postponement strategy for critical ones. To model this problem, buyback, option, and quantity discount contracts are integrated into the supplier selection and procurement management processes within the HSC. Given that suppliers' post-disaster capacities may not be enough to fully meet the demand, backup suppliers are introduced to cover any potential shortfall. Orders are placed with backup suppliers within a QD contract. The proposed model is validated through a detailed case study and supported by multiple sensitivity analyses. The results demonstrate that a win-win situation within a cooperative framework can be achieved between the HA and both sets of suppliers. Moreover, the findings reveal that the HA can confidently engage in prepositioning non-critical relief supplies when buyback prices are sufficiently high. Additionally, adopting the option contract for the pre-disaster procurement of critical relief items was found to significantly reduce the total supply chain cost. Lastly, it was observed that the inclusion of backup suppliers operating under QD contracts can further enhance the efficiency and responsiveness of the HSC.

This research may open several avenues for future investigations. Firstly, the model proposed in this study does not account for post-disaster disruptions affecting the capacity of primary and backup suppliers. Incorporating this aspect would enrich and improve the present work. Secondly, future research may extend this work by explicitly modeling buyback contract design, including endogenous pricing parameters and time-dependent return or storage-duration constraints, to examine their interaction with operational decisions under uncertainty. Lastly, integrating insurance-based mechanisms to secure funding for relief supply procurement under varying supply contracts could prove to be practical and impactful.

Appendix A.

Table A.1. Case study parameters

Parameter	Distribution	Parameter	Distribution
oc_i	$10^4 \times U(10,15)$	aep_{rjs}	$ep_{rj} \times U(1.1,1.3)$
oc_{rj}	$10^2 \times U(1,5)$	φ_{rj}	$10^2 \times U(20,30)$
bc_{rj}	$10^2 \times U(1,5)$	pc_{rj}	U(1,150)
h_{ri}	$p_{rj} \times U(0.1,0.4)$	lb_{rjc}	U(100,400)
sc_i	$10^2 \times U(10,30)$	ub_{rjc}	U(500,800)
ap_{rjis}	$p_{rj} \times U(1.25,1.75)$	π_{rjcs}	U(10,300)
ϑ_{rj}	$p_{rj} \times U(0.4,0.6)$	ψ^s	$10^6 \times U(75,110)$
sv_{rj}	$pc_{rj} \times U(1.1,1.5)$	dc_{rils}	U(1,2)
η_{rjs}	$10^2 \times U(5,7)$	Φ	$10^6 \times U(70,100)$

References

1. Wang, X., F. Li, L. Liang, Z. Huang, and A. Ashley, *Pre-purchasing with option contract and coordination in a relief supply chain.* International Journal of Production Economics, 2015. **167**: p. 170–176.
2. John, L., A. Gurumurthy, A. Mateen, and G. Narayanamurthy, *Improving the coordination in the humanitarian supply chain: exploring the role of options contract.* Annals of Operations Research, 2022. **319**(1): p. 15–40.
3. Aghajani, M., S.A. Torabi, and J. Heydari, *A novel option contract integrated with supplier selection and inventory prepositioning for humanitarian relief supply chains.* Socio-Economic Planning Sciences, 2020. **71**: p. 100780.
4. Falasca, M. and C.W. Zobel, *A two-stage procurement model for humanitarian relief supply chains.* Journal of Humanitarian Logistics and Supply Chain Management, 2011. **1**(2): p. 151–169.
5. Bozorgi-Amiri, A., M.S. Jabalameli, and S. Mirzapour Al-e-Hashem, *A multi-objective robust stochastic programming model for disaster relief logistics under uncertainty.* OR spectrum, 2013. **35**: p. 905–933.
6. Galindo, G. and R. Batta, *Prepositioning of supplies in preparation for a hurricane under potential destruction of prepositioned supplies.* Socio-Economic Planning Sciences, 2013. **47**(1): p. 20–37.
7. Balcik, B. and D. Ak, *Supplier selection for framework agreements in humanitarian relief.* Production and Operations Management, 2014. **23**(6): p. 1028–1041.
8. Pradhananga, R., F. Mutlu, S. Pokharel, J. Holguín-Veras, and D. Seth, *An integrated resource allocation and*

distribution model for pre-disaster planning. Computers & Industrial Engineering, 2016. **91**: p. 229–238.
9. Tofighi, S., S.A. Torabi, and S.A. Mansouri, *Humanitarian logistics network design under mixed uncertainty.* European journal of operational research, 2016. **250**(1): p. 239–250.
10. Safaei, A.S., S. Farsad, and M.M. Paydar, *Robust bi-level optimization of relief logistics operations.* Applied Mathematical Modelling, 2018. **56**: p. 359–380.
11. Hu, S. and Z.S. Dong, *Supplier selection and pre-positioning strategy in humanitarian relief.* Omega, 2019. **83**: p. 287–298.
12. Shokr, I., F. Jolai, and A. Bozorgi-Amiri, *A novel humanitarian and private sector relief chain network design model for disaster response.* International Journal of Disaster Risk Reduction, 2021. **65**: p. 102522.
13. Shokr, I., F. Jolai, and A. Bozorgi-Amiri, *A collaborative humanitarian relief chain design for disaster response.* COMPUTERS & INDUSTRIAL ENGINEERING, 2022. **172**.
14. Aghajani, M., S.A. Torabi, and N. Altay, *Resilient relief supply planning using an integrated procurement-warehousing model under supply disruption.* Omega, 2023. **118**: p. 102871.
15. Torabi, S.A., I. Shokr, S. Tofighi, and J. Heydari, *Integrated relief pre-positioning and procurement planning in humanitarian supply chains.* Transportation Research Part E: Logistics and Transportation Review, 2018. **113**: p. 123–146.
16. Hu, Z., J. Tian, and G. Feng, *A relief supplies purchasing model based on a put option contract.* Computers & Industrial Engineering, 2019. **127**: p. 253–262.
17. Kord, H. and P. Samouei, *Coordination of humanitarian logistic based on the quantity flexibility contract and buying in the spot market under demand uncertainty using NSGA-II and NRGA algorithms.* Expert Systems with Applications, 2023. **214**: p. 119187.
18. Wang, D., K. Yang, L. Yang, and J. Dong, *Two-stage distributionally robust optimization for disaster relief logistics under option contract and demand ambiguity.* Transportation research part E: logistics and transportation review, 2023. **170**: p. 103025.
19. Hu, S., Z.S. Dong, and R. Dai, *A machine learning based sample average approximation for supplier selection with option contract in humanitarian relief.* Transportation research part E: logistics and transportation review, 2024. **186**: p. 103531.
20. Shokr, I., F. Jolai, and A. Bozorgi-Amiri, *A new model for enhancing collaboration between humanitarian organizations and private sector in humanitarian relief chain.* Computers & Industrial Engineering, 2025: p. 111556.
21. Mulvey, J.M., R.J. Vanderbei, and S.A. Zenios, *Robust optimization of large-scale systems.* Operations research, 1995. **43**(2): p. 264–281.
22. Leung, S.C., S.O. Tsang, W.-L. Ng, and Y. Wu, *A robust optimization model for multi-site production planning problem in an uncertain environment.* European journal of operational research, 2007. **181**(1): p. 224–238.
23. Bertsimas, D. and M. Sim, *The price of robustness.* Operations research, 2004. **52**(1): p. 35–53.