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RESEARCH ARTICLE

Social Sustainability-Oriented Multi-Period Medical Supply Adjustment in Response to Disasters

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ABSTRACT Before the occurrence of disasters, medical supplies should have been prepared at warehouses to support the infected cases. As the possible mismatch between initial medical supply preparedness and actual disaster situation, it would trigger off serious social outcomes. Thus, taking medical supply adjustment operations among the warehouses is an imperative task to ensure the sustainable development of society. However, a single-period logistics action with fully uncertain information usually leads to sub-optimal schemes. In this sense, multi-period planning for medical resource adjustment is required with the concern of social sustainability, where the uncertain information is promptly adjusted following real-time cases in different periods. With the socially sustainable goals, a multi-objective stochastic optimization model is developed to facilitate the multi-period sustainable relief supply adjustment problem, which can be divided into two subproblems. The first sub-problem contains two conflicting objective functions, where a specific ε-constraint method is developed. After that, a linearization approach is applied due to the nonlinearity of the proposed model. Finally, Yushu Earthquake is considered to validate the effectiveness of the proposed model. It is found that the multi-period planning for the relief supply adjustment problem outperforms compared with a single-period one in terms of social sustainability.

INDEX TERMS Humanitarian logistics, medical supply adjustment, social sustainability, stochastic optimization model.

I. INTRODUCTION

Many large-scale natural and man-made disasters occurred over the past decades, such as earthquakes, virus outbreaks, and typhoons [1], [2], [3]. Such disasters affect a large number of people severely. Relief operations are necessary before and after the occurrence of a disaster. And many researchers have conducted different supply preparedness strategies before different types of disasters [4], [5]. Because of the unpredictable disaster, the initial medical supply preparedness strategy may not be working in a practical situation due to various factors. Some warehouses have more medical supplies than the demand, whereas some other warehouses still face shortages [6]. In this sense, taking a medical supply adjustment (MSA) action among these warehouses is quite imperative because of the following reasons. The first one is to make full use of scarce medical supplies. The other one is that these warehouses can support each other more quickly and instantly. Thus, the MSA problem in humanitarian logistics is a critical and urgent issue, which is rarely considered in previous studies.

In recent years, many approaches have been adopted to handle various issues in humanitarian logistics [7], [8], [9], [10], [11], [12], [13]. And most of them only considered single-period planning problems. However, solving a single-period problem with fully uncertain information usually leads to sub-optimal schemes. The need for incorporating multi-period planning is pressing, called the multi-period

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MSA (MPMSA) problem in this study. Thus, medical supplies should be adjusted in different periods to ensure the effectiveness of refined rescue and reduce the waste of surplus medical supplies at warehouses. Different from the uncertain information in the single-period relief operation [14], the uncertain information in this MPMSA process is revealed gradually over time [15]. And the uncertain information in the current period is estimated based on the last period. Thus, a more reliable scheme for adjusting medical supplies can be conducted.

Another main concern in the MPMSA problem is to achieve the goals of social sustainability [16], [17]. The inherent multiple priorities of different goals from different stakeholders cannot be neglected from the perspective of social sustainability. Generally, fairness in adjusting medical supplies has the highest priority and then the transportation time or cost [14], [18]. Besides, the aim of fairness is always concerned by governments and regarded as the core part of social sustainability, while that pertaining to transportation time or cost may be the focus of local governments or enterprises. There exist precedent relationships among different beneficiaries. In this sense, different goals involved in the sustainable MPMSA problem should be considered in different phases. The first-phase goal is to achieve fairness and the second-phase goal aims to minimize transportation time and cost. However, rare previous studies have been conducted to handle this sustainable MPMSA problem. As a whole, these requirements motivate us to study the sustainable MPMSA problem with the consideration of social sustainable goals as the information updates in the aftermath of large-scale disasters.

As discussed above, although many previous studies have been focused on various issues in humanitarian logistics, the MPMSA problem in the presence of social sustainability is still in its infancy. To the best of our knowledge, to handle the above problem, the following objectives are to be considered in this *paper*.

(1) How to characterize social sustainability in adjusting medical supplies from the perspective of collective and individual?

(2) How to formulate the corresponding optimization model for the sustainable MPMSA problem under uncertainty?

(3) What are the influences of the critical parameters on the performance of the sustainable MPMSA problem?

To emphasize the above objectives and fill this non-negligible research gap, this research focuses on the sustainable MPMSA problem under uncertainty. Specifically, the previous measurements used to characterize the fairness are discussed and two different fairness criteria are both considered to characterize social sustainability in this study. Then, this study proposes a scenario-based stochastic optimization model to formulate the sustainable MPMSA problem under uncertainty. It is worth noting that the performance of the sustainable MPMSA process is compared with the single-period one. After that, the influences of the critical parameters are investigated in the real case study, where some key managerial implications and insights are also concluded.

The remainder of this study is organized in the following order. Section II first reviews the previous studies and summarizes the novelties of this study. Section III describes the MPMSA process in the presence of social sustainability. A scenario-based two-phase multi-objective stochastic optimization (STPMOSO) model is developed to facilitate the sustainable MPMSA problem and the corresponding solution method is presented in Section IV. Then, a case study is implemented and the results of the sensitivity analysis on several critical parameters are presented in Section V. Finally, Section VI concludes this study, outlining its managerial insights and possible directions for future work.

II. LITERATURE REVIEW

It is well known that fairness is one of the most important goals in humanitarian logistics, which directly influences the sustainable development of society. Otherwise, it would result in social instability and negative multiplier effects. And many studies have emphasized that appropriate studies should address fairness [1], [19]. Particularly, many different approaches have been proposed to measure fairness in distributing relief commodities in humanitarian logistics by far [20], [21], [22], [23]. The most common method is the total penalty of unsatisfied demand at demand points. However, the sustainable development of society also needs to be considered [24], [25], where each individual's gain and loss is one of the most important indicators of sustainability. Thus, considering the total unmet demand with priority, the fulfill rate with priority for each of the individuals needs to be emphasized, which is also a key factor to achieve social sustainability. Different from the previous studies, this study incorporates two different criteria (namely collective, individual) into the measurement of fairness in the sustainable MPMSA process.

After large-scale disasters, the information about the number of refugees, demand, and road conditions is generally uncertain. Many studies have considered these inseparable uncertainties to make the model close to reality [6], [18], [26], [27], [28], [29], [30]. To handle the uncertainties, stochastic programming approaches are usually applied to support the decision-making process in humanitarian logistics [31]. In the last decade, a variety of stochastic optimization models have been proposed for many different issues in humanitarian logistics..Oksuz and Satoglu [31] developed a stochastic programming model for the determination of the temporary medical center locations in the presence of the damages to the roads and hospitals. Sun et al. [32] proposed a novel scenario-based robust bi-objective optimization model to formulate the medical facility location, casualty transportation, and relief commodity allocation problem under uncertainty..Caunhye and Alem [33] developed a robust stochastic optimization to solve a realistic location-allocation model for humanitarian operations in Brazil under uncertainty.

In the literature, various models and approaches have been adopted to handle the problems in humanitarian logistics. However, most of them only address static and single-period planning problems. In practice, for the entire planning horizon, it is typically unavailable to collect accurate and reliable input data for managing relief logistics operations [34]. As a result, the solutions obtained based on the complete information may result in imperfect decision-making, for example, overwhelmed storage of useless goods, goods not reaching victims, uneven relief commodity distribution, and many other problems [35]. Consequently, multi-period relief logistics planning is a critical and urgent issue in humanitarian logistics. However, only a few studies considered the issues of evolving multi-period relief logistics considering uncertain information. Cao et al. [36] proposed a fuzzy tri-objective bi-level integer programming model to formulate a sustainable multi-period relief distribution problem in humanitarian supply chains. In this sense, a reliable multi-period decision-making strategy to adjust the medical supplies among warehouses needs to be provided. Wang and Sun [37] proposed an emergency material allocation model with multi-rescue sites, multi-affected sites, and multi-periods, with objectives of three dimensions in humanitarian logistics: efficiency, effectiveness, and equity. Yang et al. [38] developed a distributionally robust model to formulate a multi-period location-allocation problem with multiple resources and capacity levels under uncertain emergency demand and resource fulfillment time.

In addition to the above discussion, this study also provides a comprehensive literature review in Table 1, which presents the main concerns of studies conducted in the five years. It is easy to outline the differences with previous studies. i) Most of the researchers focused on proposing inventory strategies, pre-positioning network design, and relief distribution models in humanitarian logistics. However, because the disaster severity is unpredictable, the imbalance between the demand and the initial inventory strategy has received insufficient attention. In this sense, adjusting the medical supplies is a critical and urgent issue. ii) Most of the existing studies concentrated on relief distribution problem from the traditional viewpoint. Such issues need to be considered in depth from the perspective of social sustainability. In addition, social sustainability is measured from the viewpoint of collective and individual. The objectives of collective's and individual's social sustainability are respectively the minimization of the total weighted unmet demand and the maximization of the minimum weighted fulfill rate. iii) Most of the previous studies focused on the single-period mathematical model. However, to avoid the sub-optimal scheme of the solution under uncertainty, a multi-period mathematical model needs to be considered with the uncertain information in different periods. Different from the previous studies, a reliable multi-period mathematical model is proposed for the sustainable MPMSA problem, which has rarely been studied until now.

TABLE 1. summary of previous studies related to relief operations.

Article	Main problem	Period type	Sustainability	Method
Haeri, Hosseini-Motlagh [39].	Disaster relief network	Single	Excluded	Exact approach
Erbeyoğlu and Bilge [40].	Humanitarian network design	Single	Excluded	Exact approach
Cao, Liu [36].	Sustainable relief distribution	Multiple	Included	Exact approach
Ransikarbum and Mason [41].	Humanitarian logistics planning	Single	Excluded	Heuristic approach
Jamali, Ranjbar [25]	Sustainable humanitarian logistics	Single	Included	Exact approach
Sun, Wang [42]	Location-allocation problem	Single	Excluded	Exact approach
Lotfi, Kheiri [43]	Confirmed infection prediction	Single	Excluded	Exact approach
Gao, Huang [1]	Medical staff rebalancing	Single	Excluded	Exact approach
Sun, Li [32]	Humanitarian network design	Single	Excluded	Exact approach
Cao, Xie [44]	Medical waste transportation	Single	Excluded	Exact approach
Caunhye and Alem [33]	Location-allocation problem	Single	Excluded	Exact approach
Wang and Sun [37]	Material allocation problem	Multiple	Excluded	Exact approach
Yang, Yin [38]	Location-allocation problem	Multiple	Excluded	Exact approach
This study	**Adjusting medical supplies**	**Multiple**	**Included**	**Exact approach**

Considering the above research gaps, the contributions of this paper include three points. Firstly, differing from traditional relief distribution issues, the sustainable MPMSA problem is the main focus of this paper. Besides, multi-period planning, two-phase decisions, social sustainability, non-negligible uncertain elements are simultaneously considered. Secondly, a STPMOSO model is proposed to formulate the sustainable MPMSA problem. Then a linearization strategy is developed by introducing several temporary variables into the model. Finally, a real case study is implemented to validate the proposed model. The results clearly show that the proposed multi-period model is more reliable than the single-period one. Also, a sensitivity analysis of several critical parameters is conducted to obtain some key managerial implications and insights in response to a disaster.

III. PROBLEM DESCRIPTION

In practice, the nature of disasters imposes a high degree of uncertain environment due to various reasons, such as the uncertain damage severities in different areas and different demographics of refugees in warehouses. Besides, it is typically unavailable to collect accurate and reliable input data for managing the relief logistics process. There is no doubt that the obtained solution may deviate from real situations based on the assumption of complete information. Accordingly, the whole process of sustainable MPMSA process needs to be divided into several periods to promote a more reliable and appropriate relief effort in adjusting medical supplies among warehouses.

Because the disaster creates a highly uncertain environment, several uncertain elements with variations are considered at the same time in each of the periods. The first uncertain element is demand. Besides, the supply is also uncertain because of the difficulty in keeping how much of a particular medical item is in-store. Here, the uncertain supply and demand in each period are updated dynamically based on the decisions in the last period. In addition, the road condition is usually uncertain during the horizon of a large-scale disaster relief effort. Practically, the uneven destructive degree of roads can be divided into several magnitudes, which is strongly associated with the velocities of vehicles in different periods. Because the road recovery cannot be precisely predicted, different availabilities are used to estimate the uncertain road conditions during the sustainable MPMSA process.

As addressed the problem here, the disaster was supposed to strike a wide area. Several warehouses are pre-determined to stock medical supplies are provided to satisfy the great need from them. However, after a disaster hits, some warehouses having surplus medical supplies are considered as supply points, whereas some other warehouses lacking in medical supplies are considered as demand points. For more details, readers are referred to as Gao [14] and Gao et al. [6]. Note that each of the warehouses can be a supply and demand point at the same time. In humanitarian logistics, fairness is one of the most important goals since it is a key factor to ensure social sustainability. To achieve fairness, this study not only aims to maximize the total weighted unmet demand but also cares about each individual's weighted unmet demand. The goal is to find a compromise strategy between the supply and demand warehouses in each of the periods.

As the urgent need for medical supplies, it is required to deliver medical supplies in time and economically to satisfy the great demand in disaster areas. It is well known that the timely delivery of medical supplies is a basic requirement in humanitarian logistics since it is strongly correlated to human suffering. In addition, a limited budget to promote disaster situations also needs to be considered. In this sense, after the medical supplies are fairly adjusted, the third goal is to assign different types of vehicles to transport them among warehouses so that the total transportation time and cost can be minimized. With the decisions (i.e., incoming and outgoing shipments) obtained in the sustainable MPMSA process, the medical supplies are transported in different periods over the transportation network according to the practical road conditions. After the completion of relief transportation in a period, the residual medical storage at each supply warehouse will be delivered in the next period. At the same time, the shortage of medical supplies at each demand warehouse will be filled with higher priority in the next period.

Before the mathematical model is provided for the sustainable MPMSA problem, the following assumptions are postulated. i) The warehouse locations and available paths between them are known, which is widely used in previous studies. A similar action was found in studies [6], [45], [46]. ii) For each of the medical items, the warehouse is always considered as a demand or supply point in all periods. iii) Vehicles with different capacities and speeds are permitted to transport medical supplies. A similar action was found in Gao [14] and ....Dukkanci et al. [47].

IV. OPTIMIZATION MDOEL FOR SUSTAINABLE MPMSA

A. NOTATIONS

The notations used in the proposed STPMOSO are shown as follows:

(1)**Sets**

$\mathcal{T}$	Set of periods, indexed by $t \in \mathcal{T}$.
ε	Set of medical items, indexed by $e \in \varepsilon$.
$\mathcal{V}$	Set of vehicle types, indexed by $v \in \mathcal{T}$.
$\mathcal{S}$	Set of warehouses with surpluses, indexed by $s \in \mathcal{S}$.
$\mathcal{D}$	Set of warehouses with shortages, indexed by $d \in \mathcal{D}$.
$\mathbb{S}$	Set of scenarios in demand and supply, indexed by $\xi \in \mathbb{S}$.
$\mathbb{A}$	Set of scenarios of road conditions, indexed by $\zeta \in \mathbb{A}$.

(2)**Parameters**

W_{es}, W_{ed}	Priority of warehouses s and d for medical-item e
TD_{sd}	Travel distance from warehouses s to d
W_e, V_e	Weight and volume of medical-item e
L_v, K_v	Weight and volume capacities of vehicle-type v
TS_v, LU_v	Travel speed and loading/unloading time of vehicle-type v
FC_v, US_v	Fixed cost and shipping cost of the vehicle-type v
A_v^t	Available number of vehicle-type v in period t.
$S_{es}^{t\xi}$	Supply of medical-item e in scenario ξ at warehouse s in period t.
$D_{ed}^{t\xi}$	Demand for medical-item e in scenario ξ at warehouse d in period t.

$R_{sd}^{t\zeta}$ Road availability connecting warehouse s and d in scenario ξ in period t.

P_ξ, P_ζ Probability of scenarios ξ and ζ.

(3)**First-phase decision variables**

qd_{es}^t Outgoing shipment of medical-item e at warehouse s in period t.

qr_{ed}^t Incoming shipment of medical-item e at warehouse d in period t.

do_{es}^t Difference between qd_{es}^t and expected outgoing shipment at warehouse s in period t.

di_{ed}^t Difference between qr_{ed}^t and expected incoming shipment at warehouse d in period t.

(4)**Second-phase decision variables**

$n_{sde}^{t\zeta}$ Flow of medical-item e between warehouses s and d in scenario ζ in period t.

$h_{sdv}^{t\zeta}$ Number of vehicle-type v from warehouses s to d in scenario ζ in period t.

B. STPMOSO MODEL

Since the objective of fairness has a higher priority, the sustainable MPMSA problem is formulated as a STPMOSO model, which is formulated as follows.

$$\begin{aligned}
&\mathrm{Min}\Psi_1 \\
&= \sum_{e\in E}\sum_{d\in\mathcal{D}}\sum_{\xi\in\mathbb{S}} P_\xi W_{ed}\max\{D_{ed}^{t\xi} - di_{ed}^{t-1} - qr_{ed}^t, 0\} \\
&\quad + \sum_{e\in E}\sum_{s\in\mathbb{S}}\sum_{\xi\in\mathbb{S}} P_\xi W_{es}\max\{qd_{es}^t + do_{es}^{t-1} - S_{es}^{t\xi}, 0\} \qquad (1)
\end{aligned}$$

$$\begin{aligned}
&\mathrm{Max}\Psi_2 \\
&= Min\left\{\begin{array}{l}\sum\limits_{\xi\in\mathbb{S}} P_\xi W_{ed}\frac{di_{ed}^{t-1}+qr_{ed}^t}{D_{ed}^{t\xi}}, \\ \sum\limits_{\xi\in\mathbb{S}} P_\xi W_{es}\frac{\left\{S_{es}^{t\xi}\right\}-qd_{es}^t-do_{es}^{t-1}}{\left\{S_{es}^{t\xi}\right\}-S_{es}^{t\xi}+\rho_{es}^t}\end{array}\right\} \qquad (2)
\end{aligned}$$

s.t.

$$\sum_{s\in S} qd_{es}^t = \sum_{d\in\mathcal{D}} qr_{ed}^t \forall e\in E, t\in\mathcal{T}. \qquad (3)$$

$$do_{es}^t = \left\lceil qd_{es}^t - \sum_{\xi\in\Xi} S_{es}^{t\xi}P_\xi \right\rceil \quad \forall e\in E, s\in S, t\in\mathcal{T}, \xi\in S. \qquad (4)$$

$$di_{ed}^t = \left\lceil qr_{ed}^t - \sum_{\xi\in\Xi} D_{ed}^{t\xi}P_\xi \right\rceil \quad \forall e\in E, d\in\mathcal{D}, t\in\mathcal{T}, \xi\in S. \qquad (5)$$

$$qd_{es}^t \geq min\{S_{es}^{t1}, S_{es}^{t2}, \ldots, S_{es}^{t\xi}, \ldots\} - do_{es}^{t-1} \quad \forall e\in E, s\in S, t\in\mathcal{T}. \qquad (6)$$

$$qd_{es}^t \leq \max\{S_{es}^{t1}, S_{es}^{t2}, \ldots, S_{es}^{t\xi}, \ldots\} - do_{es}^{t-1} \quad \forall e\in E, s\in S, t\in\mathcal{T}. \qquad (7)$$

$$qr_{ed}^t \geq min\{D_{ed}^{t1}, D_{ed}^{t2}, \ldots, D_{ed}^{t\xi}, \ldots\} - di_{ed}^{t-1} \quad \forall e\in E, d\in\mathcal{D}, t\in\mathcal{T}. \qquad (8)$$

$$qr_{ed}^t \leq \max\{D_{ed}^{t1}, D_{ed}^{t2}, \ldots, D_{ed}^{t\xi}, \ldots\} - di_{ed}^{t-1} \quad \forall e\in E, d\in\mathcal{D}, t\in\mathcal{T}.$$

are non-negative integer variables (9)

$$\forall e\in E, s\in S, d\in\mathcal{D}, t\in\mathcal{T}. \qquad (10)$$

Phase II:

$$\mathrm{Min}\Psi_3 = \sum_{s\in\mathbb{S}}\sum_{d\in\mathcal{D}}\sum_{v\in V}\sum_{\zeta\in\mathbb{A}}\left\{h_{sdv}^{t\zeta}\left[LU_v + FC_v + \frac{TD_{sd}(1+US_v)}{TS_v R_{sd}^{t\zeta}}\right]\right\} \qquad (11)$$

$s.t.$

$$\sum_{s\in\mathbb{S}} n_{sde}^{t\zeta} \geq qr_{ed}^t \forall d\in\mathcal{D}, e\in\varepsilon, t\in\mathcal{T}, \zeta\in\mathbb{A}. \qquad (12)$$

$$\sum_{d\in\mathcal{D}} n_{sde}^{t\zeta} \leq qd_{es}^t \forall s\in\mathbb{S}, e\in\varepsilon, t\in\mathcal{T}, \zeta\in\mathbb{A}. \qquad (13)$$

$$\sum_{s\in\mathbb{S}} n_{sde}^{t\zeta} = \sum_{d\in\mathcal{D}} n_{sde}^{t\zeta} \forall e\in\varepsilon, t\in\mathcal{T}, \zeta\in\mathbb{A}. \qquad (14)$$

$$\sum_{e\in\varepsilon} n_{sde}^{t\zeta} W_e \leq \sum_{v\in V} h_{sdv}^{t\zeta} L_v \forall s\in\mathbb{S}, d\in\mathcal{D}, t\in\mathcal{T}, \zeta\in\mathbb{A}. \qquad (15)$$

$$\sum_{e\in\varepsilon} n_{sde}^{t\zeta} V_e \leq \sum_{v\in V} h_{sdv}^{t\zeta} K_v \forall s\in\mathbb{S}, d\in\mathcal{D}, t\in\mathcal{T}, \zeta\in\mathbb{A}. \qquad (16)$$

$$\sum_{s\in\mathbb{S}}\sum_{d\in\mathcal{D}} h_{sdv}^{t\xi} \leq A_v^t \forall v\in V, t\in\mathcal{T}, \zeta\in\mathbb{A}. \qquad (17)$$

$n_{sde}^{t\zeta}$ is a non − negative variable

$$\forall s\in\mathcal{S}, d\in\mathcal{D}, e\in\varepsilon, t\in\mathcal{T}, \zeta\in\mathbb{A}. \qquad (18)$$

$h_{sdv}^{t\xi}$ is a non − negative integer variable

$$\forall s\in\mathcal{S}, d\in\mathcal{D}, v\in V, t\in\mathcal{T}, \zeta\in\mathbb{A}. \qquad (19)$$

where the objective function Ψ_1 in Eq. (1) aims to minimize the expected total weighted unmet demand. The objective function Ψ_2 in Eq. (2) aims to maximize the minimum individual's weighted fulfill rate, where ρ_{es}^t is the quantity of medical-item e in period t that should be reserved in warehouse s, which guarantees the rationality of the objective function Ψ_2. Constraint (3) guarantees the balance of outgoing and incoming shipments. Formulations (4) and (5) are ceiling function to obtain the integer numbers of the difference values between the actual shipment and expected shipment at warehouses s and d, respectively. Constraints (6) and (7) define the decision variable and restrict that the difference value in formula (4) should be pre-filled and pre-consumed in the next period respectively. Constraints (8) and (9) define the decision variable and restrict that the difference value from formula (5) should be pre-filled and pre-consumed in the next period respectively. Constraint (10) defines the decision variables. The last objective function in Eq. (11)

aims to minimize the total transportation time and cost. Constraint (12) restricts that the quantity of incoming shipment is not less than the demand at warehouse d. Constraint (13) guarantees that the quantity of outgoing shipment is less than the supply at warehouse s. Constraint (14) restricts the transportation balance between the warehouses s and d. Constraints (15) and (16) restrict that the vehicles can transport mixed medical supplies. Constraint (17) restricts the number of vehicles. Constraints (18) and (19) define the decision variables.

C. SOLUTION STRATEGY

In the proposed STPMOSO optimization model, the first-phase problem determines its decision variables (i.e., incoming and outgoing shipments) to achieve fairness in adjusting medical supplies, the second-phase problem reacts by selecting the decision variables to minimize the expected total transportation time and cost in transporting medical supplies. Since the first-phase problem has two conflicting objectives, it is required to generate a set of efficient Pareto solutions to analyze the trade-off between them [48]. To solve the first-phase problem, a specific ε-constraint method is proposed. For more details about the advantages of applying the ε-constraint method, readers are referred to [6]. The main steps to handle this sustainable MPMSA problem are presented as follows.

Step 1: This study first calculates the globally optimum Ψ_2^*, denoted by ε^*, with eliminating Ψ_1 subject to Constraints (3)-(10).

Step 2: A specific ε-constraint method is proposed to handle the conflicting objectives so that a set of Pareto-optimal solutions can be generated for the first-phase problem.

Step 3: After the incoming and outgoing shipments are revealed, these decisions are fixed and put into the second-phase problem.

Step 4: The second-phase problem is solved only concerning the objective function Ψ_3 subject to Constraints (12)-(19). Finally, the medical item flows and vehicle fleets among warehouses can be obtained.

In addition to following the above four steps to handle the sustainable MPMSA problem, a specific linearization approach needs to be developed since the objective function Ψ_1 are nonlinear. To solve the first-phase problem in CPLEX, two auxiliary binary variables (i.e., $\mathrm{p}_{\mathrm{ed}}^{\mathrm{t}\xi}$ and $\mathrm{q}_{\mathrm{es}}^{\mathrm{t}\xi}$) are introduced into our model. Thus, with the ε-constraint method and the linearization approach, the problem can be reformulated as the following model. Phase I:

$$\mathrm{Min}\Psi_1 = \sum_{e\in\varepsilon}\sum_{d\in\mathcal{D}}\sum_{\xi\in\mathbb{S}} \mathrm{P}_\xi W_{ed}\left(D_{ed}^{t\xi} - di_{ed}^{t-1} - qr_{ed}^{t}\right)\mathrm{p}_{ed}^{t\xi} + \sum_{e\in\varepsilon}\sum_{s\in\mathbb{S}}\sum_{\xi\in\mathbb{S}} \mathrm{P}_\xi W_{es}\left(qd_{es}^{t} + do_{es}^{t-1} - S_{es}^{t\xi}\right)\mathrm{q}_{es}^{t\xi} \quad (20)$$

$$\text{s.t.} \sum_{\xi\in\mathbb{S}} \mathrm{P}_\xi W_{ed}\frac{di_{ed}^{t-1} + qr_{ed}^{t}}{D_{ed}^{t\xi}} \le \varepsilon \forall e\in\varepsilon, d\in\mathcal{D}, t\in\mathcal{T}. \quad (21)$$

$$\sum_{\xi\in\mathbb{S}} \mathrm{P}_\xi W_{es}\frac{\left\{S_{es}^{t\xi}\right\} - qd_{es}^{t} - do_{es}^{t-1}}{\left\{S_{es}^{t\xi}\right\} - S_{es}^{t\xi} + \rho_{es}^{t}} \le \varepsilon \quad \forall e\in\varepsilon, s\in\mathcal{S}, t\in\mathcal{T}. \quad (22)$$

Constraints (3)-(9).

$$\frac{D_{ed}^{t\xi} - di_{ed}^{t-1} - qr_{ed}^{t}}{M} + 1 \ge \mathrm{p}_{ed}^{t\xi} \forall e\in\varepsilon, d\in\mathcal{D}, t\in\mathcal{T}, \xi\in\Xi. \quad (23)$$

$$D_{ed}^{t\xi} - di_{ed}^{t-1} - qr_{ed}^{t} \le M\mathrm{p}_{ed}^{t\xi} \forall e\in\varepsilon, d\in\mathcal{D}, t\in\mathcal{T}, \xi\in\Xi. \quad (24)$$

$$\frac{qd_{es}^{t} + do_{es}^{t-1} - S_{es}^{t\xi}}{M} + 1 \ge \mathrm{q}_{es}^{t\xi} \forall e\in\varepsilon, s\in\mathcal{S}, t\in\mathcal{T}, \xi\in\Xi. \quad (25)$$

$$qd_{es}^{t} + do_{es}^{t-1} - S_{es}^{t\xi} \le M\mathrm{q}_{es}^{t\xi} \forall e\in\varepsilon, s\in\mathcal{S}, t\in\mathcal{T}, \xi\in\Xi. \quad (26)$$

$$\mathrm{p}_{ed}^{\xi t} = \begin{cases} 1 \text{ if } qr_{ed}^{t} \text{is smaller than} (D_{ed}^{t\xi} - di_{ed}^{t-1}) \\ 0 \text{otherwise} \end{cases} \quad \forall e\in\varepsilon, d\in\mathcal{D}, t\in\mathcal{T}, \xi\in\Xi. \quad (27)$$

$$\mathrm{q}_{es}^{\xi t} = \begin{cases} 1 \text{ if } qd_{es}^{t} \text{is greater than} (S_{es}^{t\xi} - do_{es}^{t-1}) \\ 0 \text{otherwise} \end{cases} \quad \forall e\in\varepsilon, s\in\mathcal{S}, t\in\mathcal{T}, \xi\in\Xi. \quad (28)$$

Phase II:

$$\mathrm{Min}\Psi_3 = \sum_{s\in S}\sum_{d\in D}\sum_{v\in V}\sum_{\zeta\in\mathbb{A}} \left\{ h_{sdv}^{t\zeta} \cdot \left[LU_v + FC_v + \frac{TD_{sd}\cdot(1+US_v)}{TS_v \cdot R_{sd}^{t\zeta}} \right] \right\}$$

s.t.

Constraints(12) − (19).

where the objective function Ψ_1 in Eq. (20) is equivalent to Eq. (1). The objective function Ψ_2 is converted into Constraints (21) and (22). Constraints (23) and (24) restrict that the larger value from $(D_{ed}^{t\xi} - di_{ed}^{t-1} - qr_{ed}^{t})$ and 0 is always chosen. Constraints (25) and (26) restrict that the larger value from $(qd_{es}^{t} + do_{es}^{t-1} - S_{es}^{t\xi})$ and 0 is always chosen. Constraints (27) and (28) are auxiliary binary variables.

V. COMPUTATIONAL STUDY

A. CASE STUDY

A case study of the 2010 Yushu Earthquake in Qinghai Province, China is investigated to evaluate the proposed models outlined in Section V. The affected area with seismic intensity is shown in Fig. 1, which is obtained from.Ni,

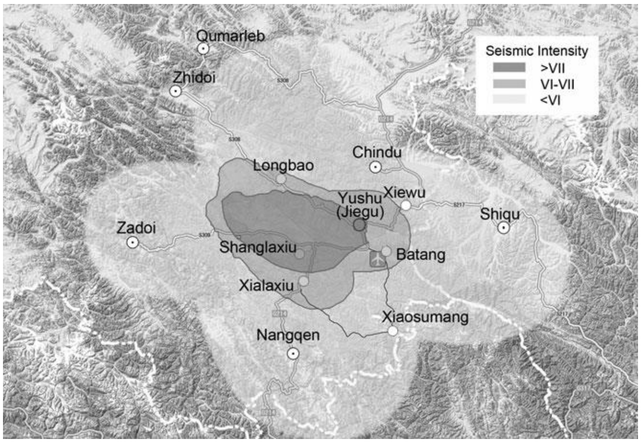


FIGURE 1. Seismic intensity map of the affected area.

TABLE 2. Characteristics of medical items and vehicles.

Character	S	A	F	B	Vehicle type I	Vehicle type II
Volume (m3)	1	1	1	1	--	--
Weight (t)	0.5	0.8	0.4	0.2	--	--
Volume capacity	--	--	--	--	35 m3	80 m3
Weight capacity	--	--	--	--	12 t	35 t
Leading cost	--	--	--	--	0.2 k/h	0.25 k/h
Fixed cost	--	--	--	--	0.2 k	0.5 k
Travel speed	--	--	--	--	60 km/h	50 km/h
Loading/unloading time	--	--	--	--	0.8 h	1.5 h

S: stretcher; A: alcohol; F: febrifuge; B: bandage

Shu [49] and has been used in many studies [6], [50], [51]. The disaster area contains 13 nodes that are considered as warehouses in this study. This study considers three time periods, two vehicle types, and four medical items. The characteristics of medical supplies and vehicles are presented in Table 2, which extended Table 4 developed by Gao and Cao [52]. And the warehouses are divided into two groups for each medical item. Suppose that for a typical medical item, the supply-point category consists of eight warehouses (i.e., warehouses 1-8) that are located at Zadoi, Qumarleb, Zhidoi, Shiqu, Nangqen, Xiaosumang, Chindu, and Xiewu; the demand-point category comprises five warehouses (i.e., warehouses 9-13) that are located at Yushu (Jiegu), Shanglaxiu, Xialaxiu, Longbao, and Batang. The warehouse weights are integers generated randomly on the intervals [20], [30], [40], [49], and [10], [30] in three periods, respectively. The simplified transportation network in disaster areas can also be identified from Ni et al. [49].

As the remaining input parameters have not yet been released by the government, these input parameters (i.e., demand, supply, and weights) are randomly generated. Considering the seismic intensities, the demand, supply, and weights in different periods are randomly generated (see Table 3). This study considers two road conditions (see

TABLE 3. Input parameters in the case study.

Period	Scenarios		Demand	Supply	Road availability	P_ξ/P_ζ
1	$\mathbb{S}$	1	[400, 600]	[250, 400]	--	0.1
		2	[600, 800]	[400, 550]	--	0.2
		3	[800, 1000]	[550, 700]	--	0.4
		4	[1000, 1200]	[700, 850]	--	0.2
		5	[1200, 1400]	[850, 1000]	--	0.1
	$\mathbb{A}$	1	--	--	[0.20, 0.50]	0.4
		2	--	--	[0.40, 0.70]	0.6
2	$\mathbb{S}$	1	[200, 400]	[150, 300]	--	0.1
		2	[400, 600]	[300, 450]	--	0.2
		3	[600, 800]	[450, 600]	--	0.4
		4	[800, 1000]	[600, 750]	--	0.2
		5	[1000, 1200]	[750, 900]	--	0.1
	$\mathbb{A}$	1	--	--	[0.30, 0.60]	0.4
		2	--	--	[0.50, 0.80]	0.6
3	$\mathbb{S}$	1	[100, 200]	[50, 200]	--	0.1
		2	[200, 400]	[200, 350]	--	0.2
		3	[400, 600]	[350, 500]	--	0.4
		4	[600, 800]	[500, 650]	--	0.2
		5	[800, 1000]	[650, 800]	--	0.1
	$\mathbb{A}$	1	--	--	[0.40, 0.70]	0.4
		2	--	--	[0.60, 0.90]	0.6

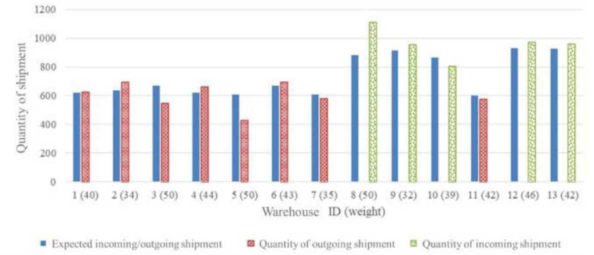
Table 3). In what follows, the numerical results are presented and compared with other studies to illustrate the advantages of the proposed model.

B. NUMERICAL RESULTS

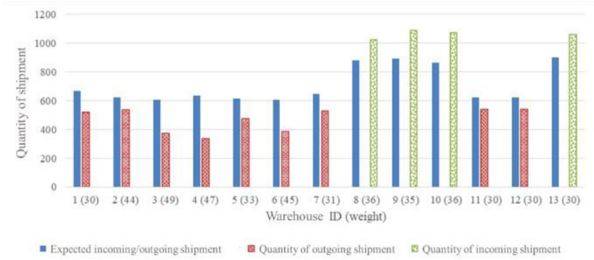
In this subsection, the main results of the case study are provided in adjusting and transporting the medical supplies when the second objective upper-bound value is fixed (say, 80). As depicted in Figs. 2-4, the sustainable MPMSA strategies are presented for three consecutive periods. Besides, the expected quantities of delivered and received medical supplies at warehouses in the first and second periods are also provided (Figs. 2 and 3). As the third period is the last one, there is no need to show the expected quantities of delivered and received medical supplies. If the expected quantity of the delivered medical supplies is greater than the actual quantity of the delivered medical supplies at supply warehouse s, there is a surplus at supply warehouse s. Otherwise, there is a shortage at supply warehouse s. If the expected quantity of the received medical supplies is greater than the actual quantity of the received medical supplies at demand warehouse d, there is a shortage at demand warehouse d. Otherwise, there is a surplus at demand warehouse d. In this sense, the surplus and shortage of medical supplies can be easily calculated through Equations in (4) and (5). Please note that warehouses 11 and 12 are supply and demand warehouses at the same time (see Figs. 2-4).

1) COMPUTATIONAL RESULTS IN THE FIRST PERIOD

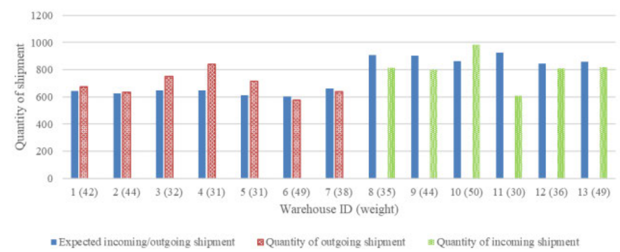
From Fig. 2, not surprisingly, the quantities of delivered and received medical supplies are closely related to the weights and expected quantities of delivered and received medical supplies at warehouses. As observed from Fig. 2(b), the



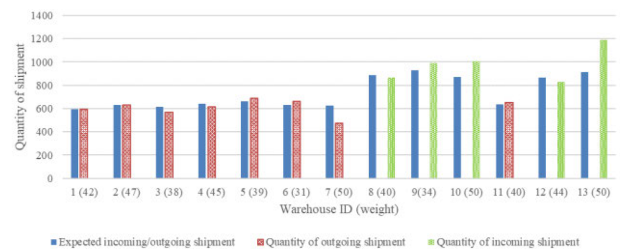
(a) Stretcher



(b) Alcohol

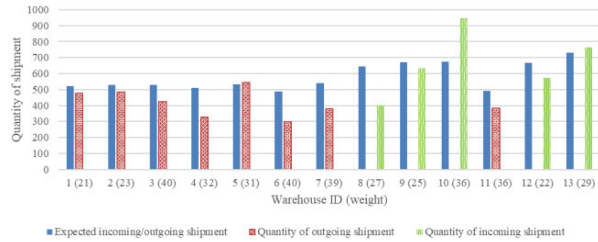


(c) Febrifuge

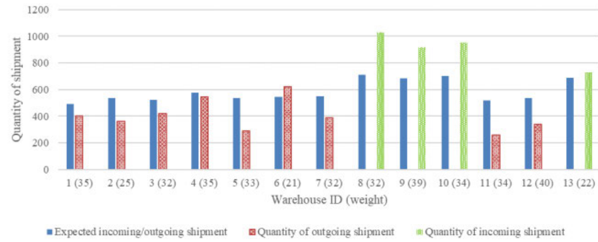


(d) Bandage

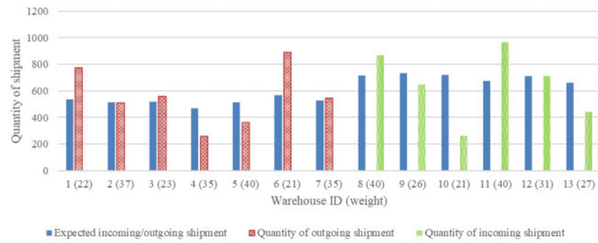
FIGURE 2. Optimal MPMSA strategy at warehouses in the first period.



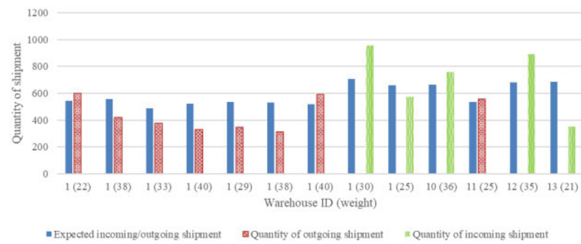
(a) Stretcher



(b) Alcohol



(c) Febrifuge



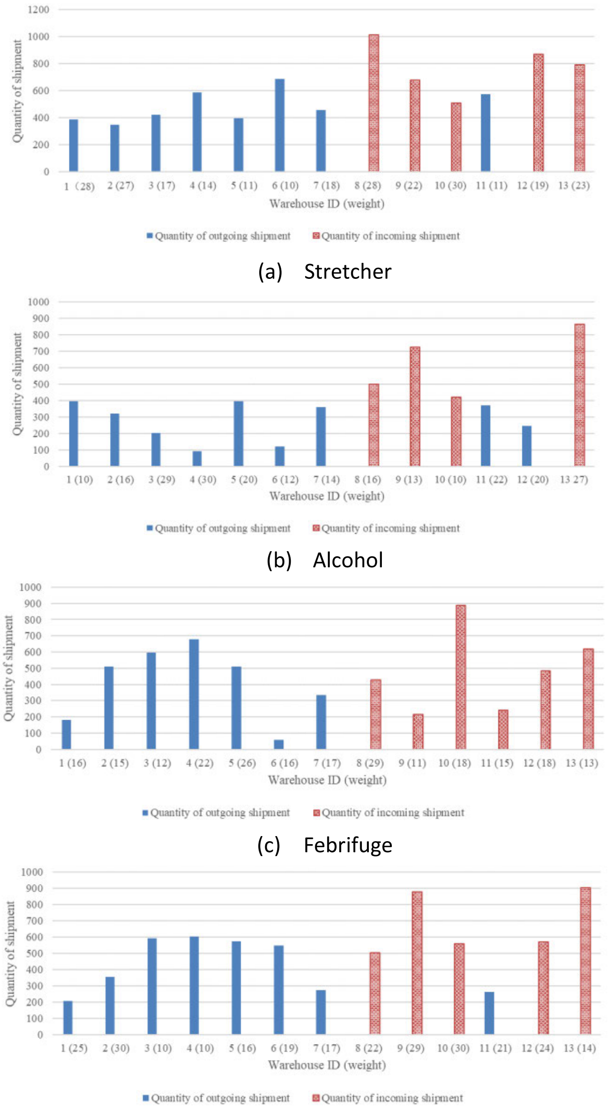
(d) Bandage

FIGURE 3. Optimal MPMSA strategy in the second period.

sixth warehouse with a higher weight shares less Alcohol compared with other supply warehouses in case of that this preferential warehouse shares too much Alcohol with others. As shown in Fig. 2(c), warehouse 4 shares more Febrifuge than warehouse 5 because warehouse 4 has a higher expected quantity of delivered Febrifuge. From Fig. 2(a), the demand warehouse 8 receives more Stretcher compared with other demand warehouses because the Stretcher has a higher superiority. Similarly, as observed in Fig. 2(d), even though warehouses 10 and 13 have the same weight, warehouse 13 receives more Bandage than warehouse 10 because warehouse 13 has a higher expected quantity of received Bandage. The above results validate the effectiveness of the proposed model based on Gao [14]. Having obtained the optimal quantities of delivered and received medical supplies at warehouses, the second-phase problem can be solved with the decisions obtained in the first-phase problem. Particularly, the previous optimal strategy is considered as the input to the second-phase problem. And the total delivered and received medical supplies at warehouses and the total used vehicles of different types in the first period are presented in Table 4.

2) COMPUTATIONAL RESULTS OF THE SECOND AND THIRD PERIODS

However, different from single-period relief operations, this study considers the sustainable MPMSA process and investigates the interaction effect of the quantities of delivered and received medical supplies in different periods. In other words, the decision variables in the current period will affect the decision variables of the next period. For the supply



(a) Stretcher

(b) Alcohol

(c) Febrifuge

(d) Bandage

FIGURE 4. Optimal MPMSA strategy in the third period.

TABLE 4. Total shipment and the number of used vehicles in the first period.

$\mathcal{T}$	Total shipment						Total vehicles	
	S	A	F	B	A_v^t	$\zeta \in \mathbb{A}$	$v = 1$	$v = 2$
$t = 1$	4800	4245	4837	4885	250	$\zeta = 1$	13	250
						$\zeta = 2$	14	250

warehouse category, as shown in Figs. 2 and 3, the shortage of Febrifuge at supply warehouse 4 in the first period is pre-filled in the second period, resulting in sharing less Febrifuge with others. On the contrary, the surplus of Alcohol at supply warehouse 5 in the second period is pre-consumed in the second period, leading to a high quantity of delivered

TABLE 5. Total shipment and the number of used vehicles in the second and third periods.

$\mathcal{T}$	Total shipment						Total vehicles	
	S	A	F	B	A_v^t	$\zeta \in \mathbb{A}$	$v = 1$	$v = 2$
$t = 2$	3317	3628	3900	3532	200	$\zeta = 1$	9	200
						$\zeta = 2$	9	200
$t = 3$	3864	2509	2873	3425	150	$\zeta = 1$	74	150
						$\zeta = 2$	76	150

Alcohol in the third period (see Figs. 3 and 4). For the demand warehouse category, the shortage of Febrifuge at demand warehouse 10 in the second period is pre-filled in the third period, which results in receiving more Febrifuge from others in the second period (see Figs. 3 and 4). On the contrary, the surplus Bandage at demand warehouse 13 in the first period is pre-consumed in the second period, leading to receiving less Bandage from other supply warehouses in the second period (see Figs. 2 and 3).

In the same way, the optimal quantities of delivered and received medical supplies in the warehouses in the second and third periods are input into the second-phase problem. And the total delivered and received medical supplies at warehouses and the total number of used vehicles of different types are obtained and presented in Table 5.

It is obvious that more large vehicles (i.e., $v = 2$) are used to transport medical supplies compared with small vehicles (i.e., $v = 1$) in each of the periods because the large vehicles can provide cheap and quick deliveries. As observed in Tables 4 and 5, different numbers of vehicles are used to transport medical supplies because of the different road availabilities, resulting in different medical-supply flows between warehouses. Specifically, more small vehicles are used in the second scenario because they have smaller fixed cost and loading/unloading time, providing cheaper and quicker deliveries on the roads with good conditions in the second scenario compared with that on the roads of worse conditions in the first scenario.

3) INFLUENCES OF ROAD AVAILABILITY ON THE RESULTS

As road availability is an important factor that delays the efficiency of vehicles and contributes to increasing cost, it is critical to test its impact on the third goal. To answer this question, the influence of road availability is conducted to show how the road availability affects transportation time and cost. Since too many decision variables are involved in medical item flows and transit-related decisions, only the total transportation time and cost in each of the periods are shown and compared given different road availabilities (see Fig. 5). It is obvious that a lower objective function value is obtained without considering the road availability, which

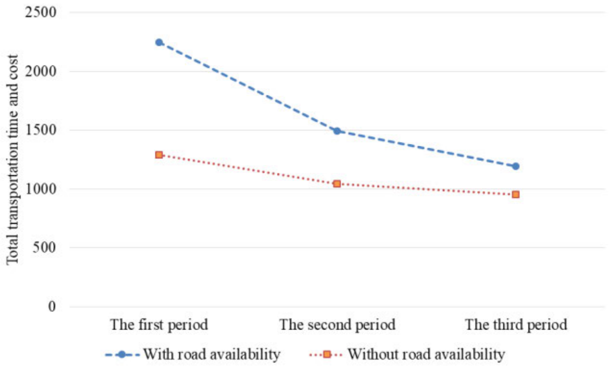


FIGURE 5. **Total transportation time and cost with and without road availability in three different periods.**

verifies that the road availability due to a large-scale disaster leads to delaying humanitarian logistics and contributing to increasing cost. It is also found that repairing roads is also an important way to reduce the transportation time and cost because a higher road availability results in lower transportation time and cost.

C. TRADE-OFF BETWEEN SOCIAL SUSTAINABLE OBJECTIVES

Different from the previous studies, this study considers two different criteria to measure fairness. Having obtained the maximum objective function value ε^* with eliminating Ψ_1, the second objective function value Ψ_2 is converted into a constraint. This study selects ten considerable upper-bound values from 35 to 80. Given different upper-bound values, four two-dimensional diagrams are provided in Fig. 6 to show the trade-off between the collective's and individual's social sustainable objective functions for four kinds of medical supplies in the first period. As shown in Fig. 6, a number of non-dominated solutions indicate that these two objectives conflict with each other. Increasing the upper-bound value of the second objective function value leads to a better first objective function value. In terms of the non-dominated solutions, it is difficult to say that one of them is better than others. In this sense, more information is needed to identify the ''most preferred'' solution in practice. At the same time, the optimal MPMSA strategies (i.e., outgoing and incoming shipments) in the first period are presented in Fig. 7.

Next, this study discusses the non-dominated solutions with respect to two different objective functions. As shown in Fig. 7, the quantities of outgoing and incoming shipments are presented given different upper-bound values. And the minimum value of the first objective function is obtained while the upper-bound value is greater than 80. When the upper-bound value is getting smaller, the quantities of outgoing and incoming shipments change accordingly. Particularly, the optimal quantity of incoming Stretcher is 1,111 in warehouse 8 with eliminating the second objective function Ψ_2 [see Fig. 7(a)]. However, when the upper-bound value to the

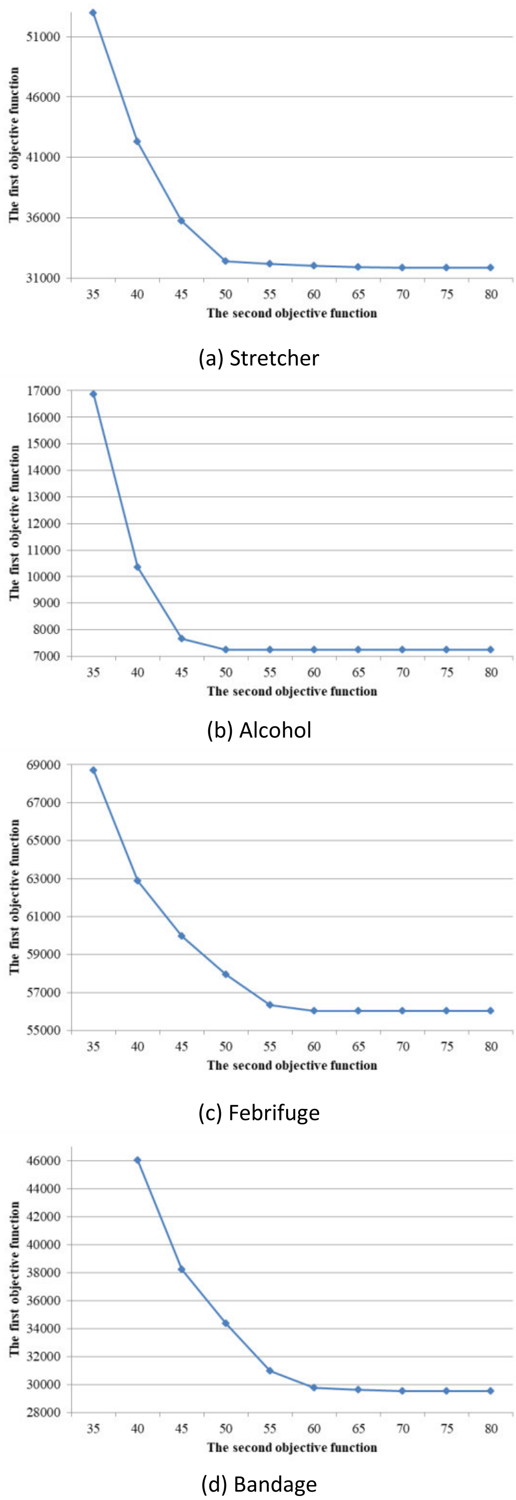
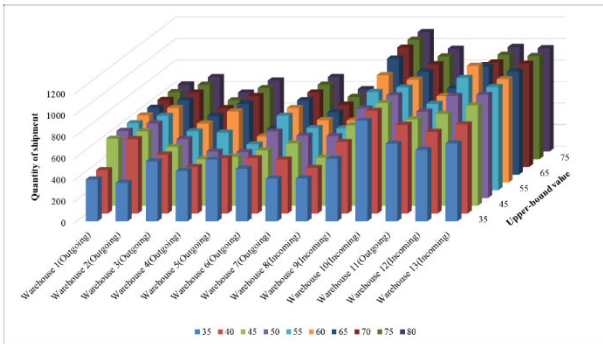
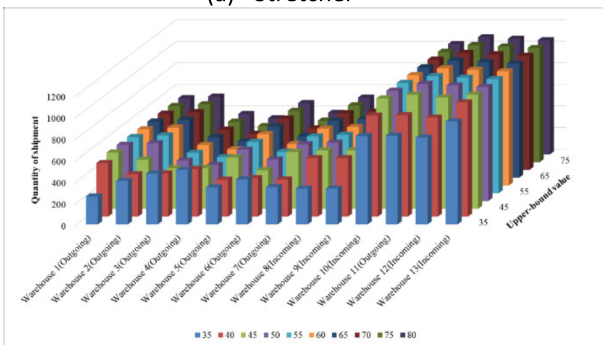


FIGURE 6. **Trade-off between objective functions Ψ_1 and Ψ_2.**

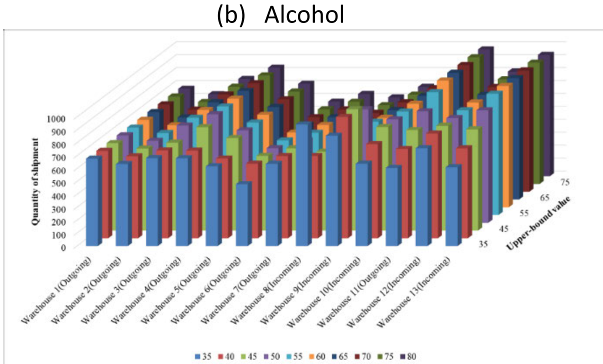
second objective function Ψ_2 is smaller than 80, the quantity of incoming Stretcher begins to decrease, which indicates warehouse 8 receiving too much Stretcher from others and neglects each individual's weighted fulfill rate. At the same time, the second warehouse shares too much Bandage with



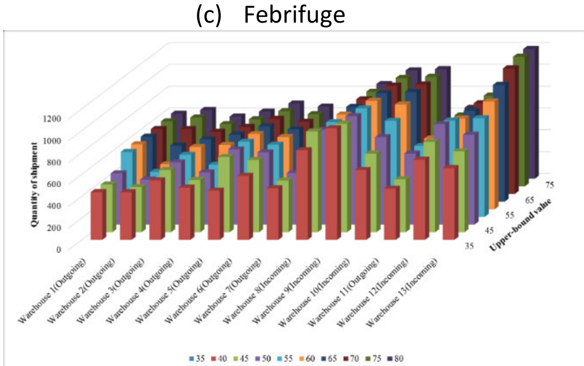
(a) Stretcher



(b) Alcohol

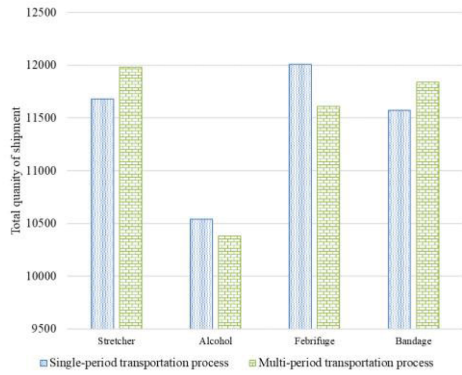


(c) Febrifuge

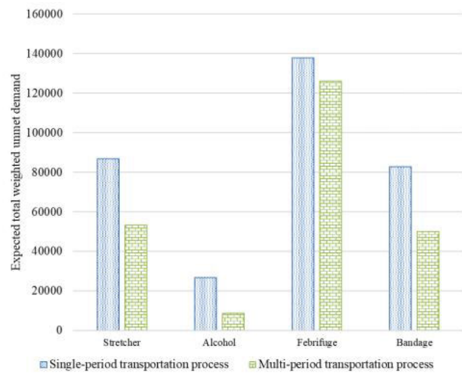


(d) Bandage

FIGURE 7. **Quantities of outgoing and incoming shipments given different upper-bound values.**



(a) Total shipment



(b) Objective function

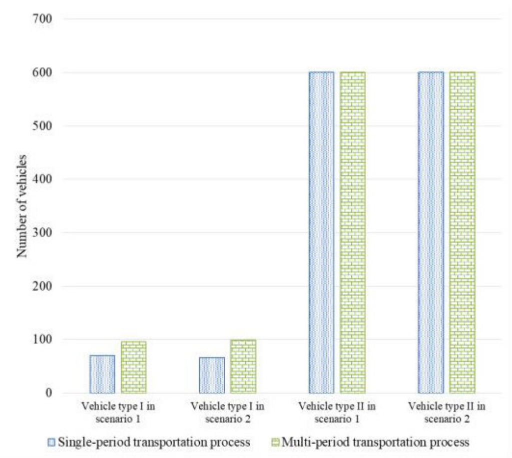
FIGURE 8. **Comparison results of the single- and multi-period MSA strategies.**

others when each individual's weighted fulfill rate is not considered [see Fig. 7(d)]. From the Figs. 6 and 7, it is obvious that the optimal MPMSA strategy with respect to two different objective functions is different from that with only one objective function.

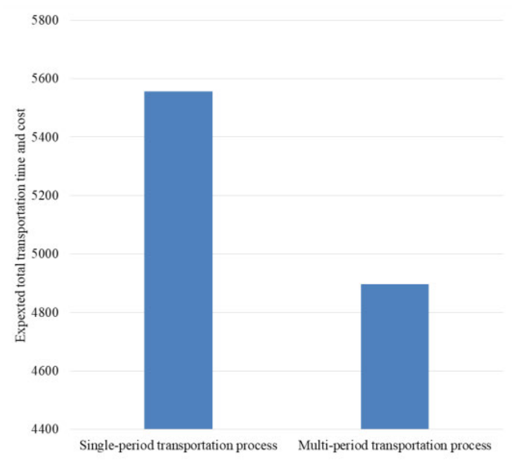
Since social sustainability cares about not only the total profit but also each individual's profit, it is easily convinced that developing MPMSA strategies is quite essential. Under such a case, the demand warehouses receive more appropriate quantities of medical supplies from other warehouses; and the supply warehouses share more medical supplies with others. In brief, adjusting medical supplies with respect to different objective functions can further promote fairness and social sustainability in disaster response. Note that the MPMSA strategies in the next two periods are similar to the results in the first period. Consequently, the two-dimensional objective function is a key factor in promoting fairness and social sustainability in disaster response.

D. COMPARISON OF RESULTS IN THE CONTEXT OF MULTI- AND SINGLE-PERIOD

To illustrate the superiority of the sustainable MPMSA process, the obtained results in this study are compared with the study in Gao [14]. Particularly, with the same input parameters, the comparison results are provided in Figs. 8 and 9 given a fixed second objective upper-bound value (say, 80). The total quantities of shipments from single- and



(a) Vehicle assignments



(b) Objective function

FIGURE 9. **Comparison results of the single- and multi-period transportation processes.**

multi-period MSA strategies are shown in Fig. 8(a) for each type of the medical supplies. The total quantities of shipments in the sustainable MPMSA strategy are different from those in the single-period one. Particularly, it is obvious that the total quantities of the rebalanced Stretcher and Bandage are not enough in the single-period MSA strategy compared with those in the sustainable MPMSA strategy, whereas too much Alcohol and Febrifuge are adjusted in the single-period MSA strategy compared with those in the sustainable MPMSA strategy. As depicted in Fig. 8(b), the expected total weighted unmet demand for each type of medical supplies is compared between single- and multi-period MSA strategies. Obviously, the sustainable MPMSA strategy outperforms the single-period one because a smaller expected total weighted unmet demand is obtained for each type of medical supplies. Thus, the sustainable MPMSA strategy has a better performance in adjusting the medical supplies to support social sustainability compared with the single-period one. This is a piece of definitely strong evidence to show that the proposed multi-period planning is much more appropriate when compared with the single-period one. Consequently, the government should implement multi-period relief operations rather than a single-period one.

TABLE 6. **Instances of different problem sizes.**

Instance ID	Number of warehouses	Number of medical-item types
1	13	2
2	13	3
3	13	4
4	13	5
5	13	6
6	16	2
7	16	3
8	16	4
9	16	5
10	16	6
11	20	2
12	20	3
13	20	4
14	20	5
15	20	6
16	30	6

Then, the third objective function considering single- and multi-period transportation processes is compared. To obtain the expected total transportation time and cost in the single-period transportation process, the summations of the delivered and received medical supplies are used in three periods. In this sense, the total quantities of medical supplies in the single-period transportation process are the same as those in the multi-period transportation process. Then these medical supplies are transported among warehouses considering the road conditions in the first period. The total number of assigned vehicles and the expected total transportation time and cost of both single- and multi-period transportation processes are reported in Fig. 9. Even though more vehicles are used in the multi-period transportation process [see Fig. 9(a)], the expected total transportation time and cost in the multi-period transportation process is smaller than that in single-period one. The inherent reason is that the worst road condition in the first period results in both longer transportation time and higher leading cost. Nevertheless, because the road condition is getting better, the transportation time and cost in the current period can be decreased compared with that in the last period. Since the third objective function emphasizes the total transportation time and cost rather than the total number of assigned vehicles, it is obvious that the multi-period transportation process has a better performance in transporting medical supplies to further reduce the transportation time and cost (see Fig. 9).

E. IMPACTS OF PROBLEM SIZE ON RESULTS

As presented in Subsection V-B, the model is solvable given the current problem size. However, once problem size is

TABLE 7. Solution performance of the problems with different size (First-phase problem).

ID	$e = 1$	$e = 2$	$e = 3$	$e = 4$	$e = 4$	$e = 6$	Ψ_1	Gap (%)
1	4,800	4,245	--	--	--	--	39,124	0
2	4,800	4,245	4,537	--	--	--	94,248	0
3	4,800	4,245	4,537	4,885	--	--	123,760	0
4	4,800	4,245	4,537	4,885	4,800	--	155,631	0
5	4,800	4,245	4,537	4,885	4,800	4,245	162,884	0
6	5,956	5,305	--	--	--	--	46,241	0
7	5,956	5,305	5,785	--	--	--	100,156	0
8	5,956	5,305	5,785	5,957	--	--	133,533	0
9	5,956	5,305	5,785	5,957	5,305	--	143,816	0
10	5,956	5,305	5,785	5,957	5,305	5,785	197,732	0
11	7,375	7,151	--	--	--	--	79,005	0
12	7,375	7,151	7,368	--	--	--	153,328	0
13	7,375	7,151	7,368	7,538	--	--	203,518	0
14	7,375	7,151	7,368	7,538	7,375	--	259,456	0
15	7,375	7,151	7,368	7,538	7,375	7,151	282,523	0
16	11,238	10,491	10,765	11,156	11,238	10,491	415,684	0

TABLE 8. Solution performance of the problems with different size (Second-phase problem).

ID	$\zeta \in \mathbb{A}$	$v = 1$	$v = 2$	Ψ_3	Gap (%)
1	$\zeta = 1$	3	168	1,439	0
	$\zeta = 2$	3	168		
2	$\zeta = 1$	1	225	1,925	0
	$\zeta = 2$	2	224		
3	$\zeta = 1$	13	250	2,246	0
	$\zeta = 2$	14	250		
4	$\zeta = 1$	0	325	2,780	0
	$\zeta = 2$	0	324		
5	$\zeta = 1$	1	420	3,591	0
	$\zeta = 2$	1	420		
6	$\zeta = 1$	4	209	1,418	0
	$\zeta = 2$	2	211		
7	$\zeta = 1$	4	275	1,885	0
	$\zeta = 2$	0	278		
8	$\zeta = 1$	0	320	2,164	0.16
	$\zeta = 2$	2	316		
9	$\zeta = 1$	1	394	2,649	0.22
	$\zeta = 2$	1	392		
10	$\zeta = 1$	0	520	3,539	0.37
	$\zeta = 2$	2	518		
11	$\zeta = 1$	40	259	1,992	0
	$\zeta = 2$	42	259		
12	$\zeta = 1$	55	339	2,635	0.410
	$\zeta = 2$	53	341		
13	$\zeta = 1$	58	385	3,016	0.74
	$\zeta = 2$	61	388		
14	$\zeta = 1$	68	485	3,792	0.41
	$\zeta = 2$	74	485		
15	$\zeta = 1$	222	600	5,137	0.63
	$\zeta = 2$	222	600		
16	$\zeta = 1$	Out of memory			
	$\zeta = 2$				

getting large, it would be more difficult to obtain the optimal solution within a reasonable computation time. To investigate the efficiency of the proposed model, the solution performances for 16 different problem sizes are tested and provided in Table 6.

To construct those problems with different size, the demand, supply, and weights at warehouses are generated by using the same method. Since the maximum total shipment between the supply and demand warehouses is obtained only when the first objective function exists, this study uses the quantities of incoming and outgoing shipments without considering the second objective function. Simultaneously, the total shipment in the first period is also higher than that in the following periods. That is, such a case is the worst case due to its high total shipment between the supply and demand warehouses. And the maximum required CPU time (600s) is considered and the total quantity of delivered medical supplies between demand and supply warehouses and the numbers of vehicles of different types in the first period are reported in Tables 7 and 8. Note that the third instance is the same as the case study in Subsection V-A.

VI. CONCLUSION

This study focuses on designing an appropriate and efficient MPMSA plan to adjust and transport the medical supplies from the perspective of social sustainability. Instead of a single-period MSA process, a reliable sustainable MPMSA process is developed. In this sustainable MPMSA process, the information is generally uncertain and revealed gradually over the period. With these uncertain elements, a STPMOSO model is proposed to formulate such issues. In the model, two objectives are considered to measure social sustainability. The first social sustainable goal is to minimize the expected total weighted unmet demand and the second sustainable goal is maximizing the minimum individual's weighted fulfil rate. The last goal is the minimization of the expected total transportation time and cost. The original problem can be divided into two sub problems, where the first sub problem contains two conflicting objective functions. In the first sub problem, a specific ε-constraint method is developed. Besides, a linearization approach is applied due to the nonlinearity of the proposed model. In the end, a case study is implemented to validate this research. Besides, compared with the single-period one, the superiority of the proposed model to handle the sustainable MPMSA problem is presented. Also, based on the numerical results and sensitivity analysis, some deep managerial implications and benefits are drawn for the researchers and managers, which are outlined as follows:

(i) It is found that the fairness needs to be quantified using different criteria since the social sustainability usually emphasize not only the collective's profit but also the individual's profit, which better promotes social sustainability (i.e., fairness) (see Figs. 6 and 7).

(ii) MPMSA relief operation outperforms the single-period one in terms of the multiple objectives considered in this study because the MSA decisions can be implemented with the updated information in each of the periods (see Figs. 8 and 9).

(iii) Through the sensitivity analysis to the road availability, it obvious that the vehicles can save transportation time and cost on roads with higher availabilities. Thus, it is advocated to repair the damaged roads so that road availability can be improved to reduce transportation time and cost (see Fig. 5).

Despite the above novelties and contributions, this work still has several limitations. With the following limitations, potential future research works can be done to:

1) It may not be able to find the optimal solution when the problem size is extremely large. Consequently, the first possible research direction is to propose the corresponding metaheuristic method to solve large-sized problems.

2) Some practical factors that delay transportation time are not considered. In this sense, some other indexes, such as traffic congestion for vehicles, will be incorporated.

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