An Analysis of Multi-objective Decision Problem in Humanitarian Supply Chains

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Abstract. In humanitarian supply chains, there is a need to consider how to distribute the limited relief supplies that have not been prepared sufficiently to each shelter. Different from commercial supply chains that prioritize cost reduction, in humanitarian supply chains, it is important to consider not only reducing the distribution cost but also how to deliver goods quickly to satisfy the demands of shelters. Three metrics have been proposed for humanitarian supply chains; efficiency, equity, and efficacy. The objective of this paper is to focus on the metric of efficacy to minimize distribution time to each shelter considering the relief goods arrival. Under the situation after the disaster, to supply relief goods agilely and fairly, it is necessary to consider the weight of each metric adequately. We formulate a multi-objective mathematical model by the multiple metrics and carry out the optimization by using the model. The results show that the proposed multi-objective model is very promising in dealing with complicated humanitarian supply chains. Moreover, we highlight the deviation between the result of each metric and multi-objective evaluation.

Keywords: humanitarian supply chains, disaster relief operations, metrics of humanitarian supply chains, multi-objective optimization

1. INTRODUCTION

The 2016 Kumamoto Earthquake hit Kumamoto Prefecture and Oita Prefecture in Japan on April 14th, 2016. Also the Great East Japan Earthquake hit the north-eastern parts of Japan on March 11th, 2011. In either case of disaster, relief goods were supplied up as far as disaster-affected prefectures. Relief goods were distributed to stockyards, but they were not properly distributed to shelters. In some stockyards of prefecture level and municipality level, supply of relief goods to shelters was sluggish and late. Even if the relief goods were distributed, there was a case that the distribution was inequity for each shelter. Hence, victims of the disaster could not receive enough the relief goods.

In this manner, in relief distribution, there are some problems such as limited relief goods, holding of the relief goods, inequity of distribution, etc. These points are difference from commercial supply chain. In the distribution of relief goods, it is necessary to consider more than one problem. Therefore, in this study, in humanitarian supply chain, we consider the necessary metric. In order to cope with several problems simultaneously, we consider more effective supplying method of relief goods in the situation after disaster by developing a multi-objective mathematical model.

2. LITERATURE REVIEW

In the humanitarian logistics, Huang et al. (2012) and Kato and Kubo (2012) proposed the three metrics of efficiency, equity, and efficacy as the metrics of humanitarian logistics. Efficiency is considered to be a measure of distribution costs from the time or cost aspect. This metric is fundamental way of thinking in logistics. Equity means equitable distribution. This metric is considered as a measure of unsatisfied demand, which is represented by using a disutility function. Concerning equity, in order to deliver relief goods fairly to every shelter, the concept of fulfillment rate for demands may be incorporated to achieve maximum equity (Soeta et al., 2015). Balcik et al. (2008) considered unsatisfied demand by using penalty costs.

In contrast with the metric of efficiency and equity, efficacy refers to rapid distribution. Huang et al. (2012) proposed minimizing distribution time weighted with amount of goods. However, Kato and Kubo (2012) proposed minimizing out of stock cost. In this manner, these two studies have different attitudes about efficacy. Regarding rapid distribution, Chacravarty (2014) suggested a smoother delivery considered cost and a way of distributing relief goods in case of two stages (before and after disaster occurrence). Similarly, in humanitarian logistics, some studies in the literature have focused on rapid response. However, there are not many studies addressing the term "efficacy".

Regarding multi-objective optimization problem in humanitarian logistics, Tzeng et al. (2007) proposed three objectives: economy, effectiveness, and satisfaction. In that study, effectiveness means minimizing the total distribution cost. Effectiveness is similar to efficiency addressed in Huang et al. (2012), and Kato and Kubo (2012), but it is different from the efficacy addressed in Huang et al. (2012), and Kato and Kubo (2012). Huang et al. (2015) proposed the lifesaving utility, delay cost, and equality. In the study, the aspects of the cost and equality were considered. Lifesaving as humanitarian aid was also considered but distinctly from the metric of efficacy. In addition, in multi-objective evaluation, it is considered that the important metric in humanitarian logistics changes over the time after disaster.

Therefore, this study considers the metric of efficacy as the necessary metric. Additionally, in order to consider the effective distribution after disaster, this study formulates the multi-objective evaluation in consideration of the time after disaster.

3. THE MODEL

3.1 The Metric of Efficacy, Efficiency and Equity

For the mathematical description of the model the following notation is introduced (adapted from Kobayashi et al., 2015).

Notation

Indices

i	Shelter index, $i = 1, 2, \ldots, N$
p	Relief goods index, $p = 1, 2, \ldots, P$
n	Metric index, $n = 1, 2$

Parameters

d_{ip}	Demands of relief goods p at shelter i
t_i	Distribution time from stockyard to shelter i
K	Number of available vehicles
Q	Capacity per vehicle
S_p	Available supplies of relief goods p from stockyard
w_p	Weight of relief goods p by the unit
f_n^+	The optimal value of metric n
f_n^-	The worst value of metric n
α	The weight value of efficacy, $\alpha = 0.1, 0.2, \ldots, 0.9$

Decision variables

x_{ip}	Amount of relief goods p to shelter i
k_i	Number of vehicles to shelter i
mf_p	Minimum fulfillment rate of relief goods p

About the definition of the metric of efficacy, different from efficiency and equity, efficacy is determined to be a measure of effective utilization of distribution time. Therefore, we define efficacy as minimizing the amount of goods that cannot be delivered during distribution time as shown in equation (1). Equation (1) is the objective function that indicates efficacy.

$$\text{Minimize} \qquad \sum_i \sum_p \left(d_{ip} - x_{ip}\right)\frac{1}{t_i} \qquad (1)$$

We also investigated the efficiency (Kobayashi et al., 2015) and equity models. About the metric of efficiency, Kobayashi et al. (2015) solved for the minimum time of the whole of distribution as shown in equation (2). Equation (2) is the objective function that indicates efficiency.

$$\text{Minimize} \qquad \sum_i k_i t_i \qquad (2)$$

About the metric of equity, in order to consider equitable distribution, we minimize the non-fulfillment rate as shown in equation (3). Equation (3) is the objective function that indicates equity.

$$\text{Minimize} \quad \sum_p \left(1 - mf_p\right) \qquad (3)$$

3.2 Multi-objective Evaluation

When a disaster occurs, actually more than one metric is important in supply of goods after the disaster. Furthermore, importance of metrics is assumed to change over time after the disaster. In this study, effective utilization of distribution time and equitable distribution should be considered aftermath of a disaster. Therefore, we carry out a set of numerical experiments on multi-objective evaluation by weighting of efficacy and equity. The metric of efficacy is indicated by f_1 as in equation (4) and the metric of equity is indicated by f_2 as in equation (5).

$$\text{Efficacy} \quad f_1 = \sum_i \sum_p \left(d_{ip} - x_{ip}\right) \frac{1}{t_i} \qquad (4)$$

$$\text{Equity} \quad f_2 = \sum_p \left(1 - mf_p\right) \qquad (5)$$

By using metric index and parameters of the optimal value, the worst value and weight of each metric, we minimize the objective function given in equation (6). The formulation of the multi-objective evaluation model is given by equation (6), and constraints are given by equation (7) to equation (13) (adapted from Kobayashi et al., 2015).

$$\text{Minimize} \quad \alpha \frac{f_1 - f_1^+}{f_1^- - f_1^+} + \left(1 - \alpha\right) \frac{f_2 - f_2^+}{f_2^- - f_2^+} \qquad (6)$$

subject to

$$x_{ip} \le d_{ip} \qquad \forall i, p \qquad (7)$$

$$\sum_i x_{ip} = S_p \qquad \forall p \qquad (8)$$

$$\sum_p x_{ip} w_p \le Qk_i \qquad \forall i \qquad (9)$$

$$\sum_i k_i \le K \qquad (10)$$

$$\frac{x_{ip}}{d_{ip}} \ge mf_p \qquad \forall i, p \qquad (11)$$

$$x_{ip} \ge 0 \qquad \forall i, p \qquad (12)$$

$$k_i \quad integer \qquad \forall i \qquad (13)$$

Equation (6) is the objective function that indicates multi-objective evaluation of efficacy and equity. Equation (7) represents the upper limit of the amount of delivery to each shelter. Equation (8) is the constraint on the supplies available to deliver. Equation (9) is the constraint on the vehicle capacity. Equation (10) is the constraint on the number of available vehicles. Equation (11) indicates the constraint on the fulfillment rate. Equation (12) shows non-negativity, and equation (13) shows that the number of vehicle is non-negative and integer.

3.3 Logistics Model

In the basic logistics model of a disaster, relief goods are supplied to shelters via a supply source consisting of a first stockyard of prefecture level and a second stockyard of municipality level. In the 2016 Kumamoto Earthquake and the Great East Japan Earthquake, relief goods were not delivered as planned from the stockyard to shelters. In this study, we focus on the last-mile distribution in humanitarian logistics.

Therefore, we set the second stockyard as one place and the shelters as *N* places. Additionally, we assume that vehicles are used as the mode of transportation, where one vehicle goes to one shelter. We consider one period and multi-relief goods.

4. NUMERICAL EXPERIMENTS – The Case of the Great East Japan Earthquake

4.1 Numerical Experiments

In this study, to carry out numerical experiments, we use the number of evacuee data of Soma City in Fukushima Prefecture (Soeta et al., 2015). We set available supplies to be 100 units of rice, 590 units of snacks, 290 units of water, 250 units of food, and 190 units of blankets. We set the Soma City Hall to be the second stockyard. The required time by a vehicle from the second stockyard to each shelter, and the demands of each shelter are shown in Table 1. We assumed that the number of available vehicles to be 15, and the capacity of one vehicle to be 750 kg. We solved the optimization problem using Gurobi Optimizer 6.5.0.

4.2 Results

The results of numerical experiments based on multi-objective evaluation for 0.1, 0.5, 0.9 are shown in Figures 1 to 3, respectively. Figures 1-3 show the fulfillment rates indicating the ratios of amount of delivery to amount of demand. Additionally, the standardized values of the objective function values of efficacy and equity are shown in Figure 4.

Table 1 Demands of each relief goods in each shelter

Shelter (the number of evacuees)	Rice	Snack	Water	Foods	Blanket	Time(min)
Sports Arena SOMA (260)	13	78	33	33	26	1
The 1st NakamuraElementary School (450)	23	135	57	57	45	1
Hamanasu Welfare Center (500)	25	150	63	63	50	5
Yamakami Community Center (22)	2	7	3	3	3	8
Yawata Elementary School (142)	8	43	18	18	15	8
Roujin Ikoino Ie (28)	2	9	4	4	3	9
Somahigashi High School (489)	25	147	62	62	49	9
Iitoyo Elementary School (150)	8	45	19	19	15	10
Koyo Junior High School (460)	23	138	58	58	46	10
Nittaki Community Center (49)	3	15	7	7	5	13
Total	132	767	324	324	257	74

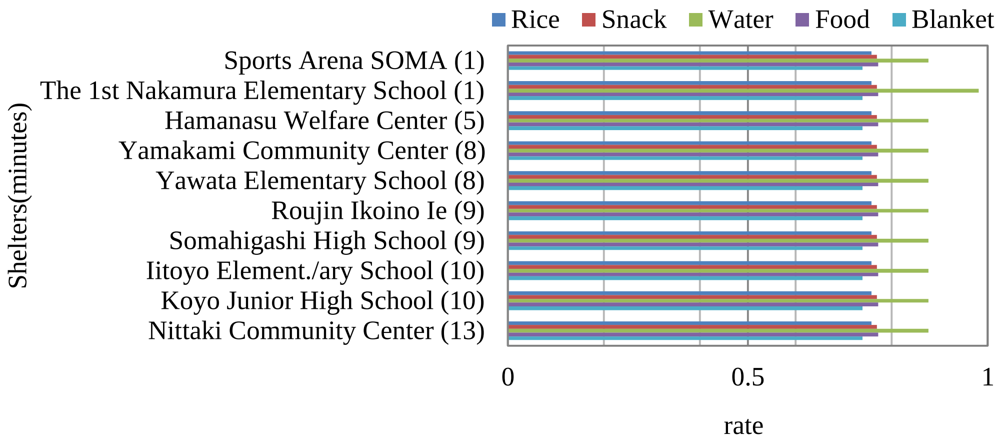

Figure 1 Fulfillment rate ($\alpha = 0.1$)

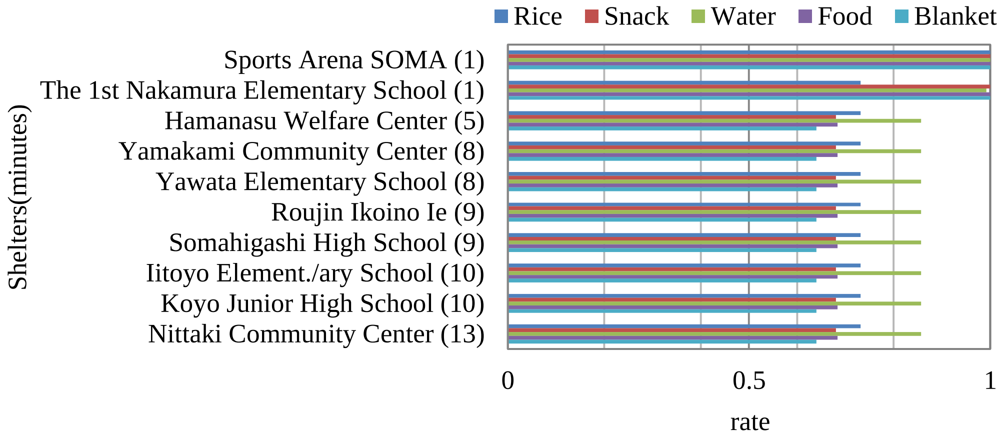

Figure 2 Fulfillment rate (α = 0.5)

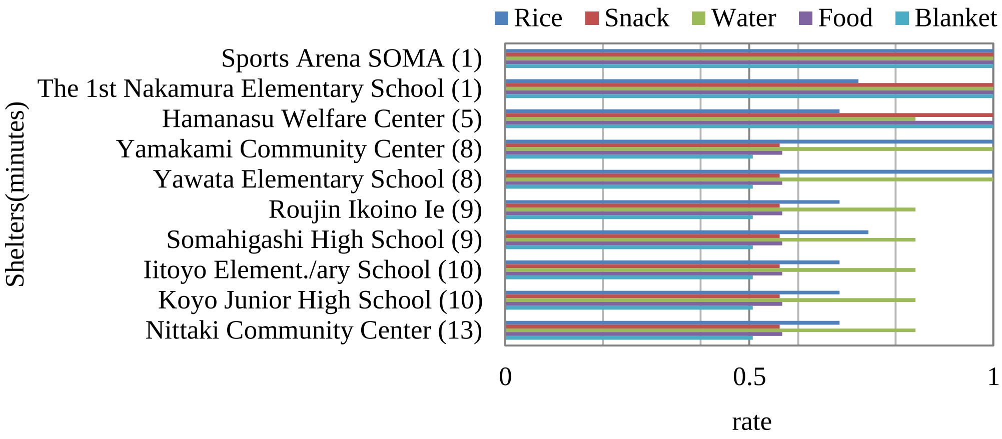

Figure 3 Fulfillment rate (α = 0.9)

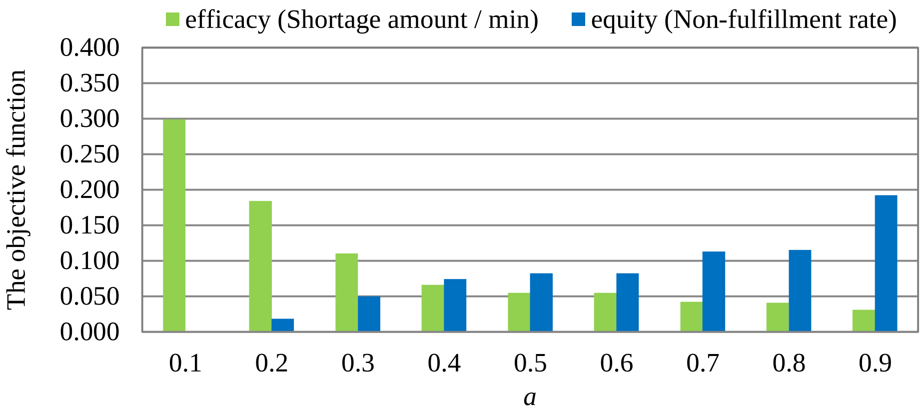

Figure 4 The objective function of each metrics

4.3 Discussion

First, Figures 1 to 3 indicate fulfillment rates that facilitate understanding of the differences of the values of α. According to these figures, decrease of minimum fulfillment rate is verified by decrement of weight of the metric of equity that indicates the value of $1-\alpha$. Additionally, if the weight value of equity is 0.1 (the weight value of efficacy is 0.9), it can be confirmed that minimum fulfillment rate is approximately 0.5.

Next, according to Figure 4, in case of corresponding efficacy and equity, the tendency of variation of the objective function values is indicated by changing the respective values of α. It is conceivable that this result shows how much the metrics of efficacy and equity are considered simultaneously. According to this result, both efficacy and equity vary infinitely when the value of α is between 0.1 and 0.4. But, when the value of α is from 0.4 to 0.6 and from 0.7 to 0.8, both efficacy and equity remain nearly unchanged. Therefore, to decide the value of α, in this case, it is considered that it is important to confirm the results of each value of α.

5. CONCLUSION

In this study, we considered the time that is required by each metric. Specially, we proposed that the metrics of efficacy for effective utilization of distribution time and equity for equitable distribution are necessary aftermath of a disaster. Moreover, we conducted numerical experiments on the multi-objective evaluation of humanitarian logistics with respect to the metric of efficacy and the metric of equity. In the numerical experiments, the weight value showed the relationship between the two metrics. The result showed that in decision making process of supply of relief goods, it is critical to consider the degree of the metrics needed for humanitarian aid.

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