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# Optimizing the supply of essential goods under closed-off management: A case study of COVID-19<sup>\*</sup>

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**Abstract:** The COVID-19 pandemic is threatening people's health and economic development around the world. Many areas and cities are opting for actions such as lockdown or closed-off management to prevent rapid spread of the virus. Under these actions, it is necessary and important to guarantee the supply of essential goods. In this paper, we develop a multi-objective optimization model to optimize the supply of essential goods under closed-off management. A mixed binary integer programming model is built to help identify the optimal safety stock level as well as the supply network so that the demands for essential goods could be guaranteed. The effectiveness of our method is demonstrated by an example. We also perform sensitivity analysis for key parameters. Our work provides a reasonable solution for the supply of essential goods under closed-off management.

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**Keywords:** essential goods, mixed binary integer linear programming, closed-off management, COVID-19.

## 1. INTRODUCTION

The infectious disease COVID-19 has been sweeping across the world since the beginning of 2020, causing massive losses of life and severe economic problems in almost all countries. It is expected that the world needs to fight with COVID-19 for a long time due to its strong transmission and fast mutation rate. Actions such as suspending gatherings, taking mass nucleic acid testing and locking down an area or even the whole city have been taken from time to time to stop the rapid spread of COVID-19. In some emergent cases, strict closed-off management policy is taken and people are even not allowed to go outside. When an area is locked down, ample and immediate supply of essential goods including food, water and other necessary daily goods is of importance for people's health and social stability. Shortages of such goods can cause severe discontent and panic. Unlike normal days when people could buy goods freely by themselves or dine out, during closed-off management period, they rely on suppliers or deliverymen to deliver goods to their door. As a result, demands of essential goods delivery usually increase in these days. On the other hand, replenishment and delivery capacities of supply centers are usually under the risk of reduction because of transportation interruption and staff shortages. Hence, it is necessary to develop an approach to optimize the supply of essential goods under closed-off management.

In this paper, we focus on the supply of essential goods under closed-off management during the COVID-19 pandemic. We develop a multi-objective optimization model by means of mixed binary integer linear programming to optimize the supply system of essential goods. This model captures the features of dynamic demands and replenishment capacity of supply centers. It identifies the optimal safety inventory level that ensures the demands for essential goods during closed-off management period are satisfied. Moreover, this model also identifies the best supply network between supply centers and communities to make goods delivery efficient and convenient. Our approach can help the policy maker not only improve the ability to respond to emergencies, but also effectively cope with demand fluctuations under closed-off management.

The remainder of this paper is organized as follows: Section 2 briefly introduces literature on this topic. Section 3 develops a multi-objective optimization model for optimizing the supply of essential goods in emergency. Section 4 demonstrates the proposed model by an illustrative example. Section 5 summarizes and concludes.

## 2. LITERATURE REVIEW

The problem we study lies in the field of emergency logistics, which study to the logistics activities that provide needed goods with the goal of maximizing efficiency and minimizing loss in the face of emergencies, such as natural disasters, unexpected human accidents and social public health events. Recently, emergency logistics in the context of COVID-19 are attracting more and more attention. We can recognize from Table 1 that scholars have proposed some solutions to solve the issue from different perspectives. For example, Sodhi et al. (2021) proposed an

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approach to develop responsive supply chains to cope with the impact of pandemic on supply chains and to improve the resilience of supply chains by analyzing the root causes of long-term shortage of key products in the United States. Jiang et al. (2020) designed a formal decision-making system to evaluate the reliability of emergency logistics system. Their empirical research shows that coordination command and material supply play a more important role in the emergency logistics system. Zhu et al. (2020) discussed the connection between the COVID-19 pandemic and shortages of essential goods, and proposed to increase safety stock to enhance resilience against risks.

In addition, most scholars proposed solutions from a quantitative perspective, such as mathematical modeling, algorithm improvement and path planning. For example, Corominas (2021) proposed a model for identifying the optimal emergency stocks. He points out that a permanent shield stock must be established to immediately meet the demand arising from the implementation of the quarantine policy. Luo et al. (2022) proposed a statistical model for system reliability evaluation by jointly considering the correlated component lifetimes and the lifetime ordering constraints. The model can be used to evaluate the effectiveness of logistics delivery strategies in the field of emergency logistics. Mehlawat et al. (2021) used Twitter data to identify customer evaluations of e-commerce platforms and established a multi-objective vehicle routing optimization model to solve the last kilometer delivery problem in the context of the epidemic. Yang et al. (2018) proposed a two-stage approach to tackle the sub-problems of vehicle routing and relief allocation in the context of emergency logistics. Liu and Ji (2019) proposed an efficient online path planning algorithm for emergency logistics based on double ant colony optimization with the aim to improve the distribution efficiency of emergency logistics vehicles. Sharma et al. (2020) presented that the risk of people going out and being exposed to the virus can be effectively reduced by developing a robotic system for the distribution of emergency supplies and essential goods at the community level. Although quite many researches have

several cities to effectively and quickly control the large-scale spread of COVID-19. To guarantee the life and health of such strict policy, supply of essential goods must be guaranteed. This is a part of the current research less considered.

### 3. METHODOLOGY

We consider an area which is under the risk of strict lockdown or colsed-off management. In this area, there are  $M$  supply centers that supply essential goods and  $N$  communities needing goods. We assume that during colsed-off period, essential goods supply is centralized controlled and each supply center is assigned to be responsible for providing goods to several communities. To prevent the risk of essential goods shortage during colsed-off management, the supply centers are required to maintain a certain level of inventory in normal times, called as safety inventory. Once lockdown begins, supply centers begin to supply goods to satisfy demands with stockpiled and replenished goods.

In this paper, we study how to make the contingency plan for supply of essential goods under COVID-19 or other similar situations. In particular, we will determine supplier centers for each community and the safety stock level for each supply center.

Before presenting our optimization model, we introduce parameters and notations used in this paper. As mentioned above, we assume that there are  $M$  supply centers and  $N$  communities. Moreover, we assume colsed-off management lasts for  $T$  days. Let  $h_{i0}$  and  $h_{it}$  denote safety inventory level and inventory level of supply center  $i$  at the end of day  $t$  respectively. Let  $a_{it}$  denote the replenishment quantity of supply center  $i$  at day  $t$ . Let  $s_{ij}$  denote the distance between supply center  $i$  to community  $j$ . Let  $d_{jt}$  denote the demand of community  $j$  at day  $t$  during colsed-off period.

Our objective is to make a contingency plan such that essential goods supply can be guaranteed in emergency. In particular, we will consider the following aspects: (1) Unmet daily demands is minimized. (2) The inventory cost of supply centers is minimized. (3) Goods delivery is convenient for the supply centers. The advantage of considering these aspects under colsed-off management is that they minimize staff mobility and contact during the pandemic.

We make the following assumptions: (1) Supply centers are assigned to supply goods to communities close to its location. Each community is supplied by only one supply center, but each supply center can supply more than one community. (2) There is no limit to the supply capacity of the supply centers.

We develop a mixed binary linear programming model for this problem. The decision variables of this model include:

- $h_{it} \geq 0, t = 0, 1, \dots, T$ : inventory level of supply center  $i$  at the end of day  $t$ .
- $I_{ij} \in \{0, 1\}, i = 1, \dots, M, j = 1, \dots, N$ : binary variable, takes 1 if supply center  $i$  is assigned to supply goods to community  $j$  and otherwise 0.

Table 1. Literature review

Technical route	Example
Conceptual model	Sodhi et al. (2021) Zhu et al. (2020)
Evaluation model	Jiang et al. (2020)
Mathematical modeling	Corominas (2021) Luo et al. (2022)
Route planning	Mehlawat et al. (2021) Yang et al. (2018)
Optimization algorithm	Liu and Ji (2019)
Distribution system	Sharma et al. (2020)

been done on this emerging topic, few scholars have been done on the supply of essential goods in extreme situations like closed-off management, where all residences are not allowed to go out at all. Closed-off management strategy is very effective in preventing the spread of the virus. For example, this strategy has been taken in China in

- $x_{ijt} \geq 0, i = 1, \dots, M, j = 1, \dots, N, t = 1, \dots, T$ :  
the amount of goods supply center  $i$  supplies to community  $j$  at day  $t$ .

The multiple objective optimization model is presented as follows:

$$\min \alpha \sum_{t=1}^T \sum_{j=1}^N \left( \sum_{t'=1}^t d_{jt'} - \sum_{t'=1}^t \sum_i x_{ijt'} \right) + \left( \beta_0 \sum_{i=1}^M h_{i0} + \beta_1 \sum_{i=1}^M \sum_{t=1}^T h_{i,t} \right) + \gamma \sum_{i=1}^M \sum_{j=1}^N s_{ij} I_{ij} \quad (1)$$

$$\text{s.t.} \sum_{i=1}^M I_{ij} = 1, j = 1, 2, \dots, N \quad (2)$$

$$x_{ijt} \leq I_{ij} \sum_{t'=1}^t d_{jt'}, i = 1, 2, \dots, M, j = 1, 2, \dots, N \quad (3)$$

$$\sum_i x_{ijt} \geq \theta d_{jt}, j = 1, 2, \dots, N, t = 1, 2, \dots, T \quad (4)$$

$$\sum_{t'=1}^t \sum_i x_{ijt'} \leq \sum_{t'=1}^t d_{jt'}, j = 1, 2, \dots, N, t = 1, 2, \dots, T \quad (5)$$

$$h_{i,t} = h_{i,t-1} + a_t - \sum_j x_{ijt}, i = 1, 2, \dots, M, t = 1, 2, \dots, T \quad (6)$$

$$h_{i,t-1} + a_t \geq \sum_j x_{ijt}, i = 1, 2, \dots, M, t = 1, 2, \dots, T \quad (7)$$

$$h_{i,t} \leq H_i, i = 1, 2, \dots, M, t = 1, 2, \dots, T \quad (8)$$

$$h_{i,t}, x_{ijt}, I_{ij} \in \{0, 1\} \quad (9)$$

The objective function (1) aims at minimizing weighted sum of three multiple objectives, with  $\alpha$ ,  $\beta$  and  $\gamma$  to be the weight coefficient. The three objectives are as follows: (1) to minimize the cost of out of inventory due to the cumulative unsatisfied demand during closed-off period; (2) to minimize the total inventory cost with safety inventory weighted by  $\beta_0$  and daily inventory weighted by  $\beta_1$ ; (3) to minimize the delivery cost, which consists of the distance between supply centers and communities weighted by  $\gamma$ .

Constraint (2) guarantees that one community is supplied by a supply center. Constraint (3) ensures that each supply center only delivers goods to the communities with which it has established delivery relationships and the supply quantity shall not exceed the accumulated total demand before the day. Constraint (4) guarantees that at least  $\theta$  percentage of daily demand at each community is satisfied for each day. Constraint (5) constrains that the cumulative supply until day  $t$  for community  $j$  is no more than its cumulative demand at day  $t$ . Constraint (6) describes how the inventory level update. The essential goods supplied to communities during closed-off management periods are from: the inventory remaining before day  $t$  and the replenishment quantity at day  $t$ . After the supply of day  $t$  is completed, the remaining quantity of goods is the inventory quantity of that day. Constraint (7) ensures that

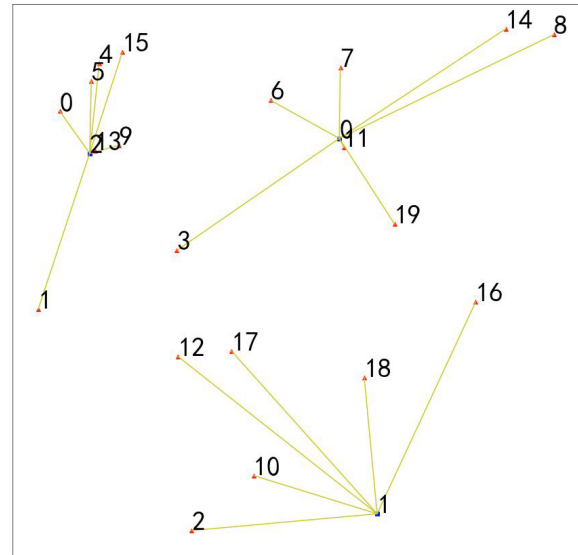


Fig. 1. Supply network of supply centers and communities

the total quantity that supply center  $i$  supply to community  $j$  does not exceed the quantity that it actually owns. Constraint (8) ensures that the inventory level at each supplier center will not exceed its inventory capacity  $H_i$ . Constraint (9) defines the domain of the decision variables.

#### 4. AN ILLUSTRATIVE EXAMPLE

In this part, we demonstrate our methodology via an illustrative example. In this example, there are 3 supply centers and 20 communities in the closed-off management area, whose locations are shown in Figure 1 where blue square nodes are supply centers and red triangular nodes are community. In the early days of closed-off management, people would buy a lot of essential goods due to negative emotions such as panic, resulting in higher daily demand than actual demand. During this period, the daily demand of each community is randomly generate from Uniform distribution  $Uniform(120, 160)$ . In other days of closed-off management, the daily demand of each community is randomly generate from Uniform distribution  $Uniform(80, 100)$ . The replenishment quantity at day  $t$  is randomly generate from Uniform distribution  $Uniform(400, 600)$ . In addition, the closed-off management is expected to last for 14 days. We set  $\theta = 0.8$  to guarantee that at least 80% of daily demands are satisfied on time. The inventory capacity  $H_i$  is set to be 5000 for all supply centers. Parameters in the objective function are set as follows:  $\alpha = 0.7$ ,  $\beta_0 = 0.2$ ,  $\beta_1 = 0.1$  and  $\gamma = 0.5$ . In particular, we emphasize the importance of avoiding essential goods shortage by set  $\alpha$  relatively larger than  $\beta$  and  $\gamma$ . In addition, as the safety inventory prepared in advance costs higher than daily inventory in emergency, we set  $\beta_0$  to be larger than  $\beta_1$ . Moreover,  $\gamma$  is the weight we put on the delivery convenience.

The model is solved by Groubi solver on a personal computer in 0.52 seconds in Table 3. By solving the model, we obtain the supply relations between supply centers

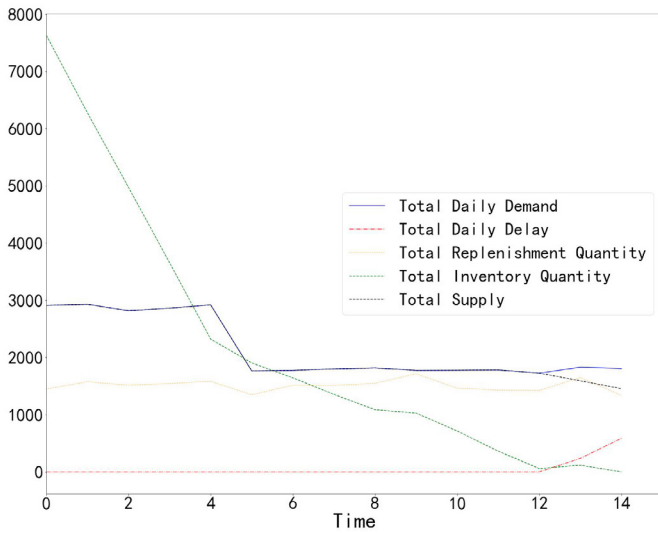


Fig. 2. The performance of the 14-days optimal supply plan

and communities, which are represented by yellow links in Figure 1. Our model assigns 20 communities to 3 supply centers. We could observe that communities assigned to each supply center are concentrated and close to supply centers, which is convenient for delivery, just as what we designed. This not only reduces the delivery distance and time, but also the risk of staff movement and contact in goods delivery.

In this example, the optimal safety inventory for the three supply centers are about 3437.0, 2010.0 and 3329.0 respectively. With the optimal supply plan obtained by our model, the key performance is presented in Figure 2. The red line and blue line shows the total unsatisfied demand and the total demands of the 20 communities at each day respectively. The yellow line shows the total replenishment quantity of the 3 supply centers at each day, which is always less than the total demand for that day. Moreover, the green line shows the total inventory quantity of the 3 supply centers and the black line shows the total supply quantity from the 3 supply centers to the 20 communities during closed-off period.

We can see that the daily demands and replenishment quantity are fluctuating with replenishment capacity always smaller. However, all demands are well satisfied, which is shown by the observation that the red line equal 0 on most days. The extra demands are well coped with thanks to the safety inventory. One thing to note is that at the end of closed-off management, the inventory is zero. This is because our plan is made for 14-days closed-off management and we do not consider periods after that. Moreover, we can find that there are shortages in the last two days of the closed-off management. In fact, this is a acceptable situation. Because communities are gradually being unsealed, people can get essential goods in other ways.

In order to discuss how length of the closed-off management influence the result, we perform sensitivity analysis of parameter  $T$ . Through sensitivity analysis, we can observe

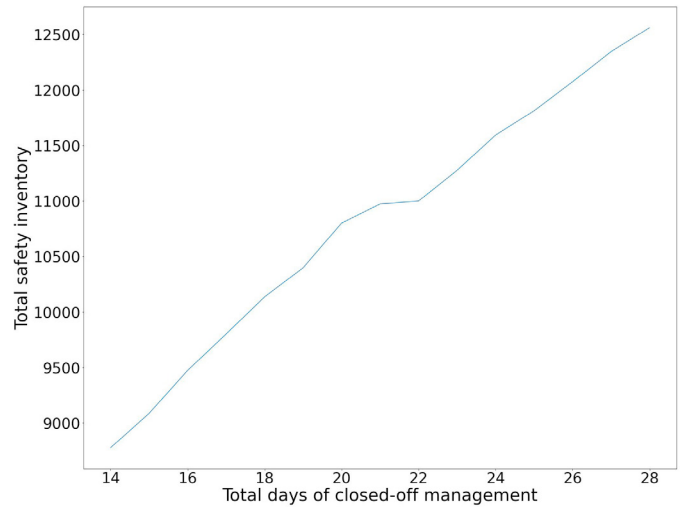


Fig. 3. Total safety inventory for different closed-off lengths

and analyze changes in key variables by changing the closed-off management length. We set the range of closed-off management time  $T$  to be [14,28]. This is because our observation of closed-off management situations shows that closed-off period in most of these areas is 2-4 weeks, such as closed-off management in Xi'an of China in 2021. In the example of this paper, the relationship between the safety inventory and total lockdown time  $T$  is shown in Figure 3. Because the daily replenishment quantity of essential goods is always less than the daily demand, the purpose of the safety inventory is to prevent the risk of essential goods shortage during closed-off period. So as shown in Figure 3, the safety inventory will increase as the closed-off management lasts longer. In Table 2, we can find that the delay of essential goods occurs during each closed-off period, but this is a small percentage of total demand. This all occurs near the end of each closed-off period and the delay of other days is 0. We can see similar results in Figure 4 as Figure 2. At the end of closed-off management, the communities gradually lift the closed-off management and people will have more access to essential goods. In other words, our essential goods delivery strategy still is effective when the closed-off management length is extended.

## 5. DISCUSSION AND CONCLUSION

Closed-off management is one of the most effective strategies for interrupting the spread of the virus, but it should be implemented on the premise of a rapid response to demand and a stable supply of essential goods. This paper proposes a multi-objective optimization model by means of mixed binary linear programming to optimize the supply of essential goods during closed-off period. Our model identifies the optimal safety inventory level and effective supply network. The optimization method is verified by an illustrative example. In addition, we also perform the sensitivity analysis for parameter  $T$  to analyze how length of the closed-off management influence the result. This shows that our optimization model is reasonable and effective in different closed-off management periods.

Table 2. Total delay

Total days of closed-off management	Total delay	Occurred Time(Day)
14	678	13,14
15	823	14,15
16	980	15,16
17	880	16,17
18	751	17,18
19	794	18,19
20	791	19,20
21	823	20,21
22	1731	20,21,22
23	1653	21,22,23
24	1411	22,23,24
25	1404	23,24,25
26	1287	24,25,26
27	1401	24,25,26,27
28	1377	25,26,27,28

Table 3. CPU time

Total days of closed-off management	CPU time(Seconds)
14	0.52
15	0.82
16	1.35
17	1.32
18	1.71
19	2.75
20	4.71
21	2.30
22	1.49
23	2.17
24	2.25
25	2.35
26	2.76
27	115.32
28	91.94

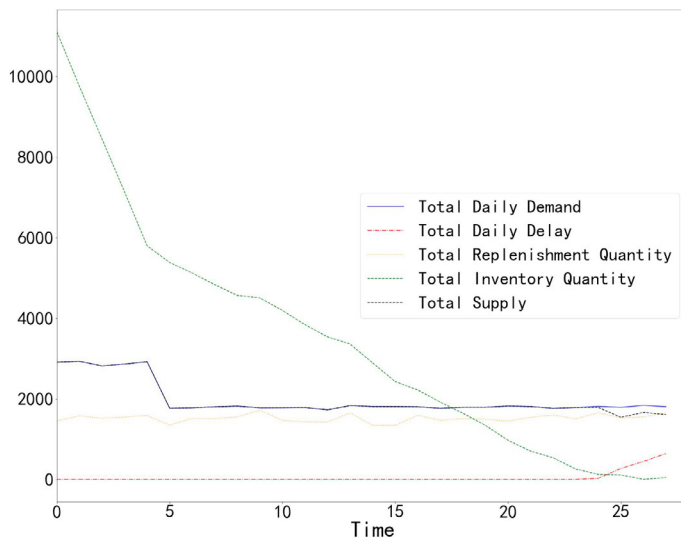


Fig. 4. The performance of the 28-days optimal supply plan

In this work, we consider a deterministic situation where closed-off management length, demands of communities and replenishment quantity of supply centers are deterministic. However, in practice, they are usually uncertain and there should be more in-depth discussion on this issue. This is going to be a focus of our work. In addition, the delivery capacity constraints of the supply centers should be fully considered. On the one hand, we can consider the daily supply capacity of each supply center, which is limited by the number of delivery vehicles it owns and the working hours it is allowed to work each day. On the other hand, the assumption about the delivery relationship between supply centers and communities could be relaxed. For example, we can consider situations where the same community is supplied by multiple supply centers. This will involve delivery path planning for the supply centers.

In future, we will take account of the uncertain property and extend our model to multiple-stage stochastic pro-

gramming model. This will involve more key variables and provide a more detailed solution.

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