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Post-disaster evacuation and temporary resettlement considering panic and panic spread

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Abstract

After a disaster, a huge number of homeless victims should be evacuated to temporary resettlement sites. However, because the number of temporary shelters is insufficient, as are shelter building capabilities, victims must be evacuated and resettled in batches. The perceived psychological penalty to victims may increase due to heightened panic when waiting for evacuation and resettlement, whereas psychological interventions can decrease the magnitude of this panic. Based on the susceptible–infective-removal model, panic spread among homeless victims and other disaster-affected people is modeled, while considering the effects of psychological interventions on panic spread. A function is derived to compute the increase in the number of victims to be evacuated due to panic spread. A novel mixed-integer linear program is constructed for multi-step evacuation and temporary resettlement under minimization of panic-induced psychological penalty cost, psychological intervention cost, and costs associated with transportation and building shelters. The model is solved by aggregating objectives into a single objective by assigning weights to these objectives. With Wenchuan County as the test case, the epicenter of the 2008 Sichuan earthquake, the influence and the sensitivity of parameters, tradeoff among costs, and the effects of various functions of panic strength on psychological penalty and monetary costs are assessed using six experimental scenarios. Analytical results reveal the complexity and managerial insights gained by applying the proposed method to post-disaster evacuation and temporary resettlement.

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1. Introduction

According to the Emergency Events Database (EM-DAT), which contains core data for the occurrence and effects of mass disasters worldwide, exactly 5516 disasters between 1990 and 2012 were reported, adversely affecting 7721 million people. According to the reports of annual disaster reviews by Guha-Sapir and Below (2013), the severe winter conditions and earthquake that hit the Sichuan Province, China, during May 2008 affected 122 million people; more than 26 million buildings were damaged and around 5 million collapsed; the 2010 Haiti Earthquake killed 222,570 people and about 250,000 homes and 30,000 commercial buildings either collapsed or were severely damaged; the Tōhoku Earthquake and Tsunami that hit Japan caused nearly 19,850 deaths and roughly 127,290 buildings collapsed, accounting for 64.5% of deaths worldwide due to disasters in 2011; in 2012, of the 357 natural disasters, 9655 people were killed and 124.5 million people were victimized.
worldwide. Over the last decade, China, the United States, the Philippines, India and Indonesia, are the top five countries most frequently targeted by natural disasters (Guha-Sapir and Below, 2013). Earthquakes, hurricanes, droughts, and floods are global challenges due to their unpredictability and potential scale of impact in terms of social, environmental, and economic costs. Many natural disasters displace people. Furthermore, natural disasters can cause psychological suffering, altering people's behaviors and decision-making, increasing rescue and relocation difficulties, and decreasing social stability and security (Hu and Sheu, 2013; Rennemo et al., 2014). Although few direct evidences of the effects of panic and its spread on post-disaster evacuation and resettlement have been recorded in literature, the synthetic effects of psychological damage on victims have been identified.

This study addresses the effects of panic and its spread on evacuation and temporary resettlement. Evacuation is the allocation and transport of disaster victims from disaster sites to sites with temporary shelters, whereas temporary resettlement refers to the resettlement of disaster victims during the period from the moment a disaster occurs to their allocation to transitional or permanent houses (El-Anwar and Chen, 2013). More than 15 million people were evacuated to temporary shelters after the 2008 Sichuan Earthquake. About 12.7 million tents and tarpaulin shelters were produced and transported to the affected areas within three months after the disaster (Lian, 2009). Many farmers and urban residents were persuaded to engage in reconstruction by subsuming their grief. About 73.55% of the victims who were evacuated and temporarily resettled returned to their houses and reconstructed their lives and buildings (Lian, 2009). Because panic was widespread, many people refused to return to their houses even through their houses were deemed safe and no aftershocks were observed. Panic spread had affected those people in Sichuan Province. The psychological effects of panic on demand for evacuation and resettlement are examined in this study. Shadow evacuation is representative of these effects.

Shadow evacuation, which is the evacuation of people outside the disaster area who “shadow” the evacuation of those within the target area, is considered in a group of studies on evidences of the psychological effects of evacuation, especially that of those experiencing panic and other emotions. In some areas, over-evacuation of people not threatened directly by a hazard can add to traffic and congestion within a network and hinder the transportation of evacuees who are directly threatened. Lamb et al. (2012) identified the factors influencing shadow evacuation. Dependent measures were used to assess the likelihood of a shadow evacuation and identify messages and presenter characteristics. Despite a 30-year experience with shadow evacuations, its causes are not sufficiently understood. Dash and Gladwin (2007) argued that studies should examine the role of perceived risk of shadow evacuation. They examined evacuation as a social process that is affected by the complex relationship between compliance with an evacuation message and an individual's perception of their risk exposure. Panic is a source of risk perceived by disaster victims, and panic spread is through typical social relations among victims. Shadow evacuations also provide clues as to the number of people affected by psychological emotions, as typical negative effects on hurricane-induced evacuation operations. Following Hurricane Andrew in 1992, Gladwin and Peacock (1997) noted that 14% of residents outside the evacuation zone also evacuated, placing considerable additional stress on transportation networks. Lindell and Prater (2007) also observed shadow evacuations associated with hurricane events, often occurring from inland areas deemed safe. Shadow evacuation overloaded the capacity of the transportation networks. Dueñas-Osorio et al. (2012) estimated risks of hurricane hazards and then compared them with risk perceptions of residents after Hurricane Ike's landfall in 2008. Comparison results show that shadow evacuation is partly attributable to risk overestimation. Overestimation of damage risk from wind or water surges resulted in 108,031 shadow evacuees. In this work, those in a shadow evacuation are motivated by panic and panic spread.

Although homeless people are in urgent need of evacuation, the number of temporary shelters is often limited immediately after a disaster. Additionally, temporary shelters (mainly tents and tarpaulin rooms) generally take three days to erect, and are costly and difficult to recycle when abandoned. Therefore, how to evacuate and resettle victims effectively with a limited number of temporary shelters is a significant problem. Uncertainty associated with a disaster and the possibility of secondary disasters typically causes panic as victims wait for evacuation and resettlement. When panic spreads among disaster-affected people, many people who should not be evacuated will request evacuation. Panic and its spread among victims are practical problems which complicate post-disaster evacuation and resettlement processes. Panic is the primary risk when a disaster occurs (Fritz and Marks, 1954; Mawson, 2005). The typical response to various threats and disasters is not to flee but to seek familiar persons and places; moreover, separation from what is familiar creates more stress than physical danger (Mawson, 2005). Mawson also asserted that waiting for evacuation can induce panic among victims because those waiting often see others leaving for resettlement sites.

Although post-disaster panic is reported frequently, quantitative studies are few. People are prone to panic and it spreads easily after disasters, namely, panic is infectious. That panic can induce a series of non-adaptive crowd behaviors during evacuation, such as pushing and trampling, and trying to jump in the line of those to be evacuated first. These actions are responsible for many disaster-related injuries and deaths. Price-Smith et al. (2013) determined that, with severe acute respiratory syndrome (SARS), which originated in Guangdong, China, in 2002, both infected and non-infected people panicked, and this panic had negative impacts (e.g., people fleeing, tourism declining, and trade slowing) on societies and their economies. This study characterized qualitatively the impact of panic spread, but did not consider the socio-psychological mechanism of panic a contagion. Based on diffusion theory of general diseases and public opinion, the effects of panic and its spread on temporary resettlement are considered in this study.

The panic degree while waiting for resettlement is quantified by this work, and panic spread typically increases the number of people who request resettlement and evacuation. To relieve panic and avoid mass incidents, governments organize mental health workers, including general mental health workers and mental health professionals (Daly et al., 2008), for
post-disaster psychological treatment. Mental health workers have become a part of teams working with the disaster-affected populations worldwide. In this study, mental health workers are the main vehicle for psychological intervention. The effects of shelter preparation, psychological intervention, and logistics on evacuation and resettlement solutions are also examined.

Compared to studies of emergency management and decision, post-disaster resettlement, evacuation, psychological intervention, and the many other issues related to post-disaster relief and recovery, this study contributes to literature in the following ways. First, the evacuation and temporary resettlement are jointly considered as a multi-step decision problem. A novel post-disaster resettlement flow with five stages is applied to identify the stages of evacuation and temporary resettlement. Second, the effects of panic and panic spread among victims on evacuation and temporary resettlement are considered. Osuna (1985) showed that the psychological stress that accumulates while waiting is a marginally increasing function of wait times. Therefore, this study formulates panic degree as a function of wait times for evacuation. Further, panic spread is formulated using the susceptible–infective-removal (SIR) model (Anderson, 1991). In this model, psychological intervention can reduce the degree of panic and panic spread. Based on these formulations, the number of victims to be evacuated due to panic spread is derived. Third, psychological penalty cost perceived by victims due to wait for evacuation, psychological intervention cost, cost of transporting victims from disaster sites to resettlement sites, and cost of building resettlement shelters are minimized in this formulation. These four costs are utilized to assess the efficacy of evacuation and resettlement solutions. The proposed models and formulated effects of panic and panic spread are characterized and analyzed based on estimated data from Wenchuan County after the 2008 Sichuan Earthquake. Via parameter sensitivity analysis and Pareto analysis of the relationship between psychological penalty cost and monetary cost, the features of the proposed method are elucidated.

The remainder of this paper is organized as follows. Section 2 briefly reviews relevant literature on temporary resettlement, psychological panic and resource allocation in disasters caused by infectious diseases. Section 3 introduces the problem of temporary resettlement impacted by panic-induced psychological panic and panic spread. Section 4 formulates a multi-objective optimization model for this problem. Section 5 lists the tasks required for acquiring data, and estimating parameter values. Section 6 gives numerical results for test scenarios, and findings based on these numerical results are summarized and discussed. Section 7 demonstrates the potential advantages and efficacy of the proposed method.

2. Related studies

This section has several parts. First, after introducing the behavioral and social features of evacuation, shadow evacuations are examined to explain the effects of panic and panic spread on demands for temporary shelters. Second, psychological panic is further examined rationally by considering panic in post-disaster evacuation and resettlement processes. Third, the principles of panic spread and base models are analyzed and applied to dynamic evacuation and resettlement.

(1) Shadow evacuation

Evacuation research can be grouped into two main categories: behavioral and social science; and modeling and operations (Tayfur and Taaffe, 2009). A fairly large body of research has focused on evacuation planning within behavioral and social science. In modeling and operations literature, researchers have focused mostly on the general population and used roadway infrastructure to move people away from a hazard. Many of these researchers proposed operational policies for mass evacuations (Daganzo and So, 2011; Guo et al., 2012), and studied routing and traffic problems during evacuation, whereas this study treats evacuation as a relief valve for psychological panic as perceived by disaster victims by considering the behavioral and social aspects of evacuation.

As mentioned, shadow evacuation is the movement of evacuees who are not required to evacuate. Numerous issues associated with shadow evacuation can affect the evacuation process. The shadow evacuation was a planning concern in the Houston Metropolitan Region, which greatly restricted the movement of evacuees from high-risk areas (Lamb et al., 2012). In fact, this particular problem was underscored by conditions during and after Hurricane Rita. Many shadow evacuees perceived that they were at high risk if they remained. Although shadow evacuation has been examined to some degree as a part of the evacuation process, few studies have investigated shadow evacuation as a phenomenon separate from necessary evacuation. Modeling techniques are similar to those outlined above. Lamb et al. (2012) asserted that evacuation efficiency can be achieved in a variety of ways: minimizing the shadow evacuation and background traffic; sheltering victim in place; and phased (staged or sequenced) evacuation. Reducing the magnitude of a shadow evacuation is likely best accomplished through clear communication and education. Evacuation decisions are largely products of government bodies feeling that a particular population is at risk of harm. Reducing background traffic also involves communication, typically urging people who do not need travel to cancel their trips. Because evacuation demand considerations are not directly controlled by transportation agencies, they are seldom explored in transportation literature. This study considered dynamic evacuation demands that are affected by victims’ psychology. As temporary shelters are for evacuated victims, shadow evacuations increase demands for shelters. This study makes a connection between post-disaster evacuation and temporary resettlement. Temporary resettlement is a time-sensitive service that should be provided for evacuees. The temporary resettlement capacity and replenishment capability should be carefully considered when making post-disaster evacuation decisions. These considerations are based on the observation that a shadow evacuation may be induced by panic and panic spread.
(2) Temporary resettlement

The temporary resettlement period plays an important role in the economic and psychological recovery of a disaster-affected society (El-Anwar and Chen, 2013). The primary goal of emergency response efforts is to provide shelter and assistance to disaster victims as soon as possible (Rawls and Turnquist, 2010). To restore normalcy and complete post-disaster reconstruction, temporary resettlement should proceed quickly. Kellett (1992) argued that temporary resettlement not only provides shelters for victims, but also satisfies the functional and social demands of victims. However, temporary shelters have strong negative effects on homeless victims when they are forced to live in temporary shelters for prolonged periods, and often lead to significant social problems such as high unemployment rates, decreased quality of life, and increased crime rates (Johnson, 2007). Therefore, those living in temporary resettlement sites should be transferred to transition resettlement houses and then resettled in permanent structures.

El-Anwar et al. (2009) proposed a multi-objective optimization model for assignments of large numbers of victims to temporary housing that minimizes social and economic disruption, temporary housing vulnerabilities, and adverse environmental impacts and public expenditures after a disaster. Furthermore, El-Anwar and Chen (2014) determined the computational efficiency of the current socioeconomic model of the temporary resettlement problem, which is formulated as an integer linear programming model. Moreover, to solve the model, an algorithm was developed based on the Hungarian algorithm. Johnson (2007) determined that erecting prefabricated temporary houses can minimize the negative effects associated with resettlement on disaster victims.

Although post-disaster housing and recovery have been well studied in literature, few researchers have formulated housing demands that are affected by shadow evacuation and the victims’ psychology. Although victim panic after a disaster is difficult to quantify, its effects on operations and management have been identified.

(3) Panic psychology

Although panic psychology is vast, for example, decision making under time pressure and safety concerns (see Adam et al., 2012, Dombroski et al., 2006), few studies are related to evacuations. This may be due in part to that fact that it is often a non-quantitative topic. Keating (1982) considered panic as a unique collective phenomenon when fear is the dominant psychological entity of a group. Neria et al. (2008) argued that when first learning of an impending natural disaster, people will have negative psychological reactions, such as insecurity, anxiety, and/or fear. Armfield (2006) argued that the danger levels associated with a disaster have a major impact on the severity and distribution of panic. Some researchers have found indirect evidence of panic, even in the evacuation processes. First, one danger is recognized and people start responding, their information-processing and decision-making capabilities may be confounded by the mentally demanding circumstances, and those pressures are related to the perception of time pressure (Adam et al., 2012). Second, egocentric behavior, a panic-related behavior, has been shown to be quite uncommon during an emergency (Bennet, 2005). Third, supported by a substantial number of empirical studies (e.g., Dash and Gladwin, 2007), disaster victims do not automatically follow advice and orders from public officials, and tend to seek information, assess personal risk, and make their own evacuation decisions. According to Adam et al. (2012) shadow evacuation is primarily motivated by people’s perception of being at risk, and shadow evacuation may most commonly occur during mass evacuations, increasing pressure on infrastructure and hindering those who need to evacuate. On the other hand, the response rate for evacuation has a marked non-linear impact on evacuation traffic conditions and arrival patterns, and a higher response rate leads to more traffic on roads, results in traffic congestion. The socio-psychological and circumstantial factors markedly affect individuals’ evacuation decisions.

(4) Panic spread

Panic affects victims’ evacuation decisions. Panic-related emotions can be minimized or spread to others in a social network. One factor influencing evacuation decisions is the strength of a person’s social network. Based on the assumption that social cues are a causal factor, Hasan and Ukkusuri (2011) created a social contagion model to investigate the conditions for a cascade through a network of the decision to evacuate. They also considered the effects of social community mixing patterns, the first person to decide to evacuate, and the decisions neighbors made in previous time steps. Their model used a mathematical approach and simulation to investigate these factors that bring about the desired behavior of evacuating people in an area based on social relationships. Wang et al. (2012) created a qualitative simulation model of a large evacuation system while considering panic spread, and analyzed uncertainty factors that can affect panic spread during the evacuation process. A threshold model of social contagion was developed by Hasan and Ukkusuri (2011). This model characterized social influence in decision about evacuation. Based on these studies, this study considers the effects of panic spread among disaster victims on temporary resettlement.

Bi and Ma (2012) and Zhang et al. (2013) investigated panic psychology during resettlement of disaster victims. Bi and Ma assessed the effects of two resettlement modes, centralized and non-centralized resettlements, on psychological health, and noted that centralized resettlement mode improved mental health better than decentralized resettlement. Zhang et al., who applied statistical methods to analyze factors affecting post-flood anxiety and psychological well-being, determined that timely and effective psychological intervention can minimize anxiety following a disaster. These two studies primarily analyzed the effects of resettlement modes, especially centralized resettlement, on the psychological health of victims; the effect of their psychology on the resettlement process did not get sufficient attention. This study differs from those by Bi and Ma, and Zhang et al. in the following ways. First, they analyzed the effects of resettlement modes on panic and panic spread among victims, whereas this study considered the effects of panic and panic spread on evacuation and temporary resettlement decisions; multi-period evacuation and resettlement...
decisions are the main focus. Second, they quantified the effects by questionnaire-based methods, which contributed to psychological research, whereas this study minimized psychological penalty or cost perceived by victims and three monetary costs by considering the effects of panic and panic spread.

Another stream of research involves resource allocation problems associated with the rapid spread of infectious diseases (Brandeau et al., 2003; Pietz et al., 2009; Ren et al., 2013; Mamani et al., 2013). Based on these studies, our study considers the following features. The resettlement problem while considering panic spread is formulated as a multi-step evacuation and resettlement problem. Next, the time-varying strength of panic, and the time-varying costs and limits of shelters and mental health workers are modeled to study the effects of wait times on evacuation and resettlement solutions. Finally, the panic spread in this study is affected by wait times and mental health workers.

3. The evacuation and temporary resettlement problem

Prevention, preparedness, response, and recovery are the four phases comprising the disaster management lifecycle (Quarantelli, 1995). Quarantelli further divided the recovery period into four stages: instant settlement (within a couple of hours after a disaster); emergency settlement (within one or two days after a disaster); temporary settlement (within a couple of weeks after a disaster); and permanent settlement (within a couple of years after a disaster). According to practices in China (Lian, 2009), before permanent resettlement, a period of transitional resettlement is considered within a couple of months to years after a disaster based on the time needed to construct permanent houses. Therefore, this study uses five-stage post-disaster resettlement processes (Fig. 1).

After a disaster, emergency rescue resources are distributed and instant settlement sites are chosen and built immediately. Shortly after rescue resources arrive, emergency settlement sites and facilities are usually built in safe spaces close to disaster sites. During this stage, young or healthy people take part in rescue operations at disaster sites, and some begin repairing their houses. For issues of water safety, sanitation, water, and electricity supply, and other management-related factors, most homeless and injured victims should be evacuated to temporary resettlement sites gradually within about 10–15 days after the disaster. During these processes, panic and panic spread markedly affect victim psychology and demands for evacuation. To achieve efficient management of order and evacuation, demands of disaster-affected people should be met as soon as possible. As an indirect evidence of panic spread, some people will return to their homes and repair their houses after living in temporary resettlement shelters for a few days, partially because they were evacuated due to “shadow evacuation”. This study focuses on the evacuation and temporary resettlement processes, which are enclosed by the grey box in Fig. 1. Shelters in the first three stages are typically tents and tarpaulin rooms, which cannot be deployed for extended periods due to issues related to safety and comfort. Victims in temporary shelters wait for transition resettlement houses that they can live in for several years. Shelters and/or houses for temporary, transitional, and permanent resettlement are generally built in successive stages because of shortages in resources and capabilities. Therefore, evacuation from one stage to the next stage is dynamic, and conducted step by step.

After a disaster, a large number of victims must be evacuated in the temporary resettlement stage from disaster sites (including instant and emergency settlement sites) (denoted as set S that has |S| sites, and are indexed by s) to resettlement sites (denoted as D that has |D| sites, and are indexed by d). However, because resources are limited and lead times for producing and building shelters are long, not all homeless or injured victims can be evacuated immediately to temporary resettlement sites. Due to these wait times for evacuation, the strengths of panic and panic spread among victims will rapidly increase. As a result, the number of panicked victims increases, as does the number of those who request evacuation and

![Fig. 1. Five post-disaster settlement and resettlement stages.](image-url)
Evacuation and resettlement considering panic and panic spread.

Disaster-affected sites (S, indexed by s)

- Panic
- Panic spread coefficient (β)
determined by:
  1) Panic degree (α) (affected by wait time (c) for resettlement)
  2) Government intervention degree (G)

\[ β_α ← (α ← c(1), G) \]

Temporary resettlement sites (D, indexed by d)

- Resettled people
- Resettlement capacity
- Erecting temporary houses

Infective people (To be resettled)

\[ P'_I → x'_I \]

Removed people (Being resettled)

\[ x'_I → x'_t \]

Susceptible people (affected by panic)

\[ P'_S → x'_S \]

\[ x'_S = c(x'_I, x'_N, + x'_t) \]

Therapists (t)

Government intervention

Based on the SIR model, \( x'_N \) is then computed by Eq. (1).

\[ x'_N = \gamma (x'_I, x'_N, + x'_t) \]

These three groups change dynamically as panic spreads (Fig. 2). Susceptible people become infective people when they are affected by infective people. The number of susceptible people who become infective people is the number of increase of infective people, denoted by \( P'_I \). The infective people become removed people when they are evacuated to resettlement sites. Notably, the NIP value, or the transformation of susceptive people to infective people, is a function of the current number of infective people and susceptible people, denoted \( x'_N \), where \( x'_N \) is the NIP added to infective people at the next time step \( x'_I, t+1 \). As \( β_α \) represents panic spread strength, \( x'_N \) is proportional to \( β_α, x'_I, \) and \( x'_t \). Based on the SIR model, \( x'_N \) is then computed by Eq. (1).
by \( e_{ts} \); and each mental health worker can provide psychological assistance to \( \sigma \) disaster victims during one time step. Obviously, \( g_{ts} \) is positively related to \( e_{ts} \) and \( \sigma \) and negatively related to the total number of disaster victims, as in Eq. (2).

Panic spread strength \( (\beta_{ts}) \) is a function of panic degree \( (x_t) \) and government intervention degree \( (g_{ts}) \), as in Eq. (3). Generally, \( \beta_{ts} \) is positively related to \( x_t \) and negatively related to \( g_{ts} \). The forms of \( \beta_{ts} \) are examined in Section 5.

Further, panic degree of infective people \( (z_t) \) is primarily affected by wait times for resettlement. Thus, \( z_t \) is a function of wait times for resettlement (Osuna, 1985). Initially, panic degree of infective people is a constant. As wait times increase, panic degree increases, indicating that wait times and panic strength are positively correlated. Moreover, when victims wait for excessively long times, psychological collapse may ensue. Thus, panic degree \( (z_t) \) is computed by a function of wait times in the numerical studies (Section 6). The function \( (z_t) \) is defined in the data estimation section (Section 5).

\[
x_{t,s}^I = c \left( x_{t,s}^1 + x_{t,s}^I + x_{t,s}^N \right) = \beta_{ts} \cdot x_{t,s}^1 \cdot \left( x_{t,s}^I + x_{t,s}^N \right) / \left( x_{t,s}^1 + x_{t,s}^I + x_{t,s}^N \right)
\]

\[
g_{ts} = \sigma \cdot e_{ts} / \left( x_{t,s}^I + x_{t,s}^N + x_{t,s}^s \right)
\]

\[
\beta_{ts} = \beta_{ts} (x_t, g_{ts})
\]

When one considers panic and panic spread among disaster victims, two factors that markedly affect temporary resettlement decisions are the NIP, and the speed at which temporary shelters are erected at resettlement sites. The number of temporary shelters that can be erected at time \( t \) is denoted by \( z_{t,s}^{INC} \). The number of erected temporary shelters directly determines the resettlement capacity, which is denoted by \( z_{t,s} \). The initial resettlement capacity at site \( s \) is denoted by \( P_{0,s} \).

Thus, to assess the efficacy of evacuation and resettlement solutions, the following costs are considered. Panic-induced psychological penalty perceived by victims when waiting for evacuation is determined by panic degree \( (x_t) \) and number of infective people \( (x_{t,s}^I) \). From the perspective of governments, three costs are considered: transportation cost; cost of building shelters; and psychological intervention cost. The cost of transporting disaster victims from disaster sites \( (s) \) to resettlement sites \( (D) \) is determined by the number of transported victims \( x_{t,s,d}^I \) and unit transportation cost \( (C_{t,d}) \). The unit cost of preparing a new shelter is denoted by \( C_{INC} \). Notably, \( C_{INC} \) is a function of time and sensitive to time. To minimize panic of victims and maintain stability in disaster areas, local governments typically dispatch mental health workers to these areas.

These psychological relief actions have allocation and training costs and emergency-related worker pay. The entire cost of one mental health worker serving for one time step at time \( t \) is denoted as \( C_t \).

### 4. Formulation

Three sets, a set of disaster sites, a set of resettlement sites, and a set of time steps, are involved, which are denoted by \( S, D \) and \( T \), and indexed by \( s, d \) and \( t \), respectively. Two groups of known data for disaster site \( s \) at the initial time step are the initial number of infective people that should be evacuated to resettlement sites, \( P_{0,s} \), and the initial number of susceptible people, \( P^s_{0,s} \). The unit cost of building a shelter at time \( t \) is \( C_{INC} \). Transportation cost for one person from a disaster site \( s \) to a resettlement site \( d \) is \( C_{t,d} \cdot P^E \), where \( C_{t,d} \) is the distance from \( s \) to \( d \), and \( P^E \) is the cost for a unit of distance (km). Additionally, the cost of a mental health worker serving for a step at time \( t \) is \( C_t \), and the strength of panic spread at time \( t \) is denoted by \( \sigma \).

Eight groups of decision variables are introduced as follows. First, the number of people who are evacuated from disaster site \( s \) to resettlement site \( d \) at time \( t \) is \( x_{t,s,d}^E \). Based on \( x_{t,s,d}^E \) define \( x_{t,s,d} = \sum_d x_{t,s,d} \) and \( x_{t,d} = \sum_s x_{t,s,d} \). Second, the number of people who are waiting to be evacuated from disaster site \( s \) to any resettlement site in \( D \) at time \( t \), namely, the number of infective people, is \( x_{t,s}^I \). Third, the number of people who should not be evacuated from disaster site \( s \) at time \( t \), namely, the number of susceptible people, is \( x_{t,s}^s \). The people at disaster sites are classified into two exclusive groups (infective people and susceptible people). Fourth, the number of people added to the group of infective people \( (x_{t,s}^I) \) from the group of susceptible people \( (x_{t,s}^s) \) at disaster site \( s \) because of panic spread, namely the NIP, is \( x_{t,s}^{INC} \). Fifth, the total number of people who have been evacuated to resettlement site \( d \) at time \( t \) is \( y_{t,d} \). Sixth, the number of mental health workers at time \( t \) is \( e_{ts} \). Each worker can treat \( \sigma \) victims during a time step. Seventh, the new capacity of resettlement site \( d \) at time \( t \) is \( z_{t,d}^{INC} \). Finally, the total capacity of resettlement site \( d \) at time \( t \) is \( z_{t,d} \). The limits of \( e_{ts} \) and \( z_{t,d}^{INC} \) are denoted by \( P_{t,s} \) and \( P_{t,d}^{INC} \), respectively.

Based on these definitions of sets and decision variables, the cost and penalty functions are formulated as follows.

Panic-induced psychological penalty is denoted as \( f_{psych} \), which is affected by panic degree \( (x_t) \), number of infective people \( (x_{t,s}^I + x_{t,s}^{INC}) \) and psychological intervention effects \( (\sigma \cdot e_{ts}) \). Thus, \( f_{psych} \) is then derived by Eq. (4).

Three monetary costs for an evacuation and resettlement solution are transportation cost \( (f_{trans}) \), psychological intervention cost \( (f_{iah}) \), and construction cost for building shelters \( (f_{build}) \). Notably, \( f_{trans} \) is the sum of people evacuated to resettlement sites in time step \( (x_{t,s,d}^E) \), with a transportation distance \( (C_{t,d}) \) and unit transportation cost \( (P^E) \), as computed by Eq. (5); \( f_{build} \) is the sum of the unit cost of increasing settlement capacity \( (C_{t,d}^{INC}) \), and the number of people who are resettled at
each time step \( (\Delta t^N_s) \), as defined in Eq. (6), and \( \psi_{\text{Psych}} \) is a function of the cost of psychological treatment by a specialized mental health worker at time step \( (C^T_t) \), and the number of mental health workers \( (e_{t,s}) \), as defined in Eq. (7).

\[
\begin{align*}
\psi_{\text{Psych}} &= \sum_t \psi_{\text{Psych}}^t, \quad \text{where} \quad \psi_{\text{Psych}}^t = \alpha_t \sum_s (x^t_s + x^{\text{NIP}}_t - \sigma \cdot e_{t,s}) \\
\psi_{\text{Trans}} &= \sum_t \psi_{\text{Trans}}^t, \quad \text{where} \quad \psi_{\text{Trans}}^t = \sum_{s,d} x^R_{t,s,d} C_{s,d} \psi_{\text{INC}} \\
\psi_{\text{Build}} &= \sum_t \psi_{\text{Build}}^t, \quad \text{where} \quad \psi_{\text{Build}}^t = \sum_d z^{\text{INC}}_{t,d} C_{t,d} \\
\psi_{\text{Gmt}} &= \sum_t \psi_{\text{Gmt}}^t, \quad \text{where} \quad \psi_{\text{Gmt}}^t = \sum_s c_s \epsilon_{t,s}
\end{align*}
\]  

(4)

The first group of constraints characterizes the conditions at the initial and end time steps. At the initial time step, the number of infective people \( (x^0_s) \) and the number of people who are evacuated from disaster areas to resettlement sites \( (y^0_s) \) equal the initial number of homeless disaster victims \( (P_{0,s}) \), as defined by Eq. (8). Second, the number of people who should remain at the disaster site \( (x^0_t + x^{\text{NIP}}_t) \) equals the number of susceptible people at the initial time step \( (P_{0,s}) \), as defined by Eq. (9). Third, the number of people who are evacuated to resettlement site \( d \) at time \( t = 0 \), as is defined by Eq. (10). Fourth, Eq. (11) sets the initial capacity of resettlement site \( d \) to \( P^A_{0,d} \). The pre-establishment of an adequate capacity and amount of resources enables efficient response to a disaster (Salmeron and Apte, 2009). At the last time step \( t = |T| \), all homeless victims should be evacuated to resettlement sites, meaning that \( x^f_s \) and \( x^{\text{NIP}}_s \) are both 0, namely, \( x^f_s + x^{\text{NIP}}_s = 0 \) for all \( t = |T| \) and \( s \). Further, by Eq. (1), when \( x^f_s \) is 0, \( x^{\text{NIP}}_s \) is 0. Therefore, as in Eq. (12), the number of infective people at the last time step \( t = |N| \) for each disaster site \( s \) must be 0.

\[
\begin{align*}
x^f_s + x^{\text{NIP}}_s &= P^A_{0,s}, \quad \forall s \\
y^0_s &= 0, \quad \forall d \\
z^0_{t,d} &= P^A_{0,d}, \quad \forall d \\
x^{\text{NIP}}_s &= 0, \quad \forall s
\end{align*}
\]  

(8)

(9)

(10)

(11)

(12)

The second group of constraints comprises flow constraints. First, Eqs. (13) and (14) formulate the dynamic transfer process from any time step to the next time step for infective people \( (x^t_s) \) and susceptible people \( (x^t_s) \). Second, the evacuated and resettled people at time \( t \) at resettlement site \( d \) \( (y_{t,d}) \) increases as the number of victims evacuated to the resettlement site \( (x^f_{t,d}) \) increases, as shown in Eq. (15). Similarly, resettlement capacity is increased by \( z^{\text{INC}}_{t,d} \) at time \( t \) at resettlement site \( d \), as shown in Eq. (16).

\[
\begin{align*}
x^f_{t,s} &= x^s_s - x^{\text{NIP}}_{t,s}, \quad \forall t, s \\
x^f_{t,s} &= x^s_s + x^{\text{NIP}}_{t,s} - x^t_s, \quad \forall t, s \\
y_{t+1,d} &= y_{t,d} + x^f_{t,d}, \quad \forall t, d \\
z_{t+1,d} &= z_{t,d} + z^{\text{INC}}_{t,d}, \quad \forall t, d
\end{align*}
\]  

(13)

(14)

(15)

(16)

The third group of constraints defines \( x^f_s \) (Eq. (17)) and \( x^f_s \) (Eq. (18)), and limits the number of the resettled people to the resettlement capacity (Eq. (19)). Furthermore, as a complementary constraint for Eqs. (2) and (20) restricts the number of people served by mental health workers to the number of disaster-affected people.

\[
\begin{align*}
x^f_s &= \sum_d x^f_{t,d}, \quad \forall t, s \\
x^f_s &= \sum_d x^f_{t,d}, \quad \forall t, d \\
y_{t,d} &\leq z^{A}_{t,d}, \quad \forall t, d \\
\sigma \cdot e_{t,s} &\leq x^f_s + x^{\text{NIP}}_{t,s} + x^S_{t,s}, \quad \forall t, s
\end{align*}
\]  

(17)

(18)

(19)

(20)
The fourth group of constraints handles the boundaries and integrities of decision variables. By Eqs. (21) and (22), the boundaries of the shelter supply and the supply of mental health workers are set. Additionally, by Eq. (23), the upper boundaries of the capacity of temporary resettlement sites are constrained. Capacity should exceed the number of disaster victims. Eq. (24) indicates that homeless victims must be evacuated and resettled. All variables are non-negative numbers, as denoted by Eq. (25).

\[
\sum_d z_{t,d}^{INC} \leq p_t^{DU}, \quad \forall t \tag{21}
\]

\[
\sum_s e_{t,s} \leq p_t^{DU}, \quad \forall t \tag{22}
\]

\[
\sum_d z_{t,d}^A \leq \sum_s (p_{0,s}^t + p_{0,s}^S) \tag{23}
\]

\[
\sum_s p_{0,s}^t \leq \sum_d y_{t,d}^A \tag{24}
\]

\[
x_{t,s,d}^{INC}, x_{t,s}^{INC}, x_{t,s}^A, y_{t,d}^A, e_{t,s}, g_{t,s} \geq 0, \quad \forall t, s, d \tag{25}
\]

Based on the above definitions, a multi-objective programming model [M1] is constructed.

[M1] Minimize \[ f = (\{f^{\text{Psych}}, f^{\text{Trans}}, f^{\text{GInt}}, f^{\text{Build}}\}) \]

Where Eqs. (4)–(7)

s.t.

Constraints ((1)–(3),) (8)–(25)

Thus, [M1] is transformed into a single objective model by defining \( \hat{f} = \sum_i (W^i \cdot f^i) \), where the weight vector \( W^i (i \in \{\text{Psych, GInt, Trans, Build}\}) \) represents the significances of the four costs. Notably, \( \min(f^i) \) and \( \max(f^i) \) denote the minimum and maximum of \( f^i \) respectively, as shown in Eqs. (26) and (27). Then, the four costs are summed as \( f \) by Eq. (28).

\[
\min(f^i) = \min_{[M1]}(\hat{f}) = \min_{[M1]} \left( \sum_i W^i f^i \right), \sum_i W^i = 1, W^i = 0, \quad \forall^*, i \neq * \tag{26}
\]

\[
\max(f^i) = \max_{[M1]}(\hat{f}) = \max_{[M1]} \left( \sum_i W^i f^i \right), W^i = 1, W^i = 0, \quad \forall^*, i \neq * \tag{27}
\]

\[
f = \sum_i \left( W^i \cdot \frac{f^i - \min(f^i)}{\max(f^i) - \min(f^i)} \right) \tag{28}
\]

Therefore, a new model [M2] is devised as follows.

[M2] Minimize \( f \)

Where Eqs. (4)–(7), (28)

s.t.

Eqs. (1)–(3), (8)–(25).

When monetary cost and psychological penalty cost are compared, the four costs, \( f^{\text{Psych}}, f^{\text{Trans}}, f^{\text{GInt}}, \) and \( f^{\text{Build}} \), in [M2] should be combined into two costs, \( f^P \) and \( f^C \). Set \( f^P = f^{\text{Psych}} \) and \( f^C = f^{\text{Trans}} + f^{\text{GInt}} + f^{\text{Build}} \); and then set \( f = W^P f^P + W^C f^C \). Similarly, \( \min(f^P) \), \( \min(f^C) \), \( \max(f^P) \), and \( \max(f^C) \) are derived by Eqs. (26) and (27). Then, [M3] is defined below.

[M3] Minimize \( f = W^P f^P + f^C \) \( \frac{f^P - \min(f^P)}{\max(f^P) - \min(f^P)} \) \( + W^C \) \( \frac{f^C - \min(f^C)}{\max(f^C) - \min(f^C)} \)

where \( f^P = f^{\text{Psych}} \)

\( f^C = f^{\text{Trans}} + f^{\text{GInt}} + f^{\text{Build}} \)

Eqs. (4)–(7)

s.t.

Eqs. (1)–(3), (8)–(25)
5. Estimation of input data

The earthquake that hit Sichuan, China, on May 12, 2008, caused numerous casualties and considerable property losses; that is, the earthquake killed 69,226 people, injured 374,643, left 17,923 people missing, damaged 23,143,000 houses, and topped 6,525,000 more (Lian, 2009). After the earthquake, about 12,348,400 people had been relocated. More than 1,500,000 tents or tarpaulin rooms were dispatched to the disaster sites.

The earthquake’s epicenter was in Wenchuan County, which has a population of 111,788, of which 23,871 (21.4%) were killed (Lian, 2009). The earthquake also brought psychological harm to residents. According to estimates by the Psychology Institute of Chinese Academy of Science, more than 500,000 people suffered psychological problems. Within five days after this earthquake, 52,419 people in Wenchuan County were evacuated to temporary resettlement sites. After that, many victims were evacuated and resettled. The number of tents or tarpaulin rooms was not revealed in news reports on Wenchuan County; neighboring Guangdong Province had built 20,000 movable houses within roughly one month after the disaster (Kong, 2008). Because approximately 56% rural peasants would return to repair or rebuild their houses after staying at temporary shelters for a couple of weeks, we estimate that about 90,000 \( \frac{20,000}{\binom{1}{0.056}} \) victims, where a house can accommodate on average two victims, were evacuated to temporary resettlement sites after the earthquake. The number of evacuated people exceeds the number of damaged houses. Panic and panic spread may account for this difference between number of damaged houses and number of evacuated people (Lian, 2009).

(1) Estimate the number of initial infective people \( P_{0,s} \) and susceptible people \( P_{0,S} \).

The 13 villages and towns in Wenchuan County were disaster sites (with instant and emergency resettlement sites). Based on the populations and geographic locations of these sites (Fig. 3), two temporary resettlement sites were established in Weizhou and Yingxiu. According to data published by Wenchuan government (http://www.wenchuan.gov.cn), the total number of people before the earthquake and the number of people killed by disaster at each village were summarized by statistical data. The total population at village after the disaster is denoted by \( P_s \). Then, by using the data from Lian (2009), the ratio of damaged houses in village to the houses before the disaster is estimated, and denoted by. When reported data about the damage ratio differ, the average value is used as the estimation. The values of \( P_{0,s} \) and \( P_{0,S} \) can thus be estimated by \( P_{0,s} = \mu_s P_s \), and \( P_{0,S} = P_s - \mu_s P_s \). Table 1 presents the statistical and estimated results (see Fig. 3).

(2) Estimate transportation cost \( C_{T,s,d} \).

The distance between a disaster site \( s \) and a resettlement site \( d(C_{T,s,d}) \) is estimated using the Geographic Information System (GIS) (Table 2). The unit transportation cost for one person for a kilometer \( (P_{TC}) \) is set to 2 Yuan.

(3) Efficiency of a mental health worker \( r \).

One psychological intervention group with one to three workers can serve for about 70 victims per day (Wo, 2008). This study presumes that one mental health worker can serve roughly 30 victims per day, \( r = 30 \).

![Fig. 3. The initial number of infective people and susceptible people at each disaster site.](https://example.com/fig3.png)
Due to urgent demands for mental health workers and temporary shelters, and the marginally increasing degree of panic perceived by victims while waiting for evacuation and resettlement, three parameters \( (C_{Pt}, C_{INC}, a_t) \) are defined as functions of wait times. Reducing the time needed to dispatch mental health workers increases dispatching cost, subsidies, and training costs. The total cost of these types of costs for each worker is represented by \( C_{Pt} \) at time \( t \). Here, \( C_{Pt} \) is a linear decreasing function of time, and the highest cost is set to 4800 Yuan, as in Eq. (29), where \( e_P(t) \) is a monotone increasing function of time \( t \). Similarly, \( C_{INC} \) (the cost of increasing a unit of settlement capacity at time \( t \)) decreases as a function of time, as in Eq. (30), where \( e_{INC}(t) \) is also a monotone increasing function of time \( t \). The space in a temporary resettlement shelter for each victim is set to five square meters; thus, resettlement cost per person is set to about 1600 Yuan and the reference cost at safe times is set to 800 Yuan, as shown in Eq. (30). Notably, for transition and permanent resettlement, the space allocated for each victim is larger than five square meters. The panic degree \( a_t \) increases with wait times, and the initial and maximum degrees of panic are set to 0 and 1, respectively, as in Eq. (31), where \( e_a(t) \) is a monotone increasing function of time \( t \).

\[
C_{Pt} = \max\{4800 - 400 \cdot e_P(t), 0\} \tag{29}
\]

\[
C_{INC} = \max\{1600 - 100 \cdot e_{INC}(t), 800\} \tag{30}
\]

\[
a_t = \min\{0.01 \cdot e_a(t), 1\} \tag{31}
\]
To decide $e^p(t)$, $e^{INC}(t)$ and $e^c(t)$, three governmental officials, three scholars, and three disaster victims, which are all affected by the Sichuan earthquake, are interviewed. Three base forms, $t$, $t^2$, and $e$ are used and their figures with descriptions are shown to the interviewees. Empirical results indicate that the answers are consistent and the analytical results are used to set the parameters: $e^c$ is extreme and too severe; the variances of $C^T_i$ and $C^{INC}_i$ can be described by linear relations (e.g., $t$), whereas $e^p(t)$ is more complex than both; and the forms based on $t^2$ are used to describe the effects of panic on evacuation and resettlement solutions.

A second interview was then conducted by using a curve figure (Fig. 4) in the questionnaire forms to determine $e^p(t)$. No distinct consistent answer was achieved for the question of choosing a property curve for $e^p(t)$. The interviewees thought the function values depended on many conditions. However, they believed that the degree affected by panic due to wait times was severe and generally managed well by the communities and local governments. Therefore, very serious situations due to panic were rare.

According to interviews and investigation results for the disaster areas, reference data for $x_t$, $C^P_t$ and $C^{INC}_t$ (Table 3) are basically linearly related to passed time.

(5) Time-varying capacities for resettlement and mental health workers

Temporary resettlement capacities vary with time ($P_{Pu}^u$) and are estimated by news reports (Lian, 2009). The values are determined by stocks of reserved disaster relief resources, and the capabilities of contracted manufacturers and suppliers.

Within several weeks after a disaster, many mental health workers ($P_{Pu}^u$) dispatched are not specialized, coming from general hospitals, nearby schools and universities, and governmental and non-governmental organizations (NGOs). These people are generally trained and can reach the disaster sites. However, because of the urgency and traveling costs, the number of people is limited. Some reference data are set for $P_{Pu}^u$ and $P_{Pu}^e$ (Table 3).

(6) Strength of panic spread

As defined in Eq. (3), panic spread strength ($\beta_{1s}$) is a function of panic degree ($x_t$) and governmental intervention degree ($g_{ts}$). Generally, $\beta_{1s}$ is positively related to $g_{ts}$, and negatively related to $g_{ts}$. Three typical forms of $\beta_{1s}(x_t,g_{ts})$ for a given $s$ are given in Eqs. (32)–(34).

\[
\beta_{1s} = \beta_{1s}(x_t,g_{ts}) = x_t \cdot (1 - g_{ts}), \quad \forall t \tag{32}
\]

\[
\beta_{1s} = \beta_{1s}(x_t,g_{ts}) = x_t / (1 + g_{ts}), \quad \forall t \tag{33}
\]

\[
\beta_{1s} = \beta_{1s}(x_t,g_{ts}) = x_t / g_{ts}, \quad \forall t \tag{34}
\]

Notably, $g_{ts} = 0.05 t$ is used as the typical function representing governmental psychological intervention degrees that vary over time (Fig. 5). However, set $x_t = t$ (Fig. 5 (a)), and set $x_t = t^2$ (Fig. 5 (b)). Notably, $x_t \cdot (1 - g_{ts})$ and $x_t / (1 + g_{ts})$ almost overlap, except for the first point ($t = 1$) (Fig. 5 (a)). The differences between these two functions shown in Fig. 5 (b) are more apparent than those in Fig. 5 (a) in their slopes. The curves of $x_t / g_{ts}$ in Fig. 5 (a) are not representative. When interviewers are invited to select representative functions, $x_t \cdot (1 - g_{ts})$ is comparably better than others when $x_t = t$ and $x_t = t^2$.

(7) Initial capacities of resettlement sites

By default, $P_{Pu}^u$ is set to 0.

By these seven groups of estimates and analyses, the data of $\Theta$ in $P$ (Eq. (35)) are determined. For ease of reference, $P_0$ represents the default settings for the parameters (Eq. (36)).

\[
P = \{ \Theta \} = \{ P_{0,\Theta} \} = \{ (x_t, P_{Pu}, P_{Pu}^u, P_{Pu}^e, C^P_t, C^{INC}_t, P_{0,\Theta}^A, C^A_t, C^{INC}_t, \sigma) \}
\]

Table 3

| $t$ | $x_t$ | $C^P_t$ | $C^{INC}_t$ | $P_{Pu}^u$ | $P_{Pu}^e$ |
|-----|-------|---------|-------------|-----------|-----------|
| 1   | 0.01  | 4400    | 1500        | 1000      | 50        |
| 2   | 0.02  | 4000    | 1400        | 1500      | 150       |
| 3   | 0.03  | 3600    | 1300        | 2300      | 250       |
| 4   | 0.04  | 3200    | 1200        | 3500      | 350       |
| 5   | 0.05  | 2800    | 1100        | 4500      | 450       |
| 6   | 0.06  | 2400    | 1000        | 6000      | 550       |
| 7   | 0.07  | 2000    | 900         | 7200      | 650       |
| 8   | 0.08  | 1600    | 800         | 9000      | 750       |
| 9   | 0.09  | 1200    | 800         | 12000     | 850       |
| 10  | 0.10  | 800     | 800         | 15000     | 950       |

Note: $x_t$, $C^P_t$, $C^{INC}_t$ are determined by setting $e^p(t) = e^{INC}(t) = e^c(t) = t$. 

\[
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\]
6. Numerical results

This section presents numerical studies, demonstrating the efficacy of the models whose primary known data are given in Section 5. Lingo (www.lindo.com) software was used to solve [M2] and [M3]. The purpose of the numerical experiments is to demonstrate application of the proposed methods for evacuation and temporary resettlement of people in Wenchuan County after the 2008 Sichuan Earthquake. Table 4 summarizes the six experimental scenarios, corresponding purposes, and experimental steps. Via these experiments, the proposed models are demonstrated; the effects of parameters on solutions and their sensitivities are analyzed; the consistencies of or conflicts between various costs are quantitatively studied. The analytical results can be used for decision-makings for post-disaster evacuation and temporary resettlement. Performance of [M2] or [M3] is examined in each scenario.

Table 4
Experiment settings.

| No. | Purposes | Experimental steps |
|-----|----------|---------------------|
| (1) | Demonstrate the effects on \( f_{Psych} \), \( f_{GInt} \), \( f_{Trans} \), \( f_{Build} \), and \( f_C \), when these objectives are minimized | (1) Use \( P_0 \) as the base setting of parameters; (2) Set each weight in \( W \) to 0.1 in turn to get the solutions by solving [M2] when \( f_{Psych} \), \( f_{GInt} \), \( f_{Trans} \), and \( f_{Build} \) are only considered, and solving [M3] when \( f_C \) and \( f_C \) are only considered; (3) The final solutions and time-varying values for the objectives are compared (Fig. 6) |
| (2) | Demonstrate the effects on \( f_{Psych} \), \( f_{GInt} \), \( f_{Trans} \), and \( f_{Build} \), and the effects on \( f_C \) and \( f_C \) when they have equal weights | (1) Use \( P_0 \) as the base setting of parameters; (2) Set the weights in \( W \) to 0.25 to get solutions by solving [M2]; (3) Set the weights in \( W \) to 0.5 to get solutions by solving [M3]; (4) Compare the solution results for [M2] and [M3] (Fig. 7) |
| (3) | Test the sensitivities of the parameters in \( \Theta \), except for \( P_{0,d} \), \( P_{IC} \), and \( \sigma \) | (1) Use [M2] and use \( P_0 \) as the base settings of parameters; (2) For each parameter in \( \Theta \), except for \( P_{0,d} \), \( P_{IC} \), and \( \sigma \), adjust the values by \(-75\%, -50\%, \ldots, 0\%, +75\%\); (3) For each adjustment, solve [M2] (Table 6) |
| (4) | Analyze the precaution strategy by testing the effects of \( P_{0,d} \) on the solutions | (1) Use [M2] and use \( P_0 \) as the base settings of parameters; (2) Increase \( P_{0,d} \) by 50 for 100 times; (3) For each adjustment, solve [M2] (Fig. 8) |
| (5) | Analyze the tradeoffs for the psychological penalty cost and the monetary penalty cost (\( f_C \) and \( f_C \)) | (1) Use [M3] and use \( P_0 \) as the base settings of parameters; (2) Adjust weights \( (W^w = 0.001, \ldots, 1, 1 + W^r = 1 - W^s) \) to generate 101 test cases and solve each [M3]; (3) Draw and analyze the Pareto fronts between \( f_C \) and \( f_C \) (Fig. 9) |
| (6) | Analyze the effects of the strength of psychological penalty on the solutions by altering \( e(t) \) | (1) Use [M3] and use \( P_0 \) as the base settings of parameters; (2) Set \( e(t) \) to \( 0.02, 0.04, 0.06, 0.08 \) and sequentially in the following experiments; (3) Set \( W_0 = W^w = 0.5 \), and solve [M2]; (4) Compare the experimental results of the five functions of (Fig. 10) |
Based on the results (Tables 5 and 6; Figs. 7–10) for the six experiments (Table 4), experimental results are summarized as follows.

1. The [M2] and [M3] used in the experiments are solved. The solutions depend on the parameters settings in $P$, including weights ($W^{Psych}$, $W^{GInt}$, $W^{Trans}$ and $W^{Build}$ for [M2]; or $W^{P}$ and $W^{C}$ for [M3]). The parameters’ values may affect the values of $\min(f^*)$ and $\max(f^*)$. Therefore, in Experiments 3–6, $\min(f^*)$ and $\max(f^*)$ are computed repeatedly for solving [M2] and [M3] because their values will be changed when the parameters change. Table 5 presents values of $\min(f^*)$ and $\max(f^*)$ for the first and second experimental scenarios.

2. Experimental results by minimizing only $f^{Psych}$, $f^{GInt}$, $f^{Trans}$, $f^{Build}$ or $f^c$ (Fig. 6).

(1) By minimizing $f^{Psych}$, the evacuation and resettlement can be completed within the first 9 days. The psychological penalty cost reaches its lowest (0) after six days, and building cost remains high from day 1 to day 7. The psychological intervention cost also reaches the allowed maximum within the first 5 days. Minimization of psychological penalty cost increases the costs of building shelters and psychological intervention.

(2) The minimum of $f^{GInt}$ reaches 0 while psychological penalty cost increases gradually during the first 7 days. Minimization of psychological intervention delays building shelters and victim evacuation. Therefore, minimizing psychological intervention cost lowers psychological penalty costs and ignores the importance of evacuation and resettlement.

(3) Minimizing $f^{Trans}$ reduces the NIP and the number of infective people who attempt to evacuate. Therefore, the number of temporary shelters will also be minimized. Psychological penalty cost also reaches its minimum on the sixth day. Psychological intervention cost gradually increases during the first 6 days and then declines to 0 the following 4 days. However, the reduction in this value does not minimize building cost. Generally, the minimization of transportation cost is paid by the psychological intervention cost and building cost.
(1a) objectives of minimizing $f_{\text{Psych}}$

(1b) decisions of minimizing $f_{\text{Psych}}$

(2a) objectives of minimizing $f_{\text{GInt}}$

(2b) decisions of minimizing $f_{\text{GInt}}$

(3a) objectives of minimizing $f_{\text{Trans}}$

(3b) decisions of minimizing $f_{\text{Trans}}$

(4a) objectives of minimizing $f_{\text{Build}}$

(4b) decisions of minimizing $f_{\text{Build}}$

(5a) objectives of minimizing $f^C$

(5b) decisions of minimizing $f^C$

Fig. 6. Solutions of by minimizing only $f_{\text{Psych}}, f_{\text{GInt}}, f_{\text{Trans}}, f_{\text{Build}}$ and $f^C$ (No. 1).
The minimization of $f_{\text{build}}$ postpones building temporary shelters. Before construction of many temporary shelters, psychological penalty cost and psychological intervention cost increase gradually. This increase in monetary costs is also reflected by the increase to the NIP and number of mental health workers needed.

Minimizing psychological intervention cost has effect similar to those effects of minimizing $f_{\text{build}}$. Psychological penalty cost gradually increases over the first 7 days. As building cost increases, psychological penalty cost decreases because more victims can be evacuated to temporary shelters.

When weights of the costs returned by solving [M2] and [M3] are equal, the resulting solutions indicate that building costs have almost the same tendency during the first 10 days, whereas the other three costs (psychological penalty cost, psychological intervention cost, and transportation cost) are distributed differently (Fig. 7). When the four costs are equally weighted, psychological penalty cost is high while psychological intervention cost is minimized (Fig. 7(1a)). The curves of the four costs are explicitly distributed (Fig. 7(2a)). As indicated by the curves (Fig. 7(1b) and (2b)), many mental health workers are needed during the period from day 3 to day 9 in the results of solving [M3]. When the sum of monetary costs (psychological penalty cost, psychological intervention cost, and transportation cost) is a single objective, the significance of psychological intervention is reflected by the fact that many mental health workers are deployed. However, when the four costs are weighted equally, building cost remains high while psychological penalty cost is also high.

Table 6 presents sensitivity test results for eight groups of parameters ($P_{0,i}^S, P_{0,i}^G, \alpha, C_t^P, P^2_{\text{PU}}, C_{\text{INC}}^T$, and $C_t^d$).

Notably, $P_{0,i}^S$ markedly affects solutions, especially when the values are increased. Moreover, among the four costs, psychological intervention cost is affected most. When $P_{0,i}^S$ increases by 75%, psychological intervention cost increases by roughly 63 times. In addition to the psychological intervention cost, psychological penalty cost is affected considerably, especially when $P_{0,i}^S$ decreases.

Although $P_{0,i}^S$ affects all four costs, the percentages of all variances for costs, expect for psychological intervention cost, are less than 10%. Comparatively, the psychological intervention cost is affected by $P_{0,i}^S$ more than the other costs. When $P_{0,i}^S$ decreases by 75%, the psychological intervention cost will decrease by 81%.

Psychological penalty cost and psychological intervention cost are markedly affected by $\alpha$. The values of $\alpha$ also affect slightly the other two costs (transportation and shelter building costs). The values of $\alpha$ in this study are linearly related to time.

![Fig. 7](image-url) Minimizing $f_{\text{psy}}$, $f_{\text{int}}$, $f_{\text{trans}}$, $f_{\text{build}}$ and $f_t$, which are equally weighted (No. 2).
(4) Although psychological intervention cost is directly affected by $C_{\text{ZU}}^t$, it has no effect on other costs.

(5) Notably, $P_{\text{ZU}}^t$ affects psychological intervention cost most, followed by psychological penalty cost. Rationally, because the number of mental health workers is limited, sufficient workers in the early stages would be recruited when the recruit cost is high. When $P_{\text{ZU}}^t$ is increased markedly, the psychological intervention method will be used excessively, which can be seen with the large increase in psychological intervention cost, while its effects on other costs are minimal.

(6) Decreasing $P_{\text{ZU}}^t$ affects the four costs significantly, especially psychological intervention cost. By decreasing $t_i^{ZU}$, decision-makers will use the capacities as many as possible, such that capacities in the early days after a disaster with high building costs may be fully utilized. When $P_{\text{ZU}}^t$ is increased to the extent that resettlement sites can accommodate all disaster infective victims soon after the disaster, no worker is needed to treat the victims at the disaster sites.

(7) Although $C_{\text{INC}}^t$ directly affects building cost, it affects psychological intervention cost more, and affects psychological penalty cost consistently. The effect of $C_{\text{INC}}^t$ on transportation cost is minor.

(8) Transportation cost is markedly affected by $C_{\text{INC}}^t$ and also slightly affects psychological intervention cost; however, it does not affect the psychological penalty cost and building cost.

(4) Fig. 8 shows the effects of varying the initial stock of shelters at resettlement sites ($P_{\text{ZU}}^t$) on the four costs. Notably, this study does not consider the cost for reserving the initial stock of shelters. With the increase in stock, the building cost decreases linearly; psychological intervention cost drops to almost 0 when the stock increases to 500 at each resettlement site; psychological penalty cost drops rapidly when stock reaches 1000 and then declines slowly; the varying curve of transportation cost reaches the minimum and then increases very slowly.

(5) By solving the [M3] with different weights for psychological penalty and monetary costs, 101 pairs of the two costs are obtained. Fig. 9 shows the distribution of solutions and their Pareto font. A decrease of 80% to psychological penalty cost can be achieved by increasing monetary cost by 37.5%.

(6) Fig. 10 shows the effects of different psychological penalty costs associated with wait times on the solutions. Here, a linear function ($t$) and four functions with different coefficients (1/4, 1/2, 3/4 and 1) for squared wait times ($t^2$) are considered and computational results for the four costs are compared. Psychological intervention cost, transportation cost, and building cost increase almost linearly when $e^2(t)$ is formulated as $t$, $t^2/4$, $t^2/2$, $3t^2/4$ and $t^2$. However, the increase in psychological intervention cost is fastest. Psychological penalty cost increases nonlinearly when $e^2(t)$ is sequentially formulated as $t$, $t^2/4$, $t^2/2$, $3t^2/4$ and $t^2$. When $e^2(t)$ is formulated as $3t^2/4$ and $t^2$, the cost increases rapidly.

The discussion of experimental results is generalized as follows.

(1) The costs of psychological penalty, psychological intervention, and transportation and building shelters may be correlated or conflict. First, minimizing psychological penalty cost is consistent the increased costs for building shelters and psychological intervention. Second, when psychological intervention is excessively emphasized, the evacuation and resettlement process is delayed. Third, although transportation cost is minor when compared to total monetary cost, it is representative of the number of victims affected by panic spread because it is computed based on the number of evacuated victims. Fourth, building cost conflicts with psychological intervention cost and psychological penalty cost. Further, psychological intervention cost and psychological penalty cost also conflict. Fifth, minimization of transportation cost indicates that the number of victims influenced by panic spread is reduced, which in turn increases psychological intervention cost. Finally, when psychological penalty cost and the entire monetary cost are considered separately, psychological intervention cost can be used to balance psychological penalty and psychological intervention costs.

![Fig. 8](image-url) Objectives varying with increases in initial resettlement capacity (No. 4).
(2) Of all eight groups of parameters, $P_{1.0}$ affects solutions most. All costs are related to the number of infective people and the increase in number of infective people. When the value of $P_{1.0}$ is increased and resources are limited, the costs of psychological intervention and psychological penalty will increase markedly. The initial number of infective people and susceptible people affect the four costs greatly. Therefore, these numbers should be reduced as much as possible. Although the number of infective people cannot be reduced, some susceptible people can be persuaded to take part in the rescue processes. Therefore, mental health workers can focus on infective people. The psychological pressure due to wait times ($\alpha$) imposes great effects on costs related to victim psychology.

(3) Psychological intervention may be overused when the number of available mental health workers is adequate. This overuse does not reduce psychological penalty cost significantly, and it also does not affect building and transportation costs significantly.

(4) Expanding the limits of resources (e.g., mental health workers, reserved resettlement resources and replenishment capability for resettlements) can affect psychological intervention cost and psychological penalty cost considerably. And the expansion itself may have a high cost because the probability of disaster occurrences is in fact low. Therefore, the increase in replenishment capability is practical for critical relief resources.

(5) Although the unit cost of building a shelter affects building cost directly, it affects psychological intervention cost more, and also affects psychological penalty cost. Therefore, controlling unit building cost for temporary shelters contributes markedly to cost reductions related to victim psychology. Increasing the supply of shelters by emergency supply chain management and logistics is important to post-disaster psychological relief.

(6) In comparing to psychological intervention cost and building cost, the ratio of transportation cost to the overall monetary cost is small. Although the ratios affect solutions, they can be neglected. However, when disasters such as earthquakes and landslides occur, road damage may increase transportation costs and evacuation difficulties.

(7) Psychological intervention cost is the cost affected most by the initial resettlement capacity because infective people can be accommodated quickly after a disaster. Then, the psychological penalty cost and building cost can be markedly reduced. Therefore, improving the stock of temporary shelters or providing alternatives can reduce psychological and monetary costs significantly.

(8) By the Pareto analytical tool, the tradeoffs between psychological penalty cost and monetary cost can be examined. In the experiments, a small increase to monetary cost (37.5%) can cause psychological penalty cost to decrease significantly (80%). Therefore, when the budget allows, psychological penalty perceived by victims can be minimized. By extending the proposed methods, the tradeoffs among four costs are revealed.
(9) The magnitude of psychological penalty cost induced by wait times directly affects total psychological penalty cost. However, this magnitude cannot be determined directly according to disaster type or other simple quantification methods. It is affected by the extent of damage, disaster severity, and post-disaster natural and social environments. Therefore, minimizing the strength of panic and panic spread is important for evacuation and resettlement, and the recovery of disaster areas. Psychological intervention and timely rescue are general ways to reduce the strength of panic and panic spread.

7. Conclusions

This study addressed the post-disaster evacuation and temporary resettlement problem for victims affected by psychological penalty induced by panic and panic spread. Psychological penalty due to panic is strengthened by wait times. Victim panic and panic spread among victims may increase the number of people to be evacuated to temporary resettlement sites. This problem is formulated with following features. First, the considered period of evacuation and temporary resettlement is divided into time steps. Second, panic degree is quantified as a function of wait time, and degree of governmental psychological intervention is determined by the number of dispatched mental health workers, infective people and susceptible people. Third, based on the SIR model of infectious disease spread, the increase in the number of people who are panicked and need to be evacuated to temporary resettlement sites in each time step is quantified. Then, a multi-objective optimization model for evacuation and temporary resettlement was developed with the objectives of minimizing panic-induced psychological penalty, psychological intervention cost, transportation cost, and shelter building cost during evacuation and temporary resettlement. The model is solved by aggregating the objectives into a single objective by weights. The allocation of mental health workers to disaster sites, the shelter building and evacuation solutions are researched by solving the model and considering parameter sensitivities and tradeoffs among the four costs.

The following experimental results are obtained. The costs of psychological penalty, psychological intervention, and transportation and building shelters may be affected by the number of victims that evolve from susceptible people to infective people, the number of dispatched mental health workers, timely evacuation, and building shelters. These factors also influence each other. Indeed, among all parameters and factors, the initial number of homeless infective people imposes great effects on costs and solutions. Psychological intervention apparently prevents the evolution of susceptible people to infective people. However, overuse of psychological intervention yields a big increase in monetary costs and a minor decrease in psychological penalty cost. Therefore, timely and efficient evacuation and resettlement are very important. Generally, psychological penalty cost and monetary costs conflict, and can be analyzed by the Pareto analytical tool. Experimentally, a small increase to monetary cost (37.5%) can cause psychological penalty cost to decrease markedly (80%). This study used various functions to represent the strength of psychological penalty cost affected by wait times. The functions should be based on various conditions, such as extent of damage, disaster severity, and post-disaster natural and social environments. Psychological intervention and timely rescue are general ways to reducing the strength of panic and panic spread.

Due to a lack of quantitative research on panic and panic spread during post-disaster relief and recovery, this study proposed a framework that considers the effects of panic and panic spread on post-disaster evacuation and temporary resettlement. Therefore, quantification methods could be further researched and incorporate the new developments with practical evidence and theoretical research results in disaster psychology. Next, this study formulated evacuation and temporary resettlement as a multi-step optimization model, where parameter uncertainties and conditions are assessed by sensitivity analysis. Bell et al. (2014) asserted that the post-disaster transportation network may degrade due to disasters. In post-disaster scenarios, due to secondary disasters and disruptions, robust solutions for evacuation and resettlement should be researched. The evacuation routing problem is complex when one considers the roads adversely affected by disaster. Third, this study focused on the temporary resettlement period and does not consider dependencies on other stages. Moreover, pre-determined resettlement sites may affect the evacuation and resettlement solutions (Rawls and Turnquist, 2010). Incorporating the analytical results of this study, the entire post-disaster relief and recovery processes deserve further research under the consideration of psychological penalty as perceived by victims and rescuers.

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### Appendix A. Notations

(1) Set

- \( S \): A set of 2^N disaster sites, denoted by \( S = \{1, 2, \ldots, |S|\} \) and indexed by \( s \).
- \( D \): A set of 2^N resettlement sites, denoted by \( D = \{1, 2, \ldots, |D|\} \) and indexed by \( d \).
- \( T \): A set of 2^N time steps, denoted by \( T = \{1, 2, \ldots, |T|\} \) and indexed by \( t \).

(2) Parameters

- \( P_{0,s} \): Number of homeless disaster victims who should be evacuated.
- \( P_{0,s} \): Number of susceptible people at the initial time step, namely, the disaster-affected people, excluding homeless victims.
- \( P_{0,d} \): Number of initial temporary resettlement capacity at resettlement site \( d \).
- \( C_{INC} \): Cost of increasing a unit of resettlement capacity at time \( t \).
- \( C_{INC} \): Distance (km) from a disaster site \( s \) to a resettlement site \( d \).
- \( C_p \): Cost of a mental health worker for psychological relief at time \( t \).
- \( \alpha_t \): Panic degree at time \( t \).
- \( P_{INC} \): Cost of transporting a person for a unit of distance (km).

(3) Decision variables

- \( x_{t,s}^f \): Number of susceptors at disaster site \( s \) at time \( t \).
- \( x_{t,s}^{INC} \): The NIP at disaster site \( s \) at time \( t \).
- \( x_{t,s}^f \): Number of susceptors at disaster site \( s \) at time \( t \).
- \( x_{t,s,d}^{INC} \): Number of people who are transported from disaster site \( s \) to resettlement site \( d \) at time \( t \).
- \( x_{t,s,d}^f \): The value is derived by \( x_{t,s,d}^f = \sum_d x_{t,s,d}^{INC} \).
- \( x_{t,s,d}^f \): The value is derived by \( x_{t,s,d}^{INC} = \sum_d x_{t,s,d}^f \).
- \( y_{t,d} \): Number of people who have been evacuated to resettlement site \( d \) at time \( t \).
- \( e_{t,s} \): Number of mental health workers dispatched to disaster site \( s \) at time \( t \).
- \( L_{INC} \): Cost of increasing a unit of settlement capacity at resettlement site \( d \) at time \( t \).
- \( Z_{t,d}^A \): Total resettlement capacity at resettlement site \( d \) at time \( t \).

(4) Other notations

- \( \beta_{t,s} \): Panic spread strength representing the speed of panic spread, which affects the NIP \( x_{t,s}^{INC} \) based on the number of infective people \( x_{t,s}^f \) and susceptible people \( x_{t,s}^s \) in the SIR model.
- \( \alpha_t \): Panic degree at time \( t \). Panic degree affects psychological penalty cost perceived by disaster victims.
- \( \gamma_t \): Degree of governmental intervention at disaster site \( s \) at time \( t \).
- \( \sigma_t \): Number of victims. Each mental health worker can counsel during one time step.
- \( \zeta(t) \): A function returning panic degree when waiting for \( t \) time steps for evacuation and resettlement.
- \( f_{Psych} \): Panic-induced psychological penalty cost at time \( t \).
- \( f_{Psych} \): Total psychological penalty cost, computed by \( f_{Psych} = \sum_t f_{Psych}^{t} \).
- \( f_{Trans} \): Transportation cost at time \( t \).
- \( f_{Trans} \): Total transportation cost, computed by \( f_{Trans} = \sum_t f_{Trans}^{t} \).
- \( f_{Int} \): Psychological intervention cost at time \( t \).
- \( f_{Int} \): Total psychological intervention cost, computed by \( f_{Int} = \sum_t f_{Int}^{t} \).
- \( f_{Build} \): Shelter building cost at time \( t \).
- \( f_{Build} \): Total shelter building cost, computed by \( f_{Build} = \sum_t f_{Build}^{t} \).
- \( \zeta(t) \): A function returning the NIP with the infective people \( x_{t,s}^f \) and susceptible people \( x_{t,s}^{INC} \) as inputs.
- \( W^r \): Weight of an objective \( \in \{\text{Psych}, \text{Int}, \text{Trans}, \text{Build}\} \).
- \( f \): An alias for the psychological penalty cost \( f_{Psych} \).
- \( f \): Monetary cost \( f = f_{Psych} + f_{Trans} + f_{Build} \).
- \( e(t) \): Sum of the weighted cost of \( f^r \) and \( f \), or \( f_{Psych} f_{Int} f_{Trans} f_{Build} \).
- \( e(t) \): A function of time \( t \), which determines the cost of a mental health worker at time \( t \).
- \( e(t) \): A function of time \( t \), which determines the cost of increasing a unit of resettlement capacity at time \( t \).
- \( e(t) \): A function of wait time, which determines panic degree at time \( t \).

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