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Bi-objective evacuation problem in ships or buildings

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Abstract In this paper, we introduce an evacuation problem that involves several real-world evacuation elements, such as different types of evacuees and different types of exits, applicable to the evacuation of buildings or ships in emergency, e.g., fire. In particular, we exploit the multiple commodity flow in a time-expanded network to model the evacuation routes for different commodities. The commodities characterize the different types of evacuee groups which have different speeds during evacuation. We use the bi-objective programming to consider two different objectives of the evacuation planning from both time and space dimensions. Then we propose a method to solve this newly developed evacuation model. Based on a series of computational experiments and sensitivity analyses, we find that the evacuation speed of evacuees is a critical element to be considered when planning an evacuation on ships or buildings in emergency.

Keywords Evacuation problem · Bi-objective programming · Multi-commodity · Network flows

1 Introduction

Evacuation aims to find a set of emergency evacuation routes that leads the people inside some high-rise buildings or cruises away from a threat or actual occurrence of a hazard (e.g., fire, smoke, gas leakage, explosion and so on), in a short period of time (Tac et al., 2020). For example, in 2015 there was a private cruise operated by French line Ponant catching a fire suddenly during a trip to Antarctica and up to 264 passengers were evacuated (USA-TODAY, 2015). In 2016, a cruise ship caught fire in Puerto Rico, which forced 500 passengers, including different groups of people to evacuate in a short time (Associated-Press, 2016). This evacuation always arises at short notice or without notice, and it is highly necessary to schedule the routes as soon as possible so as to minimize the risk during evacuation (Xu and Hu, 2019). Furthermore, modern buildings as well as modern ships like cruises, passenger liners are usually high and have very complex layouts, which makes it difficult and challenging for the evacuation planner to establish a proper plan for evacuation in a short time (García-Ojeda et al., 2013; Wang et al., 2021).

A proper evacuation plan for buildings or ships should not only consider their layouts, but also take the types of evacuees and the means of evacuation into account. People staying in a building or a large cruise usually comprise different genders, ages and physical sizes. Some of them may need special attention (e.g., babies, pregnant women, or people with disabilities) during evacuation. Therefore, different types of people (evacuees' mix) may have different evacuation speeds, which leads to different evacuation times even in the same route. In general, an elderly person moves much slower than an adult, and it is expected that the elderly person needs more time to evacuate than an adult (Wong et al., 2017). In terms of the evacuation means, two types of exits are commonly found in a building or ship, namely the exits which lead the evacuees to leave the building or ship, and the exits to the refugee layers/building roof located inside the building or ship. Generally speaking, when evacuees are guided to the refugee layers/building roof, rescue facilities such as firefighter ladders, evacuation lifts or helicopters, would be used to assist the evacuees to leave the building or ship. The use of these facilities are subject to situation and resources availability. If evacuees are trapped in a refugee layer which cannot be reached by ladders nor evacuation lifts, the firefighters have to consider using helicopters to rescue them, particularly when the situation is critical. The case for the ships is also similar. These elements make their evacuation specific, comparing with other types of evacuations such as regional evacuation in transportation area, and hence make the corresponding planning be much more complicated.

The evacuation planners always care for the risk associated with the evacuation routes planned, which consist of two aspects: one is from the time-dimension, the other is from the space-dimension. In particular, the time dimension risk, as a well-known one that has been commonly concerned, mainly refer to the total time required for the people to evacuate safely. Any delay would cause unwanted injuries or deaths. For instance, when there is a fire, the fire and its smoke may spread quickly. Thus, it is critical to evacuate the people as quickly as possible. The space dimension risk is related to the exits of the evacuees after the evacuation, which affects the evacuation means used. According to the interview from Fire Service Department in Hong Kong, from the evacuation planners perspective, different types of exits correspond to different levels of risk. As mentioned, when there is a fire, the exits provided for the evacuees to leave the building or ship are much more safer than keeping the evacuees in the refugee layers or building roof, where further rescue facilities are required to aid them to leave the building or ship.

In this paper, we aim at studying a new evacuation problem that takes the above factors into account. In particular, we exploit the multiple commodity flow in a time-expanded network to model the evacuation routes for different commodities. The commodities characterize the different types of evacuees having different speeds of evacuation. A bi-objective programming is formulated with two conflicting objectives. The first one is to minimize the total evacuation time of evacuees; whereas the other one is to minimize the weighted sum of different types of exits which have different priorities or risk levels. The latter objective implies that an evacuation planner prefers moving evacuees out of the places in fire to guiding them to the refugee layers or ship desk, which is consistent with the practical requirement under the situation with limited evacuation resources. Moreover, we provide a method to solve this newly developed model for evacuation. This is followed by a series of numerical experiments and sensitivity analyses on different parameters so as to study the properness of this model as well as the efficiency and effectiveness of the solution algorithm. Our results have shown that the evacuee type as well as the evacuation speed, which have been firstly captured in the bi-objective planning model, have greatly affected the evacuation plan as well as the evacuation time.

The remainder of this paper is organized as follows. In Section 2, we review the relevant literature on evacuation. Section 3 presents the bi-objective model for the evacuation problem. In Section 4, we propose a solution algorithm for the proposed model. In Section 5, we report the results generated from the numerical experiments and sensitivity analysis on several important parameters. Finally, our conclusions and discussion on future research directions are presented in Section 6.

2 Literature review

Evacuation, which is a critical element in emergency response operations, has been widely researched over the past few decades. See Bayram (2016), Murray-Tuite and Wolshon (2013), and Tanka (2015) for a review of relevant works in the literature. There are mainly two types of models that are able to capture the movement of evacuees over time: microscopic evacuation and macroscopic evacuation (Hamacher and Tjandra, 2000). For the microscopic models, simulation-based methods are frequently used to simulate the behavior of the evacuees and their interactions that affect their movement. One may refer to Miah (2011) and Hoffmann et al. (2013) for detailed surveys of these models. In some of these simulation works, the speeds of people is considered as an important human characteristics (Pelechano and Badler, 2006; Poulos et al., 2018). Different from the microscopic evacuation, the macroscopic evacuation does not consider any individual behavior but aims at finding the evacuation routes such that the evacuees can escape from the threat as soon as possible. The evacuation problem proposed in this paper belongs to this type, and also takes the speeds of the evacuees into account.

Most of the literature on evacuation exploit network flow-based models, either in a static network, or in a time-expanded network that replicates the original evacuation network for each discrete time period (Hoppe and Tardos, 1994; Hamacher and Tjandra, 2000; Cova and Johnson, 2003; Liu et al., 2021). These models vary with different objective functions. In one of the earlier works conducted by Choi et al. (1988), they used the network flows with side constraints to model the building evacuation, and they provided the maximum flow, the minimum cost and the minimax objectives. Chen and Miller-Hooks (2008) considered an evacuation problem with a shared information constraint, where the objective is to minimize the total evacuation time of evacuees, given that the arc travel time and arc capacity vary over time. They developed an exact technique based on Benders decomposition to solve the problem. Opasanon and Miller-Hooks (2009) studied a safest escape problem which aims to minimize the evacuee's risk during evacuation. In particular, their problem attempts to maximize the minimum probability of arrival at an exit for any evacuee under a similar setting on arc travel time and capacity as that in Chen and Miller-Hooks (2008).

Recently, Lim et al. (2012) have used a time-expanded network flow model to find evacuation paths, flows, and schedules, with the objective function of maximizing the total number of evacuees. Tang et al. (2014) assumed that the travel time of the evacuees is uncertain and provided a chance constraint model to find an evacuation route in a building with the minimum expected evacuation time. Moreover, they proposed a new pseudo-polynomial-time dynamic programming algorithm to solve the problem. Osman and Ram (2013) introduced a two-phase evacuation route planning approach for the building evacuation problem to finding the routes, with the objective function of minimizing the maximum evacuation time for each individual object. Osman and Ram (2017) provided a centralized hybrid approach for the evacuation routing and scheduling problem, which minimizes the sum of the evacuation times of individual objects. In spite of this, none of these network flow models have explicitly considered the evacuation speed, which is one of the important factors affecting the total evacuation time.

The problem considered in our work can be seen as an evacuation problem with multiple sources and multiple destinations, see the reference in the review paper (Hamacher and Tjandra, 2000). It can be noted that the evacuees in the recent studies share the same network where each arc has a corresponding fixed travel time. This implies that the recent models and algorithms can not be directly applied to the case considered in our work where evacuees can have a different evacuation speed, which causes them having a different travel time even in the same arc. Moreover, there are few works considering the evacuation speed during evacuation. For example, Liu et al. (2016) assume that the speed of evacuees is not fixed among every arc in the evacuation network and depends on evacuation time and the path situations, like the smoke. Therefore, the travel time along the arc depends on the length of the arc and the speed in this arc. They proposed an iterative updating method to find an evacuation plan that minimizes the total evacuation time for all the evacuees. However, the evacuation speed in practice is highly relevant to the types of evacuees, which cannot be addressed by the model and method in Wong et al. (2017). Moreover, we consider the problem using multiple objective programming, different from their single objective setting.

Multiple objective programming, which is an effective methodology for coping with multiple conflicting objective functions, has been widely used in the evacuation problems (Hamacher and Tufekci, 1987; Saadatseresht et al., 2009; Aleksandrov et al., 2019). In particular, Hamacher and Tufekci (1987) proposed the lexicographic minimum cost flow to optimize the building evacuation problem in a time-expanded network with multiple objective functions. Saadatseresht et al. (2009) exploited the multi-objective evolutionary algorithms when planning an evacuation with two objective functions: one is to maximize the total number of evacuees saved, and the other one is to minimize the overload capacity in each area. Aleksandrov et al. (2019) studied the evacuation problem in a tall building with two objectives, namely the total evacuation time and the number of evacuees waiting on their floors to start the evacuation. Nonetheless, few studies have associated the exits with different weights and taken the space dimension risk into account as we do in this paper. As far as we know, this paper is the first in the literature of evacuation problems that simultaneously considers different types of evacuees and different types of exits, which can improve the level of the risk management facing the emergencies in daily life or maritime operations (Wan et al., 2019; Cao and Lam, 2019).

3 Bi-objective evacuation problem

In this section, we first provide a problem description for our Bi-objective Evacuation Problem (BEP), and then propose a formulation for it based on a physical and time-expanded network.

3.1 Problem description

The bi-objective evacuation problem exploits a network representation of a high-rise building or a huge cruise. In such a representation, the network represents the possible connections in the buildings or ships, such as the building/ship during or after a fire. The nodes in the network correspond to the locations inside the building/ship, such as rooms, lobbies, exits, and the arcs in it correspond to the connections between these places, like the doorways, and corridors of the building/ship. The cost in the arc is the traversal distance along it, and the capacity in the arc represents the allowable number of evacuees that passes through the associated passageway per unit time. The nodes include the nodes having the evacuees, intersection nodes, and the exits, including those in the underground or to the land and those in the refuge floors or ship desks.

For each node having evacuees that need to be evacuated, there may have different attributes, such as genders, ages and physical sizes, and some of them may need special attention (e.g., babies, pregnant women, or people with disabilities). As shown in Wong et al. (2017), different groups of evacuees have different evacuation speeds due to their attributes. A large group of evacuees may take a longer time to evacuate. Likewise, if the evacuees consist of children, women, or elderly people, the evacuation time is expected to be extended. In our model, we assume that the evacuees in the same location (node) will evacuate as a group (Wong et al., 2017) in a specific evacuation speed, which results in that the traversal time in each arc can be different. To incorporate these into the model, we model the movement of each group of evacuees in a commodity-dependent time-expanded network. That is, each commodity has a corresponding network. Based on this network, the objective for BEP is to find a feasible flow (a sequence of movements for the evacuees to leave the threat and go inside the safe zones) such that the flow starts from the origin nodes and ends in the safe nodes.

As the speed of different evacuation groups varies, in each time period, we consider the capacity in each arc to ensure that the number of evacuees passing through the associated passageway (i.e., an arc) does not exceed its capacity. By having this setting to limit the flow in each arc, all unnecessary congestions during evacuation can be avoided.

We consider two different types of exits in our problem. The first one is the exits in the underground (if it is a building), which can be viewed as the safest exits and without any capacity. The other type is the exits to the refuge floors or other floors like building roof floor, ship desk, etc. (Aleksandrov et al., 2019), which are temporary safe because they need other facilities, such as helicopters, evacuation lifts or ladders, to assist in further rescue operations. These exits have capacity on it, because it is impossible to evacuate all the evacuees to the refuge floors due to the capacity and the facilities limitation. In other words, for different types of evacuees, these two types of exits can have different priorities and different capacity restrictions.

Our bi-objective evacuation problem aims at finding a set of emergency evacuation routes so as to: (i) minimize the total evacuation time of evacuees, i.e., the time dimension risk, and (ii) minimize the space dimension risk during evacuation, which is represented as the weighted sum of the matching between the group of evacuees and the exits in different locations.

3.2 Physical network

In the three-dimensional (3D) geometric structure of an evacuation network $G = (V, A)$, each room/exit is designated as a node $v \in V$ and the staircases/corridors/links between the rooms are directed arcs $a \in A$. Each node contains the evacuees in the set V_E needing to evacuate to an exit node in the set V_S, and $V_E \subset V, V_S \subset V, V_E \cap V_S = \emptyset$. We assume that the evacuees in the same node (e.g., a room) move as a group during evacuation. We also assume that the number of evacuees in each group is not too large, such that each group can be evacuated to at least one exit. This assumption is reasonable and practical because if the group is too large, it is the natural human behavior to separate into relative small groups. Let q_v be the number of evacuees in node $v \in V_s$. As mentioned before, there are two types of exit nodes, denoted as V_{S1} and V_{S2}, respectively. The first type in V_{S1} represents the exit type that is totally safe and no further help is needed. The second one in V_{S2} represents the exit type that needs further rescue by using facilities such as helicopters, evacuation lifts or ladders. Let Q_i be the capacity of the exit i in V_{S2}, which refers to the capacity limitation of this node as well as the capacity limitation of the facilities being used. For each $a \in A$, let d_a denote the distance of arc $a \in A$. Similar to many studies on location problems and evacuation problems (Melkote and Daskin, 2001; Wang et al., 2011; Tang et al., 2014), we use a simple example to illustrate the evacuation, from either the buildings or ships, as shown in Figure 1 throughout the paper. For each node pair (u, v) with $u \in V$ and $v \in V$, let $Q_{(u,v)}$ be the capacity of a pair (u, v), which may contain two directed arcs $< u, v > \in A$ and $< v, u > \in A$. Since each group may contain different types of evacuees with different speeds, we let s_v be their overall speed for the groups of evacuees in node $v \in V_E$. It implies that the travel times needed for different groups, denoted by t_a^v, are different when they travel along the same arc $a \in A$. For example, for two groups $v_1 \in V_E$ and $v_2 \in V_E$ with different speeds s_1 and s_2, their travel times along the arc a with a distance d_a are, respectively, $t_a^{v_1} = \frac{k_a d_a}{s_1}$ and $t_a^{v_2} = \frac{k_a d_a}{s_2}$, where k_a is an arc-dependent parameter. Different directed arc can have different values of k_a. For instance, k_a can be used to adjust the speed when the evacuees are going downstairs or upstairs. Finally, we assume that the travel time along the edge is always an integer.

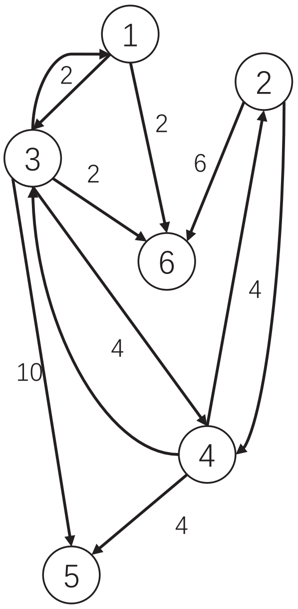


Fig. 1 A simple example of a physical network $G = (V, A)$ with six nodes and nine directed arcs, where $V_E = \{1, 2\}$, $V_S = \{5, 6\}$, $V_{S1} = \{5\}$, $V_{S2} = \{6\}$ and the number next to each arc represent its distance.

As mentioned in Section 3.1, one objective function of our evacuation problem is to minimize the evacuation time of each group. This time dimension objective makes the problem hard to be formulated in a physical network. This motivates us to model the problem in a time-expanded network, which will be introduced in next subsection. Since different groups of evacuees have different travel times, we also need to incorporate the commodity concept into the network to represent the groups of people, and let the flows of commodities represent the movements of different groups of evacuees. In the next two subsections, we first introduce the time-expanded network and then provide in detail the bi-objective multiple commodity network flow model based on both the physical network and the time-expanded network.

3.3 Time-expanded network

We formulate the evacuation problem by using a bi-objective multiple commodity network flow model. Let H be the set of commodities, which represent the different groups of evacuees during evacuation. As described in Section 3.1, each commodity located in one node of the network G moves as a group. If there exist any nodes in G having more than one commodities, we only need to duplicate the nodes until the number of nodes is equal to the number of commodities. Based on the number of evacuees and their types in each group, each commodity $h \in H$ has a distinct speed during evacuation, denoted as s_h, and the number of evacuees is denoted as q_h. Similar to other evacuation models discussed in the literature, we divide the planning period into small time intervals $\{0, \cdots, T\}$, where T represents the time before which all groups of evacuees should egress. Here T can be interpreted as the last time point all the evacuees should be out of the building or the ship during the emergency, and the value of T also affects the complexity of our model. For each commodity $h \in H$, we define a time-expanded network $G^h = (N^h, A^h)$ by replicating the physical network G over time, where N^h is the set of nodes and A^h is the set of arcs. Each node $i \in N^h$ is associated with some time $t(i) \in \{0, \cdots, T\}$ and some location $l(i) \in V$, representing a location at a point in time. Each arc $a = (i, j) \in A^h$ has $t(i) < t(j)$. Without loss of generality, there is a single source node 1 and a single sink node n, where $n = |N^h|$, $b_1^h = -1$ and $b_n^h = 1$. Let $v(h) \in V_E$ be the corresponding location in the physical network. Moreover, in the network G^h of commodity $h \in H$, there is exactly one unit of supply and one unit of demand at node 1 and node n, respectively. The supply and demand for other nodes are assumed to be zero. Therefore, we have $b_j^h = 0$ with $j \in N^h$.

For each commodity $h \in H$, there are totally four types of arcs in the time-expanded network (see an example in Figure 2, which is the time-expanded network for commodity 1 based on the physical network shown in Figure 1):

- Supply arc $(1, i)$ with $i \in N^h$, $l(i) = v(h)$ and $t(i) = 0$: from the source node 1 to the node where the group of evacuees is located. Clearly, there is only one supply arc in each network G^h. The travel time along the arc is zero. The set of supply arcs is denoted as A_S^h.
- Demand arcs (i, n) with $i \in N^h$, and $l(i) \in V_S$: from the exit node in V_S in different time to the sink node n. Let $t((i, n)) = t(i)$ be the travel times along these demand arcs. The travel times along these arcs are zero. The set of demand arcs is denoted as A_D^h.
- Connecting arcs (i, j) with $i, j \in N^h$, $a = (l(i), l(j)) \in A$ and $t(i) + d_a/s_h = t(j) \leq T$: from the location $l(i)$ to the location $l(j)$. The travel times along these arcs are equal to $t(j) - t(i) = d_a/s_h$. The set of connecting arcs is denoted as A_C^h. The dash lines in Figure 2 only show part of the connecting arcs for commodity 1.
- Holdover arcs (i, j) with $i, j \in N^h$, $l(i) = l(j)$ and $t(i) + 1 = t(j) \leq T$: from the node $i \in N^h$ to node $j \in N^h$ where $l(i) = l(j)$. These arcs allow

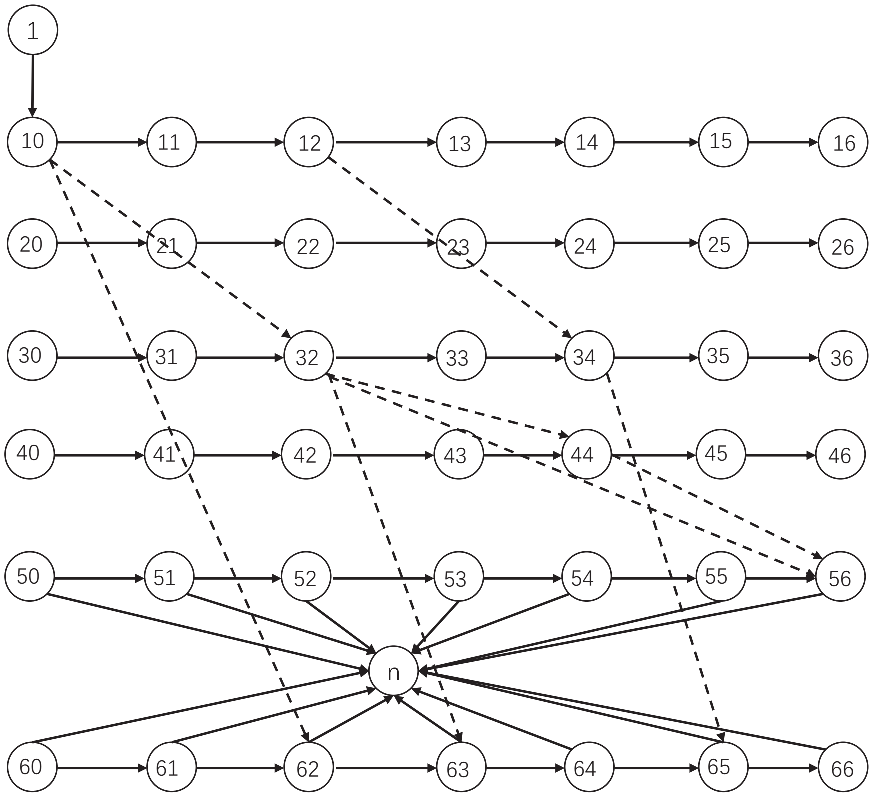


Fig. 2 An example of a time-expanded network for commodity 1 based on the physical network in Figure 1, with the speed of group 1 equals to 2, and $T = 6$.

evacuees to stay in their intermediate locations and wait for the capacity to be available at the next connecting arc. The travel times along these arcs are equal to one. The set of holdover arcs is denoted as A_I^h.

Clearly, consider the example in Figure 2, if the speed of group 2 is different from that of group 1, i.e., not equal to 2, then the resulting time-expanded network of commodity 2 is also different from that shown in Figure 2.

3.4 Bi-objective programming formulation

Based on both the physical network and the time-expanded network, our evacuation problem is formulated as a bi-objective programming, denoted by P. Let $x_a^h \geq 0$ be the flow variable (binary) of commodity $h \in H$ along arc $a \in A^h$. x_a^h takes value 1 if and only if the group $h \in H$ moves through arc a during evacuation, and 0 otherwise. For each commodity $h \in H$ and each node $i \in N^h$, let $\mathit{\Gamma}^-(i) = \{j|(j,i) \in A^h\}$ and $\mathit{\Gamma}^+(i) = \{j|(i,j) \in A^h\}$ be the set of arcs directed in and out of the node i in G^h, respectively. Our problem aims to minimize the risk during evacuation from both time and space dimensions:

- Minimize the time dimension risk during evacuation: this objective aims to minimize the maximum evacuation time of each group of evacuees, i.e., the total evacuation time of evacuees. We have the following objective function:

$$\textbf{OBJ1} \;\; \min \max_{h \in H} \sum_{a \in A_D^h} t(a) x_a^h \tag{1}$$

  where the inner maximization objective is to find the maximum evacuation time of each group and the outer minimization is to optimize the evacuation time of all evacuees. Note that the evacuation time for each group is equal to the time required for the group to leave from at least one of the exits, representing by the flow in the demand arcs.
- Minimize the space dimension risk during evacuation: this objective aims to minimize the weighted sum of the groups of evacuees leaving from different exits with different priorities. We have

$$\textbf{OBJ2} \;\; \min \sum_{h \in H} \sum_{(i,n) \in A_D^h} w_{l(i)}^h x_{(i,n)}^h \tag{2}$$

  where w_j^h represents the weight of group h when the group evacuates through exit j in network G. Note that different groups of evacuees may have different weights. Different exits may also have different weights due to the further rescue hardness from the evacuation planner's perspective. Generally speaking, an evacuation planner prefers guiding the evacuees to a completely safe exit to guiding them to a refuse floor which demands further rescue operations. Also, a group with many children should evacuate from the totally safe exit instead of a refuse floor because it is more challenging for the evacuators or firefighters to rescue this group than an adult group.

There are totally four sets of constraints for the bi-objective BEP, namely flow conservation constraints (3), capacity constraints on arcs (4), capacity constraints on nodes (5), and nonnegative constraints on flow decision variables (6).

$$\sum_{j \in \Gamma^+(i)} x_{(i,j)}^h - \sum_{j \in \Gamma^-(i)} x_{(i,j)}^h = b_j^h, \;\; \forall h \in H, j \in N^h \tag{3}$$

$$\sum_{h \in H} \sum_{a \in A(t,u,v)} q^h x_a^h \leq Q_{(u,v)}, \;\; \forall t = \{0, \cdots, T\}, u, v \in N \tag{4}$$

$$\sum_{h \in H} \sum_{a \in A_D^h(i)} q^h x_a^h \leq Q_i, \;\; \forall i \in V_{S2} \tag{5}$$

$$x_a^h \in \{0,1\}, \;\; \forall h \in H, a \in A^h \tag{6}$$

It is worth noting that the capacity constraints on arcs (4) limit the total flow of the evacuees at any given time. That is, if the capacity of an arc is used up, other evacuees should not be guided to there so as to avoid unnecessary congestion during evacuation. Moreover, the set $A(t, u, v)$ in (4) represents the set of arcs in the time expanded network of all the commodities at time t when all the commodities pass the arcs with the node-pair (u, v) in the physical network. The constraints in (5) ensure that the total number of evacuees should not exceed the capacity of each exit, and $A^h_D(i)$ in (5) is the set of the demand arcs related to the exits $i \in V_{S2}$ for commodity $h \in H$.

Based on the physical network in Figure 1, we provide an example below to show the balance between these two objective functions and the effect of the capacity on an arc.

Example 1 Consider the physical network shown in Figure 1. Suppose there are two commodities located in node 1 and node 2, i.e., two groups of evacuees who need to evacuate. To simplify the presentation and to easily illustrate the balance between the two objective functions, here we assume that their speeds are the same, which results in the same travel time on the same arc. For the same node pair, e.g., node 3 and node 4, the travel time from node 3 to node 4 is different from that from node 4 to node 3. The reason is that the former one is going downstairs and the latter one is going upstairs. There are two exits in the network, nodes 5 and 6, where node 5 represents a totally safe exit and node 6 is a refugee floor. If there is no difference between the weights of exit 6 and exit 5, as shown in Figure 3(a), then the two groups of evacuees are sent to exit 6 and the first objective value is equal to 3. If the weight of exit 5 increases, as shown in Figure 3(b), the solution is to send group 2 to exit 5 and send group 1 to exit 6, which results in the first objective value equals to 4. If the weight of exit 5 becomes large, i.e., the evacuation planner prefers to sent the evacuees to the totally safe exit, then both groups are sent to exit 5. In Figure 3(c), there is no capacity constraint for arc $(4, 5)$, while in Figure 3(d), there exists capacity restricted on arc $(4, 5)$. These two cases lead to two different objective values of the first objective function. The former one is 5 and the latter one is 6. This illustrates if one group of evacuees occupies some arc in a certain time period, then other groups at the same time period are not allowed to enter this occupied arc to avoid congestion.

4 Solution algorithm

In this section, we propose an ϵ-constraint algorithm for finding a set of solutions for the bi-objective model described in the previous section. This algorithm can transform our model into a mono-objective optimization problem with additional constraints. To begin with the transformation, we first define the set called *a minimal complete set of Pareto-optimal solution.*

Definition 1 Let X be the set of all feasible solutions of problem P, and $z(x) = [z_1(x), z_2(x)]$ be the objective vector that is associated with $x \in X$,

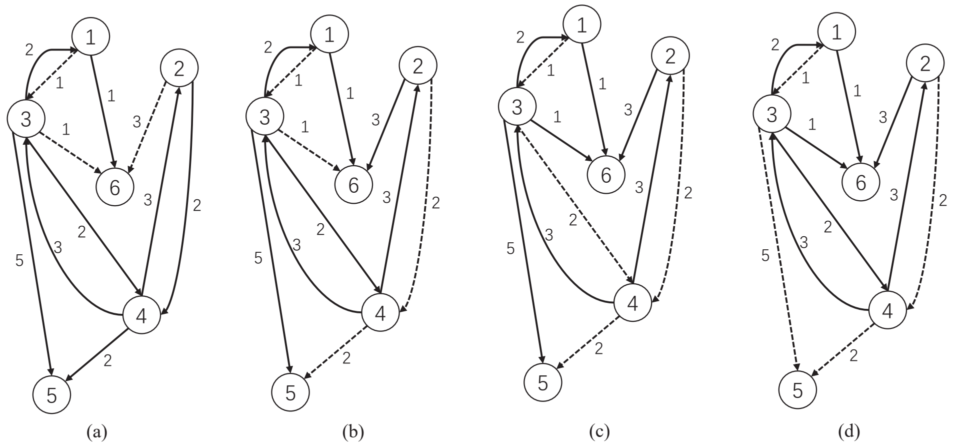


Fig. 3 An example showing the relationship between the two objective functions and the effect of arc capacity.

where

$$z_1(x) = \min_{h\in H} \sum_{a\in A_D^h} t(a)x_a^h,$$

and

$$z_2(x) = \min \sum_{h\in H} \sum_{(i,n)\in A_D^h} w_{l(i)}^h x_{(i,n)}^h.$$

1. Given any two solutions of problem P, denoted by $x_1 \in X$ and $x_2 \in X$, we define that x_1 dominates x_2 if one of the following two conditions holds:

$$\begin{aligned} &(a) \;\; z_1(x_1) < z_1(x_2) \text{ and } z_2(x_1) \leq z_2(x_2), \\ \text{or } &(b) \;\; z_1(x_1) \leq z_1(x_2) \text{ and } z_2(x_1) < z_2(x_2). \end{aligned}$$

2. We call a solution $x \in X$ is a Pareto-optimal solution only if there is no other solution in X that dominates x.
3. A minimal complete set $X^* \subset X$ is a Pareto-optimal solution set that satisfies the following two conditions:
   (a) For any $x_1^* \in X^*$ and $x_2^* \in X^*$, we always have $z(x_1^*) \neq z(x_2^*)$, i.e., at least one of the objective values is not the same.
   (b) For any Pareto-optimal solution $x \in X$, there always exists $x^* \in X^*$ such that $z(x) = z(x^*)$, i.e., $z_1(x) = z_1(x^*)$ and $z_2(x) = z_2(x^*)$.

Next, we use the ϵ-algorithm to find a minimal complete set of Pareto-optimal solutions for problem P. Given a position parameter ϵ, we solve a single-objective problem, denoted by P_ϵ and detailed below, in each iteration of the algorithm. Note that the setting of the parameter ϵ affects the number of single-objective problems needed to be solved. Since there are two objective functions in our model $[P]$, we need to treat one of them as a constraint and optimize the other one. In our problem, we can treat the objective **OBJ2** as a constraint by imposing a bound ϵ. The resulting problem is denoted as P^1_ϵ below:

$$[P^1_\epsilon] \quad \min \max_{h\in H} \sum_{a\in A^h_D} t(a)x^h_a \tag{7}$$

subject to

$$\sum_{h\in H} \sum_{(i,n)\in A^h_D} w^h_{l(i)} x^h_{(i,n)} \leq \epsilon \tag{8}$$

$$\sum_{j\in \Gamma^+(i)} x^h_{(i,j)} - \sum_{j\in \Gamma^-(i)} x^h_{(i,j)} = b^h_j, \ \forall h \in H, j \in N^h \tag{9}$$

$$\sum_{h\in H} \sum_{a\in A(t,u,v)} q^h x^h_a \leq Q_{(u,v)}, \ \forall t = \{0, \cdots, T\}, u, v \in N \tag{10}$$

$$\sum_{h\in H} \sum_{a\in A^h_D(i)} q^h x^h_a \leq Q_i, \ \forall i \in V_{S2} \tag{11}$$

$$x^h_a \in \{0, 1\}, \ \forall h \in H, a \in A^h \tag{12}$$

where the additional constraint (8) limits the weighted sum of the exits not to be larger than a given parameter ϵ. This constraint is used to control the space dimension risk through imposing a bound for the weighted sum of exits. Note that the problem is non-linear due to the min-max objective function in (7). We can further linearize it by introducing a new variable R. Through adding a new objective function and a new set of constraints, the new formulation of P^1_ϵ is described as follows:

$$[\bar{P}^1_\epsilon] \quad \min R \tag{13}$$

subject to (8)-(12), and

$$\sum_{a\in A^h_D} t(a)x^h_a \leq R, \ \forall h \in H \tag{14}$$

$$R \geq 0 \tag{15}$$

The problem $[\bar{P}^1_\epsilon]$ is a mixed integer programming problem with a single objective. The problem can be solved by the off-the-shelf commercial solver, such as ILOG CPLEX or Gurobi. For this problem, we assume that the planner prefers to mitigate the time dimension risk, which acts as the objective function. Similarly, we can also consider the case for mitigating space dimension risk.

Table 1 Data summary of each group of evacuees.

Node in set V_E	1	2	3
The number of people (n_v)	5	4	6
The speed of each group (s_v)	3	1	2
The weight in exit 7 (w_7^h)	0.45	0.25	0.35
The weight in exit 8 (w_8^h)	0.8	0.85	0.55

5 Computational results

In this section, we show the applications of our bi-objective model through numerical experiments. Based on an example which simulates the network of a building or a ship in practice, we run a series of tests to verify the efficiency and effectiveness of our proposed model and the proposed solution algorithm. The algorithm is implemented in a C++ environment. Each formulation $\bar{P}_\epsilon^1$ is solved by the solver ILOG CPLEX 12.8, and all tests are run on a PC with 24.0 GB of RAM and an Intel Core i7-4790 CUP at 3.60 GHz.

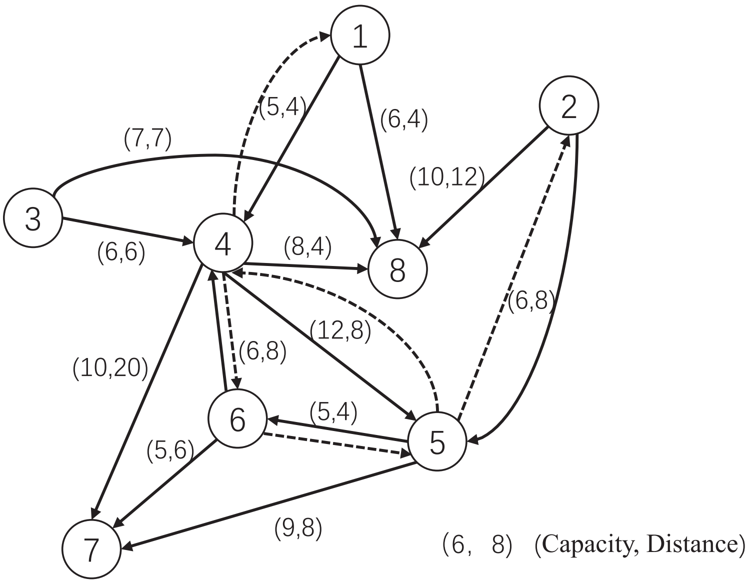


Fig. 4 An example of evacuation physical network for testing, where the dash lines and the solid lines represent two different arc parameters k_a along the same edge.

The evacuation network for the tests is depicted in Figure 4, which is modified from the example in Figure 1. The network is also similar to the example on short notice evacuation planning presented in Lim et al. (2012). The network consists of three groups of evacuees ($V_E = \{1, 2, 3\}$), three intersections

($V \setminus V_E \setminus V_S = \{4, 5, 6\}$), and two exit nodes ($V_S = \{7, 8\}$), where one is the exit to the refugee floor ($V_{S1} = \{7\}$) and the other one is the exit to the underground of the building ($V_{S2} = \{8\}$). The two numbers above each arc represent the arc capacity on the number of evacuees and travel distance along the arc, respectively. The evacuation time horizon is assumed to be 25 time units ($T = 25$), where one time unit is equal to 1 minute, 2 minutes or 5 minutes, depending on different network. Table 1 summarizes the data of each group of evacuees. The speed of each group has taken account of the number and the types of evacuees. The same set of data is also used for sensitivity analyses.

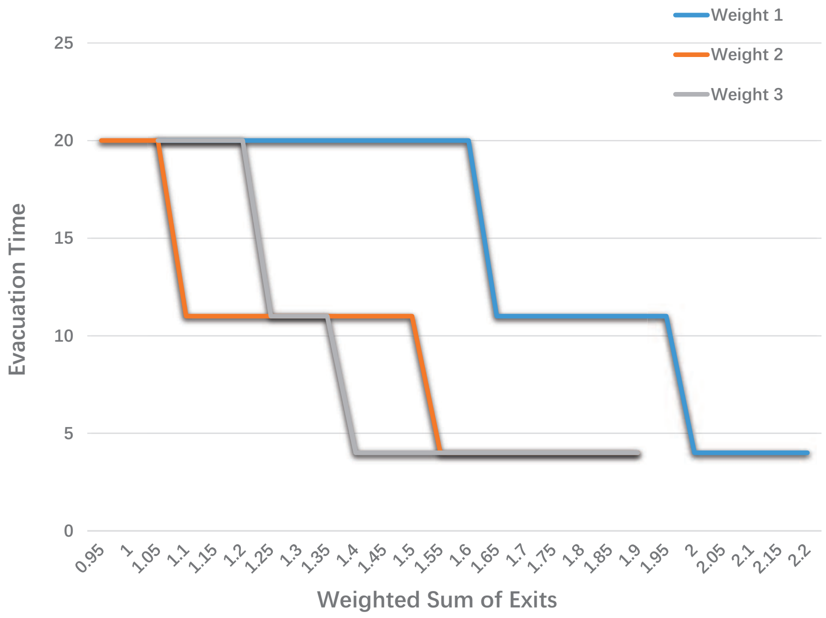
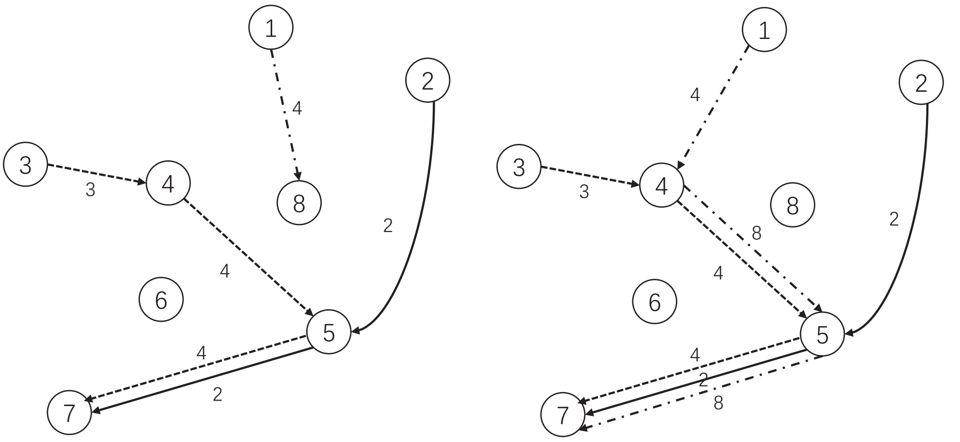


Fig. 5 Trade-off between the evacuation time and weighted sum of exits for the example with different weights in the OBJ2.

First, we provide the computational results when the weights for the two exits were not the same. The different weights reflected the preference of an evacuation planner when assigning the group of evacuees to the type of exit. For instance, a group without elderly people or children may have a higher priority to be guided to evacuate through the refugee floor when comparing with a group with elderly person or children. The weight for the former is smaller than the one in the latter. Our model could output the evacuation routes which consider the two conflicting objectives or the two dimension risks. As shown in Figure 5, the x-axis represents the weighted sum between the group of evacuees and the exits, whereas the y-axis represents the evacuation time of the last group that evacuates to any exit. Through the results, it is found that the two objective functions form a conflicting relationship as expected. That is, if the weight is large, which implies that there is a need for further rescue operations, then the whole evacuation time is small, and vice versa. Figure 6 presents the evacuation routes for different groups of evacuees having different speeds (different line types in the figure) under different ϵ values, which implies that different ϵ values affect the planning results. This is because the restriction on the weighted sum of the exits makes all the evacuees change the exits and increases the time.

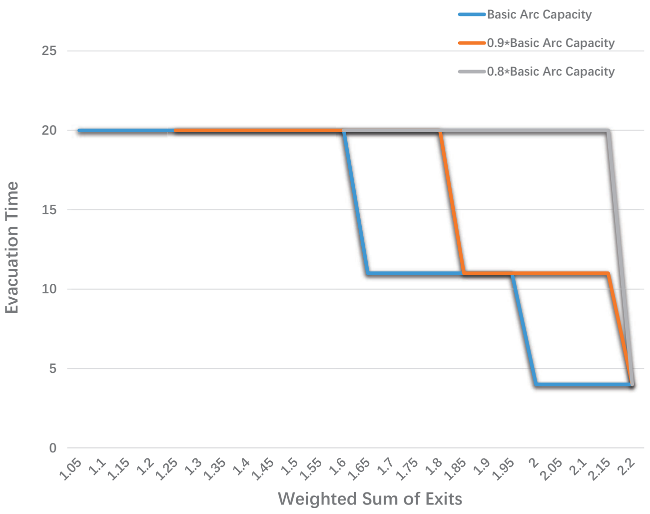


(a) $\epsilon = 1.65$ with evacuationt time equals to 11 time units.

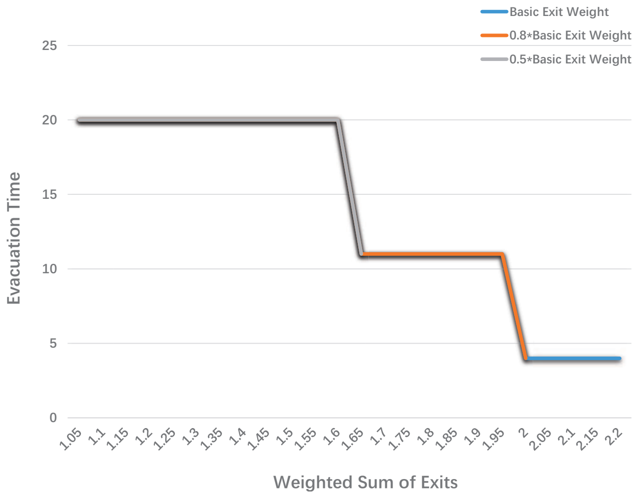
(b) $\epsilon = 1.60$ with evacuationt time equals to 20 time units.

Fig. 6 Evacuation routes for the example with two different values of ϵ.

Second, we vary the capacity on the arc and the exits in V_{S2} so as to test how the change in capacity affects the evacuation routes. From Figure 7(a), we find that as the arc capacity decreases, some arcs do not have enough capacity for some group of evacuees to evacuate. It results in a longer evacuation time with the same weighted sum of exits. In this case, some exits are not used due to the limited arc capacity. A similar impact happens when decreasing the exit capacity, as shown in Figure 7(b). In particular, the decrease in capacity of the refugee floor causes more groups of evacuees evacuated from the underground exit. These results on capacity restriction are consistent with those in the studies on network design and network flows (Melkote and Daskin, 2001; Wang et al., 2011). As a result, the evacuation time becomes longer than before, even in the situation that the planners have sufficient facilities or resources for further rescue operations. Furthermore, from Figure 8, we observe that the decreased capacity in edge $(4, 5)$ causes group 3 to change to a new route with an additional unit of evacuation time (from 11 units as shown in Figure 8(a) to 12 units as indicated in Figure 8(b)).



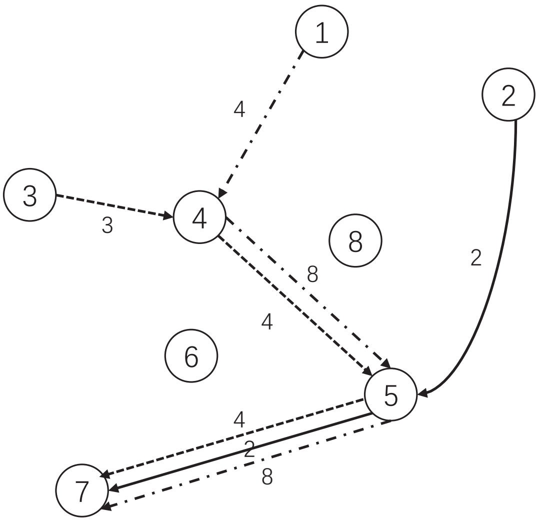
(a) Different arc capaicityies



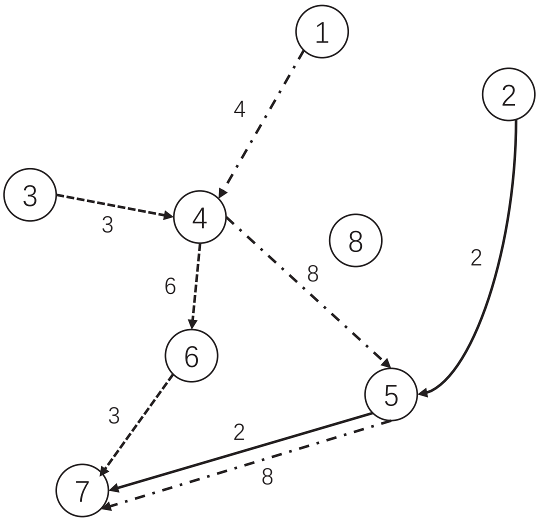
(b) Different exit capaicityies.

Fig. 7 Trade-offs between evacuation time and weighted sum of exits for the example with different capacities of the arcs and the exits.

Finally, we adjust the speed of the evacuees during evacuation and conduct a sensitivity analysis on speed. The trade-off results are presented in Figure 9. We find that speed greatly affects the whole evacuation plan and the evacuation time, which implies that speed plays an important role when conducting the evacuation planning for different types of evacuees. The reason is that different speeds can result in different evacuation networks as defined before, and hence lead to different evacuation plans. Moreover, when the speed of group



(a) Capacity of edge $(4, 5)$ equals to 12.



(b) Capacity of edge $(4, 5)$ equals to 8.

Fig. 8 Evacuation routes for the example with different capacities of edge $(4, 5)$ when $\epsilon = 1.60$.

2 changes from 3 to 2, as shown in Figure 10, the evacuees of group 3 need to wait in node 5 for 1 time unit (flows through the holding arc corresponding to node 5) due to the limited capacity in edge $(5, 7)$. Thus, the evacuation time becomes longer than before.

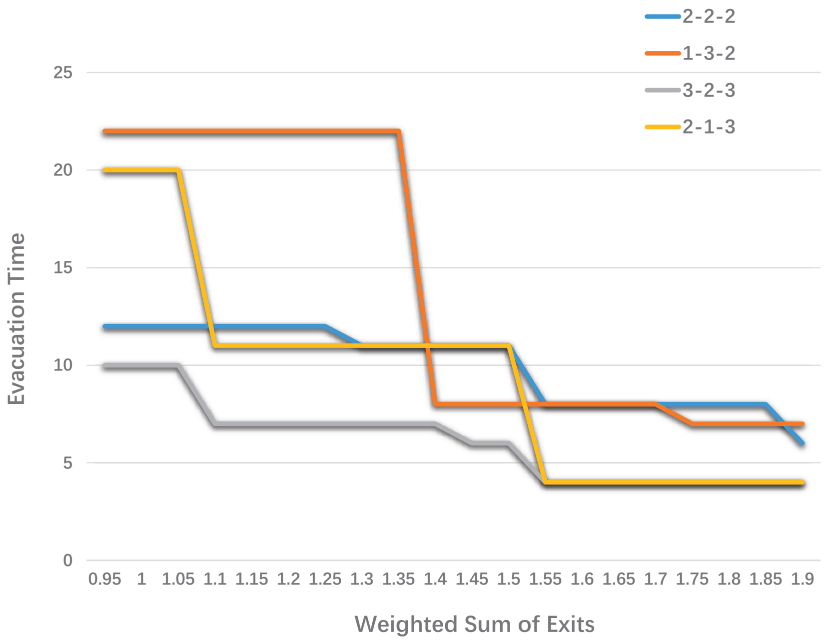
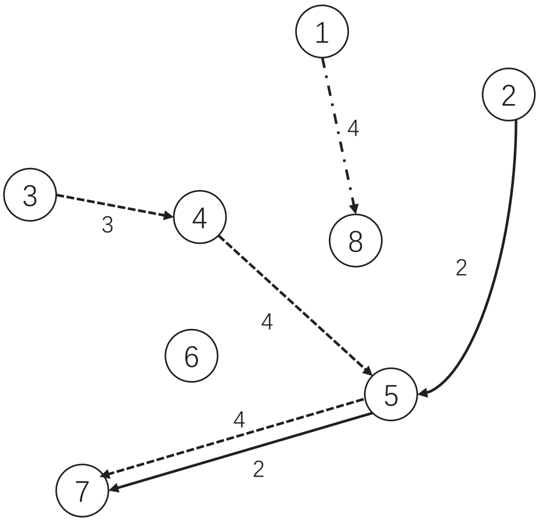


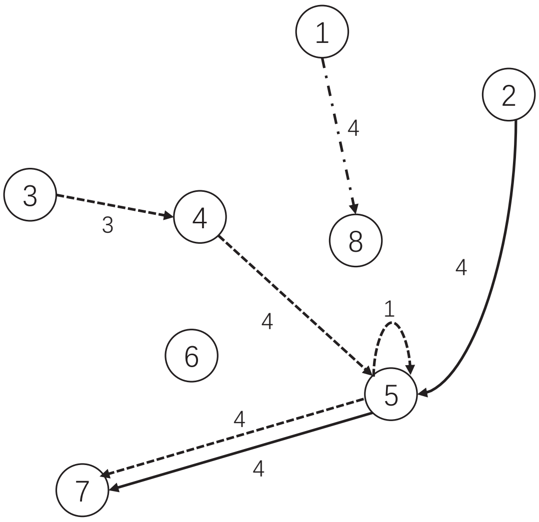
Fig. 9 Trade-offs between evacuation time and weighted sum of exits for the example when the three groups of evacuees have different evacuation speeds.

6 Conclusions

In this paper, we have studied a new evacuation problem that considers both the time and space dimension risks during evacuation. In particular, we have exploited the multiple commodity flow in a time-expanded network to model the evacuation routes for different commodities, where commodities are used to characterize the different types of evacuation groups having different speeds during evacuation. Moreover, the bi-objective programming have been also used so as to involve two conflicting objectives on the evacuation risks. Specifically, two different dimension objectives are introduced to represent both the time and space dimensions risks. The time dimension objective is to minimize the total evacuation time of evacuees. The space dimension objective is to minimize the weighted sum of different types of exits, those have different priorities or risk level. This objective is set for tackling the case in which an evacuation planner prefers to move the evacuees out of the places in emergency instead of keeping them in the places inside the building or ship in emergency where further recuse is needed. Furthermore, we have provided a method to solve this newly developed model for evacuation. Computational experiments have been conducted to show the properness of the model as well as the efficiency and effectiveness of the solution algorithm. The sensitivity analysis on different objective weights, capacities and speeds have shown that the speed



(a) If the speed of group 2 equals to 3, the evacuation time equals to 11 time units.



(b) If the speed of group 2 equals to 2, the evacuation time equals to 12 time units.

Fig. 10 Evacuation routes for the test example with different evacuation speeds of group 2.

of each group greatly affects the evacuation time, which implies that the type of evacuees and the speeds of different groups are key considerations in this type of evacuation. On one hand, our model as well as the solution method can serve as a possible way to improve the emergency preparedness, as what were done in Tac et al. (2020) and Lai et al. (2020). On the other hand, our findings on the type of evacuees and their speeds suggest that the speed of the evacuees is an important element during evacuation, which should be paid more attention by the planners in practice.

This paper considers a bi-objective evacuation problem under a setting of unsplittable flows during evacuation, one possible extension is to consider the splittable flows case where each group of people can be split into small groups or reformed into bigger or smaller groups for evacuation. In such case, how the group is formed would become an issue and simulation-based methods could be applied (Wang et al., 2014). Moreover, we consider the problem in a deterministic context. It is of interest to extend to a stochastic or dynamic setting where the network capacity varies with the time and the capacity should be captured over time. In this case, more complicated network flow technique may be applied to. In terms of the results, our analyses have revealed that speed is an important element during evacuation. Therefore, how to estimate the speeds of different groups of evacuees becomes a critical practical issue. This is currently out of our scope in this paper but it should be an interesting research topic in the future. One possible way is to use big data analysis to develop several forecast models based on the data like video records, and entry records in the building/ship monitor system. Finally, the use of an evolutionary algorithm for solving a multiple-objective problem can be another future research direction so as to improve the algorithm performance and to solve the problem in a larger scale.

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