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Emergency Evacuation Planning for Highly Populated Urban Zones: A Transit-Based Solution and Optimal Operational Strategies

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1. Introduction

Natural and man-made disasters (e.g. hurricanes, floods, terrorist attacks) could cause huge economic loss and society damage. In many hazardous events, the best option is to relocate threatened populations to safer areas, which is commonly referred as emergency evacuation. During the process of evacuation, people would usually use their own vehicles to evacuate from the impacted area. However, there are some cases where people may not have access to reliable personal vehicles or using personal cars are not possible; then they need to rely on other forms of transportation. There are different modes of transportation that can be used to evacuate people, such as public transit, school buses, charter buses, demand-responsive vans, rail, and ambulances.

In view of literature, though significant contribution has been made in evacuation modelling considering passenger cars only, there are only a limited number of quantitative studies discussing the use of transit to evacuate the people during emergency management. One stream of researchers has employed simulation-based tools to study the feasibility and performance of transit evacuation plans. Liu et al. (2007, 2008) have presented an integrated system that embeds the evacuation of carless people; however the transit demand is converted into passenger car traffic in their system. Elmitiny et al. (2007) have performed a traffic simulation based study to evaluate alternative plans for the deployment of transit during an emergency situation in a transit facility such as a bus depot. Evacuation strategies evaluated include traffic diversion, bus signal optimization, access restriction, different destinations, and evacuation of pedestrians. Naghawi and Wolshon (2011a, 2011b) conducted a simulation-based assessment of the performance of the multi-modal evacuation traffic networks. The simulation results have shown that buses were able to increase the total number of people evacuated from the threat area while adding average queue length on some interstate freeway segments. Mastrogiannidou et al. (2009) developed an effective integration of the micro-simulation software package (VISTA) with transit based emergency evacuation models. A heuristic was developed to assign vehicle(s) to pickup points based on the shortest time criterion. They also study the impact of different numbers of available buses on routing strategies.

Another group of researchers have developed mathematical optimization models to obtain the best transit evacuation strategy. Perkins et al. (2001) discussed the use of buses to evacuate people (elderly and disabled) under a no-notice scenario. They assume that buses are at a garage, and optimize departure time of buses from the garage to pickup points such that the total travel time of buses is minimized. However, the routing strategy is static in their model and each bus would travel on a pre-set route to leave the affected area. No number of evacuees for each pickup point is mentioned. Sayyady (2007) has formulated the carless evacuation problem with a minimum cost flow model under additional side constraints. Their model assumes that bus stops are the pickup locations and the carless are guided to the stop that is closest to their current location waiting for pickup during an emergency. A Tabu search technique is used to identify evacuation routes for buses. In those studies, buses will only carry out one single trip and will not return to pick up the carless after leaving the affected area. Further studies (Tunc et al. 2011, Sayyady and Eksioglu, 2010) have also developed mixed-integer linear programming models to find optimal evacuation routes for transit.

Margulis et al. (2011) develop a binary integer-programming model to determine the assignment of buses to pickup points and to shelters during an evacuation. The objective of their model is to maximize the number of evacuee throughput in a given time period. However, their model assumes buses are at the pickup points at the beginning of the evacuation, and regulate each bus to return to the same evacuation site. He et al. (2009) has developed a stochastic optimization model to generate evacuation plans for transit-dependent residents in the event of a natural disaster. Their formulation features a location-routing problem (LRP) framework and solves for the number of shelters, their locations, the number of buses required, and their routes with the objective to minimize the total evacuation time. Comparative studies have also been performed to analyse single-stage and two-stage transit evacuation strategies. However, their assumption that all buses are at shelters might not be appropriate. Chen and Chou (2009) developed an optimal waiting spots and service locations selection model for transit-based emergency evacuation planning, and study the impact of transit-based evacuation to a highly dense populated area based on effectiveness measures such as network clearance time, move time, delay time, total travel time, and average speed of the traffic.

A very recent study by Chan (2010) has proposed a two-stage model for carless evacuation including a location problem that aims at congregating the carless at specific locations and a routing problem with the objective to pick up the carless from these evacuation sites and deliver them to safe locations. They explicitly consider the dynamic demand pattern of evacuees to pick up points as well as multiple trips of buses from pickup points to shelters. However, how to optimally guide evacuees to pick up points to better utilize the available buses is not discussed in their model.

Despite the significant contribution of previous studies in transit-based evacuation, none of those studies have integrated the dynamic processes of evacuee guidance (from buildings or parking lots to pick up points) and bus routing (from pick up points to shelters). Such integration will significantly improve the performance of the transit routing in response to the evacuee demand variation and maximize the utilization of available number buses by dynamically adjusting the demand distribution of evacuees at pick up points. In response to such critical research and operational needs, this study will propose an integrated

optimization model that is capable of coordinating the evacuee guidance and transit routing process seamlessly and simultaneously.

This chapter is organized as follows. The problem and the proposed mathematical model are presented in section 2. An algorithm to solve the given model is provided in section 3 of this chapter. Section 4 gives an illustrative example of the validity of mathematical model along with a brief sensitivity analysis on objective function weights. The chapter is finalized by concluding remarks in section 5.

2. Methodology

2.1 Problem description

As aforementioned, the proposed problem features a two-level optimization framework. The first level model guides evacuees from buildings and parking lots to designated pick-up points (e.g. bus stops, metro stations), and the level-II dispatches and routes buses from depots to pick-up points and transport evacuees to their destinations or safe places. This two-level problem can be converted into a graph form as shown in Figure 1. In this figure, nodes represent parking lots, pickup points, depots and safer area and arcs connecting those nodes represent the road network. The aim of the proposed of mathematical model is to find a sub-graph which is optimal with respect to maximizing the efficiency of the evacuation. In this network, evacuees are assigned to pickup points based on capacity of pickup points and distance, and once the demand is known the evacuation route for each bus will be constructed to transfer evacuees waiting at the pickup points to the safer area (shown in green circle in Figure 1). Considering the nature of this problem, we formulate it as a combined vehicle routing and assignment problem.
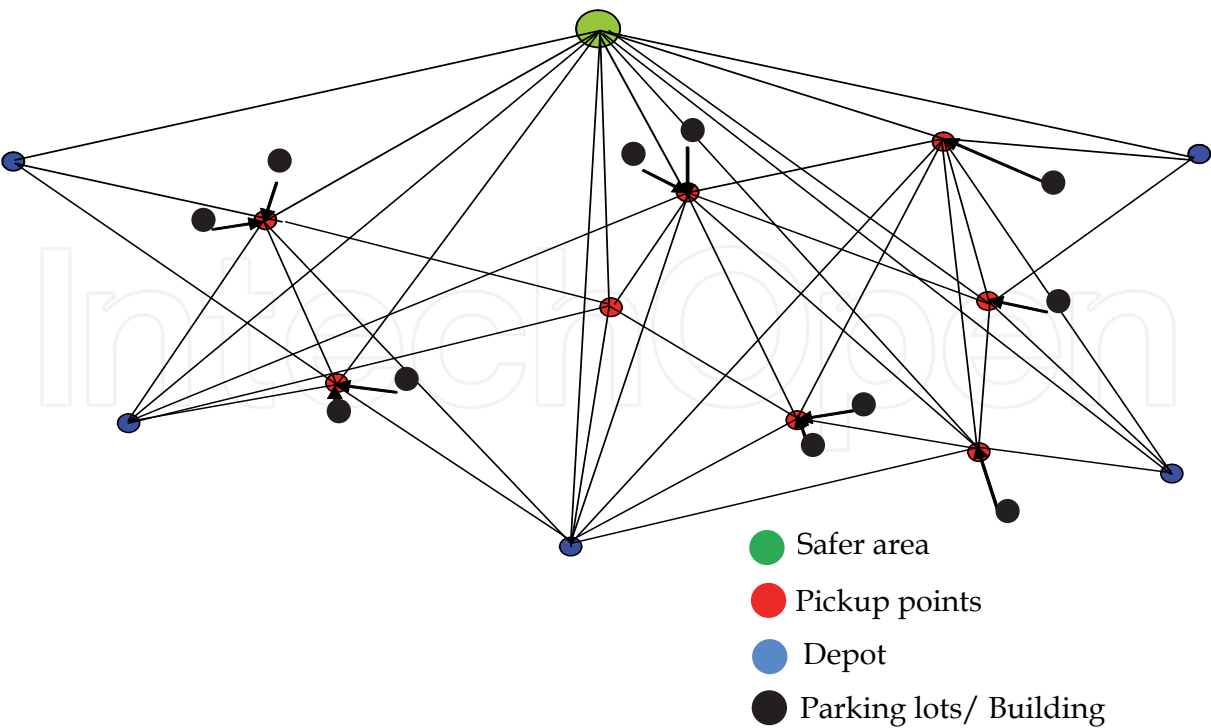

Fig. 1. Graphical representation of the two-level evacuation problem.

2.2 Assumptions

To ensure that the proposed formulations for the proposed problem are tractable and also to realistically reflect the real-world constraints, this study has employed the following assumptions in the model development.

- Evacuee walking time from buildings/parking lots to pickup points and bus travel time among pickup points;
- There exists a super evacuation destination in the network;
- The location and capacity of each pickup point is known;
- The capacity of buses are known as a priori; and
- Buses are restricted to go back to the same deport after sending evacuees to the destination.

2.3 Notation

To facilitate model presentation, notations used hereafter are summarized in Table 1.

I	Set of parking lots/buildings
L	Set of depots
H	Set of pickup points
H_0	Set of pickup point and the evacuation destination
K	Set of buses
d_{ip}	Distance between parking lot/building i and pickup point p
l_{pq}	Distance between pickup point p and q
s_{ped}	Evacuee walking speed
Di	Evacuation demand at parking lot/building i
C_p	Capacity of pickup point p, $p \in H$
Q_k	Capacity of bus k
w_i	Weight of expression i in the objective function
X_{ip}	Number of passengers/evacuees at building i assigned to pickup points p
Y_{pqk}	1- If arc (p, q) belongs to the route operated by bus k 0- Otherwise
T_{pqk}	Number of evacuees at pickup point q assigned to bus k goes from p to q
U_{pk}	An auxiliary variable for sub-tour elimination constraint in route k

Table 1. Notation of parameters and variables for the mathematical model

2.4 Model formulation

The two-level evacuation problem can be formulated as the following mixed integer program (MIP):

$$\text{Minimize} \quad w_1 \sum_p \sum_q \sum_k l_{pq} Y_{pqk} - w_2 \sum_i \sum_p \frac{S_{ped}}{d_{ip}} X_{ip} \tag{1}$$

s.t.

$$\sum_{k \in K} \sum_{p \in L \cup H_0} Y_{pqk} \geq 1 \quad \forall q \in H_0 \tag{2}$$

$$U_{pk} - U_{qk} + |H| \times Y_{pqk} \leq |H| - 1 \qquad p, q \in H_0, k \in K \tag{3}$$

$$\sum_{p \in L \cup H} Y_{pqk} - \sum_{p \in L \cup H_0} Y_{qpk} = 0 \quad q \in L \cup H_0, k \in K \tag{4}$$

$$\sum_{p} \sum_{q \in L \cup H_0} Y_{pqk} \leq 1 \quad \forall k \in K \tag{5}$$

$$\sum_{k \in K} \sum_{p \in L \cup H_0} Y_{pqk} \geq 1 \quad \forall q \in L \tag{6}$$

$$\sum_{p \in H} X_{ip} = D_i \quad \forall i \in I \tag{7}$$

$$\sum_{i \in I} X_{ip} \leq C_p \quad \forall p \in H \tag{8}$$

$$\sum_{p} \sum_{q} T_{pqk} \leq Q_k \qquad p, q \in H_0 \quad \forall k \in K \tag{9}$$

$$T_{pqk} \leq Q_k Y_{pqk} \quad \forall p \in H \cup L, \forall q \in P, \forall k \in K \tag{10}$$

$$\sum_{p \in L \cup H} \sum_{k \in K} T_{pqk} - \sum_{i \in L} X_{iq} \geq 0 \quad \forall q \in H \tag{11}$$

In this formulation the objective function is defined as Eq. (1). The objective function includes two terms: the first term deals with routing and the second one is related to assigning evacuees to the pickup point. The first term minimizes the total distance and second term tries to maximize total number of evacuees assigned to pickup point considering the walking distance. Since the objective function finds the minimum possible value for total bus traveling distances and the maximum total number of evacuees assigned, it implicitly maximizes total evacuees transported over the shortest path for each bus, and therefore maximizes the number of evacuees to the safer area.

The number of buses dispatched from each depot must be at least one which as given by constraint (2); Constraint (3) is used for sub-tour elimination in the VRP problem; Constraint (4) ensures flow conservation of network; Constraint (5) guarantees that each bus can be utilized at most once during one round of the evacuation period; Constraint (6), unlike conventional constraints in the VRPs, ensures that each link can be served by more than one bus, even for those leaving from pickup points.

Eq. (7) is the first assignment-type constraint of the model, which guarantees all evacuees must be assigned to pickup points. Moreover, this number must be less than each pickup point capacity constrained by Eq. (8). Constraint (9) limits the number of evacuees transferred from pickup points to the evacuation destination must be less than the bus capacity during each tour or route.

Constrain (10) relates assignment of evacuees to buses only if the bus serves that link or pickup points. Constraint (11) guarantees that all evacuees at pickup points are assigned to vehicles and transferred to the evacuation destination.

3. Solution algorithm

Note that the proposed formulation of the model is a NP-hard problem, solution of the large-scale instances are intractable. To ensure the applicability of the proposed model in real-world scenarios, this section develops a two-stage Tabu-search-based approach to solve the model.

In the first stage, a relaxed assignment problem is solved to find the evacuee demand at each pickup point based on which a route for each bus is constructed through a meta-heuristic algorithm. The second stage is a Tabu search meta-heuristic which solves the VRP sub-problem. The flowchart for the proposed solution algorithm is depicted in Figure 2 with each of its elements explained as follows:

3.1 Parameter initialization

Before implementing the heuristic, some parameters should be known and initialized in advance. These parameters are the number of buildings, pickup points, depots, buses, capacity of each, and size of TABU list.

3.2 Stage-1: Solve the assignment problem with relaxation

At this step, the assignment part of the problem is considered. In order words, those constraints related to the routing part of the problem are relaxed; then a solver is used to solve the assignment problem. The output of this step is the number of evacuees that are assigned to the pickup points waiting for buses.

3.3 Stage-2: Tabu search

3.3.1 Step 1- initial solution generation

To generate the initial solution, we have developed the following steps:

- Step 1.1: A distance-based proximity matrix for each pair of nodes is developed;
- Step 1.2: Find the minimum value between depots and pickup points;
- Step 1.3: Based on the waiting evacuees and bus capacity, assign the maximum possible evacuees to the bus; go to step 1.4;
- Step 1.4: If bus has room for more evacuees, go to step 1.5; otherwise go to step 1.6;
- Step 1.5: Add the nearest pickup point to the route and go to step 1.4;
- Step 1.6: The bus goes to the safer area to drop off passenger; go to step 1.8;
- Step 1.7: If there are evacuees waiting at any pickup point, go to step 1.2; otherwise go to step 1.6;
- Step 1.8: END.

3.3.2 Step 2- neighborhood generation

In order to search the solution space, some solution, known as a neighbour, must be generated from the current solution. If the newly generated solution is better than current

one, a move will be made and that move will be added to a list called the Tabu list, which is necessary to avoid from falling back to same point and local optima. By definition, a solution S' that does not include TABU moves is the neighbour of solution S if it is feasible to the problem and represents an adjacent flow. The TABU search algorithm implements the 2-opt search mechanism to find a better solution (Cordeau et al., 1997).

In the proposed problem, a neighbour is defined based on the order of the pickup points served by a bus or exchanging two pickup points in two different routes. However, this may result in an infeasible solution due to the bus capacity violation constraint. Therefore, to make sure the neighbour solution is feasible; one needs to check the capacities of two buses before making the move, and then swap the two pickup points. Assume, without loss of generality, vehicles are v_1 and v_2 and pickup point in v_1 route is p_1 with number of evacuees assigned T_1 and pickup point in v_2 route is p_2 with number of evacuees assigned T_2. If $T_1 > T_2$, two pickup points are swapped and another p_1 is added to v_1 to pick up the remaining evacuees at p_1. The same procedure will apply to the other case, which will keep the heuristic from generating infeasible solutions.

3.3.3 Step 3- selection strategy

The selection strategy determines the rule for selecting the next neighbouring solution. In this study, we employ the first better move strategy (Cordeau et al., 1997), in which the neighbouring solutions are investigated in a predetermined order, and the first solution that shows an improvement is selected as the next solution.

3.3.4 Step 4- TABU list

Since in this heuristic, contrary to classical methods, the current solution may deteriorate from one iteration to the next iteration, recycling may occur. To avoid this some recently explored solutions, bus routes in our case, are temporarily declared as Tabu or forbidden. We use the TABU list (θ) defined as a finite list with fixed size containing TABU sub-paths. When a move is made based on the selection strategy, that move is added to the list to make sure that the algorithm does not go to the current solution. Since the size of the TABU-list is bound by L, when the $|\theta| = L$, the new one is added after removing the oldest one.

3.3.5 Step 5- evaluation criterion

Based on the first better strategy (Cordeau et al., 1997), the first neighbouring solution that improves the evaluation criterion is selected as the better solution. We simply define the evaluation criterion to be value of objective function for mathematical model to minimize.

3.3.6 Step 6- termination criterion

The TABU search algorithm implements the 2-opt mechanisms for a fixed number of iterations. If no better neighbouring solution is found, then it moves to the best neighbouring solution, even if it does not improve the current solution. Such moves are known as bad moves, *badMoves*. After making a fixed number of bad moves (*maxBad*), the algorithm stops by reporting the best-found solution over all iterations.
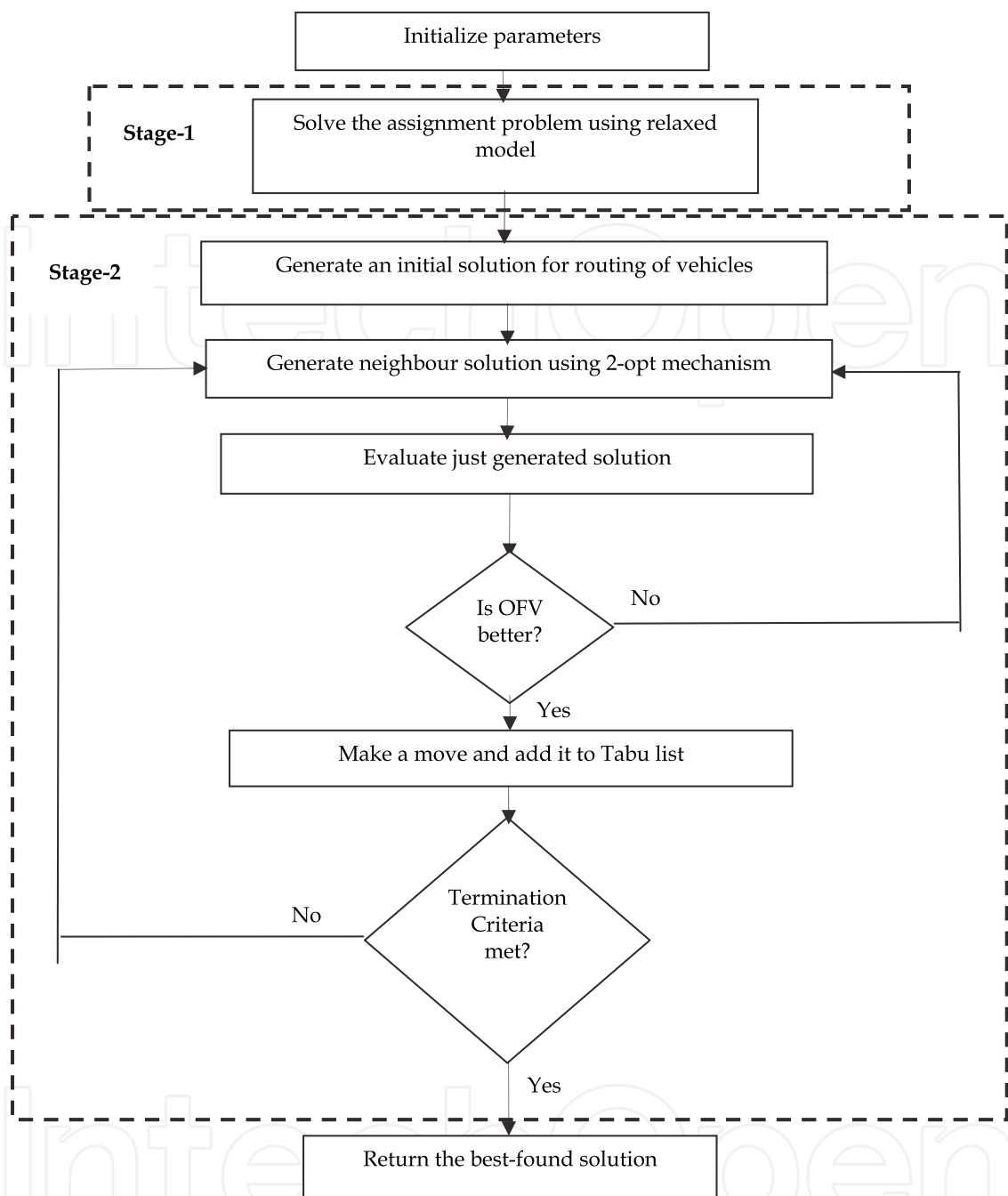
Fig. 2. Flowchart of the proposed heuristic algorithm.

In the next section, we will use a small-scale numerical example to validate the applicability and feasibility of the proposed mathematical model.

4. A numerical study

4.1 Test case description

In order to validate the structure and applicability of the proposed formulation, a numerical example is solved and discussed in this section. The data used in this example is given in Table 2. In all Tables 2(a)-(e), buildings, pickup points and depots are shown by initials.

(a) Number of nodes and vehicles of the numerical example

Parking Lots	Pickup Points	Depots	Vehicle	Vehicle capacity
10	6	3	8	45

(b) Distances from buildings (B) to pickup points (P) (unit: in 0.1 miles)

	P1	P2	P3	P4	P5	P6
B1	3	4	1	2	1	3
B2	2	1	3	1	1	1
B3	1	1	1	1	2	2
B4	1	2	2	1	2	3
B5	1	2	3	3	4	1
B6	3	4	1	2	1	3
B7	2	1	3	1	1	1
B8	1	1	1	1	2	2
B9	1	2	2	1	2	3
B10	1	2	3	3	4	1

(c) Distance matrix for vehicular network (unit: in 0.1 miles)

	P1	P2	P3	P4	P5	P6	D1	D2	D3
P1	1000	20	30	20	10	30	20	10	15
P2	20	1000	40	30	10	20	30	40	15
P3	30	40	1000	10	20	5	15	25	35
P4	10	20	30	1000	40	25	35	40	45
P5	20	10	40	30	1000	25	35	45	5
P6	20	20	40	30	10	1000	30	40	15
D1	30	40	15	10	20	5	1000	25	35
D2	20	40	40	30	10	20	30	1000	15
D3	10	20	30	45	40	25	35	40	1000

(d) Number of evacuees at each building (unit: # of evacuees)

Building/ Parking lot	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Demand	10	40	36	64	14	10	40	36	64	14

(e) Capacity of each pickup point (unit: # of evacuees)

Pickup points	P1	P2	P3	P4	P5	P6
Capacity	80	60	70	60	50	80

Table 2. Data used in the numerical example.

Table 2(a) lists all problem indices, which will be used to solve the example. Entries in this table are self-explanatory. Table 2(b) depicts distances from buildings/parking lots to each

pickup point. Distances between nodes of vehicular network (pickup points, depots and safer area) are given in Table 2(c), in which P's and D's stand for pickup points and depots. Tables 2(d) and 2(e) give the number of evacuees at each building/parking lot and the capacity of each pickup point, respectively. For example, the number of evacuees waiting at the first building is 10 and the first pickup point can accommodate no more than 80 evacuees.

Note that data used in the numerical example is for the purpose of validation of the proposed model and may not be realistic considering a real-world evacuation. However, the proposed model is generic and can handle real-world evacuation scenarios when the data is available.

4.2 Results and discussion

The numerical example is solved with CPLEX 11.2 in 704 seconds of computer time. The assignment of evacuees from buildings or parking lots to pickup points (the first level problem) and the bus routing plans among pickup points and depots (the second level problem) are solved concurrently with the proposed formulation. Eight buses are used to take evacuees to the safer area. In should be noted that since one term of objective function is related to route cost, the model indirectly minimized the number of buses used to evacuate carless people. A graphical illustration of the numerical example results is shown in Figure 3. In the figure, blue points are building/parking lot from which evacuees are assigned to pickup points (shown by red arrow in the figure). The bus routing plans that take evacuees from pickup points to the safer area and then come back to their depot are also illustrated in Figure 3. For instance, one route (bus) starts from depot 2 to pickup point 1, goes to safer area (shelter) and finishes its journey by coming back to its origin.
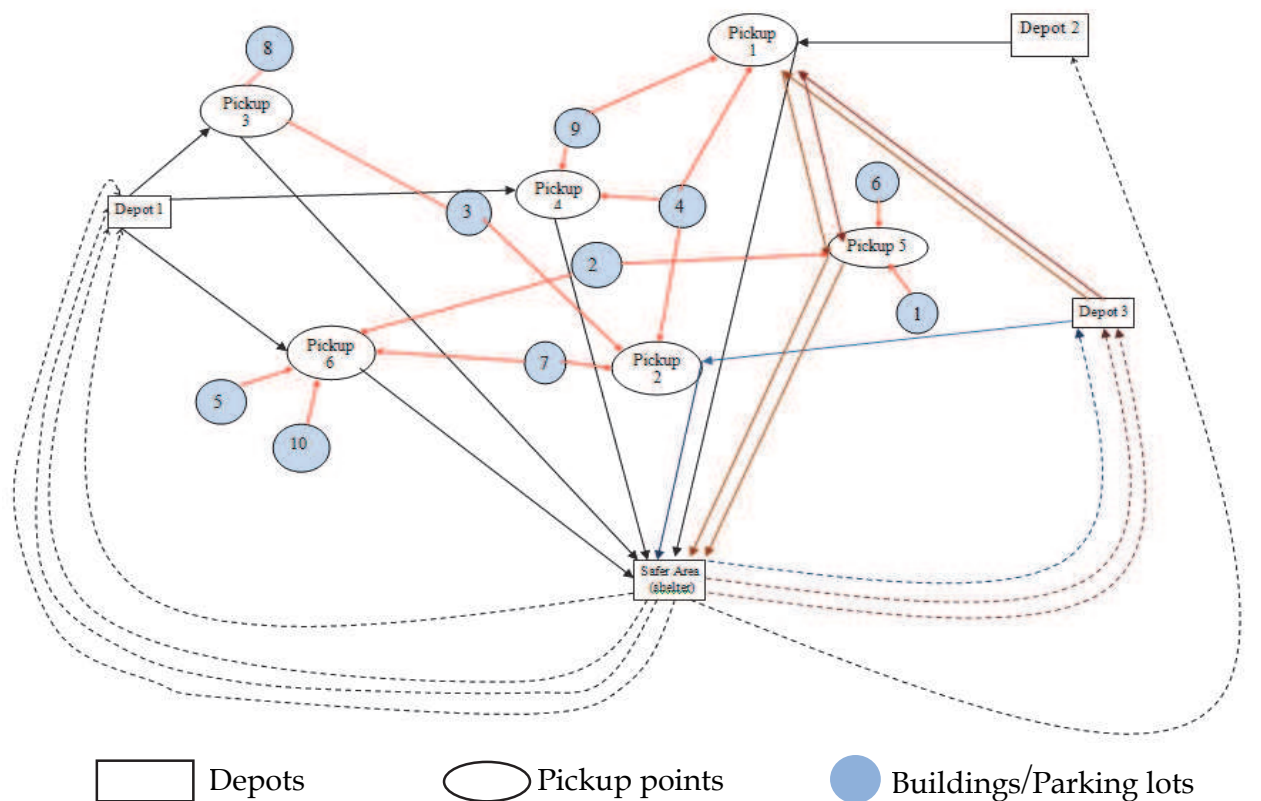

Fig. 3. Graphical representation of the numerical example results.

For the first level, evacuees are assigned based on the accessibility and available capacity at designated pickup points, as shown in Table 3. For instance, there are 36 evacuees waiting at building 3, 9 of them are assigned to pickup point 2 and the remaining 27 are assigned to pickup point 3. On the other hand, the capacity of pickup point 2 is 60, which take 9 evacuees from building 3, 3 from building 4, and other 33 from building 7.

	Pickup 1	Pickup 2	Pickup 3	Pickup 4	Pickup 5	Pickup 6	Total
Building 1					10		10
Building 2					30	10	40
Building 3		9	27				36
Building 4	30	3		31			67
Building 5						14	14
Building 6					10		10
Building 7		33				7	40
Building 8			36				36
Building 9	50			14			64
Building 10						14	14
Total	80	45	63	45	50	45	

Table 3. Assignment of evacuees from buildings/parking lots to pickup points (unit: # of evacuees).

For the second level, the routing plan for each bus during the evacuation process is summarized in Table 4. Also reported in Table 4 is the number of evacuees taken at each pickup point and transported to the evacuation destination by each bus. It can be observed that more than one bus has been assigned to each route depending on the number of evacuees. For example buses 4 and 5 in this table have the same route because number of evacuees at pickup point 1 is 80 and bus 8 will take 45, and the remaining 35 evacuees are transported by buses 4 and 5. This is due to the fact that the proposed problem structure allows multiple buses on each route, which is different from the assumption of traditional vehicle routing problem. Another notable fact is that the capacity of each bus is fully utilized. Since bus capacity is 45, if we look at results in Table 4, it can be observed that buses 2, 3, 6, 7 and 8 are used with full capacity and other buses carry less than capacity because the numbers of evacuees waiting in those places are less than bus capacity. For instance, bus 1 takes only 18 remaining evacuees at pickup point 3.

Buses	Routing Plan	#of Evacuees/Throughput
1	Depot 1 – Pickup 3 – Depot 1	18
2	Depot 1 – Pickup 4 – Depot 1	45
3	Depot 1 – Pickup 6 – Depot 1	45
4	Depot 3 – Pickup 1 – Pickup 5 – Depot 3	22 + 22 = 44
5	Depot 3 – Pickup 1 – Pickup 5 – Depot 3	13 + 28 = 41
6	Depot 1 – Pickup 3 - Depot 1	45
7	Depot 3 – Pickup 2 – Depot 3	45
8	Depot 2 – Pickup 1 – Depot 2	45

Table 4. The routing plan of each bus and the total of number of evacuees transported.

Based on the results given in Tables 3 and 4, it is apparently clear that the proposed mathematical model can solve this evacuation example to optimality, and both the evacuee assignment and bus routing plans generated from the model are valid. The next step is to check the power of the model in dealing with large and real size problems and to show how model parameters can affect outputs and the solutions. In addition, the validation of the model will give us some guidelines to design a heuristic algorithm to find good solution faster, which will be discussed in the next section in more details.

4.3 Sensitivity analysis on objective function weights assignment

For sensitivity analysis, the effect of different weights of objective function terms on the result and computational time for the above case is studied. Each term of objective function is assigned a weight in range [0, 1] summing up to one. The result of this test is tabulated in Table 5. It can be observed that the value of each term of objective function is not sensitive to its weight assignment, which indicates that the problem is not sensitive to the objective weights. On the other hand, there is one case in which total number of evacuees taken to safer area is different from others. While other cases have 328 evacuees as throughput, this case, in which w_1 = 0.4 and w_2 = 0.6, has 340 evacuees as throughput. This reveals the fact that there might be multiple solutions with the same objective value, if weights are not considered.

Weights		Value of objective term		Structure of the solution	Throughput (# of evacuees)	Time (sec.)
w_1	w_2	1	2			
1	0	305	0	V1: 25 V2: 45 V3: 45 V4: 45 V5: 35 V6: 45 V7: 45 V8: 35 + 8 =43	328	309
0.9	0.1	305	328	V1: 25 V2: 45 V3: 45 V4: 30 + 15 = 45 V5: 45 V6: 45 V7: 12 + 33 = 45 V8: 33	328	567
0.8	0.2	305	328	V1: 25 V2: 45 V3: 35 + 10 = 45 V4: 45 V5: 45 V6: 45 V7: 33 V8: 43 + 2 + 45	328	856

Weights		Value of objective term		Structure of the solution	Throughput (#of evacuees)	Time (sec.)
w_1	w_2	1	2			
0.7	0.3	305	328	V1: 35 V2: 45 V3: 30 V4: 45 V5: 45 V6: 45 V7: 45 V8: 25	328	557
0.6	0.4	305	328	V1: 43 V2: 35 V3: 25 V4: 28 + 17 = 45 V5: 45 V6: 45 V7: 45 V8: 45	328	392
0.5	0.5	305	328	V1: 45 V2: 30 + 15 = 45 V3: 45 V4: 17 + 28 = 45 V5: 45 V6: 35 V7: 45 V8: 23	328	352
0.4	0.6	305	328	V1: 25 V2: 45 V3: 45 V4: 45 V5: 15 + 30 =45 V6: 45 V7: 45 V8: 30 + 15 = 45	340	794
0.3	0.7	305	328	V1: 45 V2: 45 V3: 25 V4: 35 V5: 35 + 10 = 45 V6: 45 V7: 45 V8: 43	328	1051
0.2	0.8	305	328	V1: 45 V2: 25 V3: 27 + 18 = 45 V4: 45 V5: 43 V6: 45 V7: 35 V8: 45	328	734

Weights		Value of objective term		Structure of the solution	Throughput (#of evacuees)	Time (sec.)
w_1	w_2	1	2			
0.1	0.9	305	328	V1: 45 V2: 25 V3: 22+23=45 V4: 45 V5: 45 V6: 33 V7: 30+15=45 V8: 45	328	525

Table 5. Effect of objective weights on throughput.

The effect of weights on throughput (number of evacuees) for both terms in objective function is graphed in Figure 4. In this figure, the blue line is for the first term in the objective function, and the red one is for the second term in the objective function. As shown, there is one peak for each term. This peak happens when the weight for the first term (w_1) is 0.4 and weight for the second term (w_2) is 0.6 ($w_1 + w_2 = 1$), which yields the highest throughput (340 evacuees). During the process of evacuation, operators can use the proposed model and select proper sets of weights for the objective terms to achieve the expected evacuation system performance.
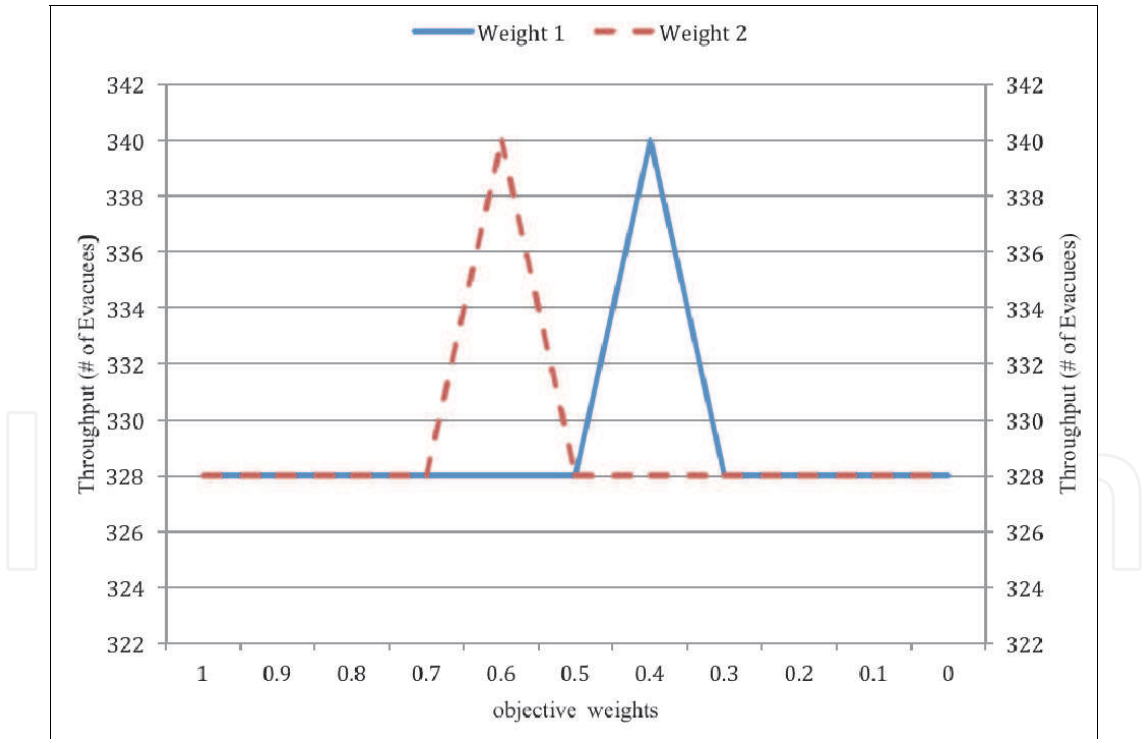

Fig. 4. Effect of objective terms weights on throughput (# of evacuees).

5. Conclusions

This chapter presents a mathematical model for evacuation planning in highly populated urban zones where a potentially large number of pedestrians depend on transit for

evacuation. The uniqueness of the proposed model lies in its capability to concurrently operate the dynamic processes of evacuee guidance (from buildings or parking lots to pick up points) and bus routing (from pick up points to shelters). Such integration will significantly improve the performance of the transit routing in response to the evacuee demand variation and maximize the utilization of available number of buses by dynamically adjusting the demand distribution of evacuees at pick up points.

The model is formulated as a combined vehicle routing and assignment problem and solved by a two-stage Tabu-based heuristic to yield meta-optimal solutions. The feasibility and applicability of the proposed model is illustrated with a numerical example solved to optimality. Results show that the proposed model can yield valid and detailed evacuee guiding and transit routing plans during the evacuation within a reasonable time window. Sensitivity analysis of the impact of objective function weights indicates that the proposed model is robust and not sensitive to the weight variations. It also provides guidelines for evacuation operators on best customizing the objectives to achieve expected evocation operational performance.

Note that the proposed model is only validated with a numerical test, and the results remain preliminary. Next step research will be testing the model's applicability in real-world evacuation scenarios. Computational performance of the proposed solution algorithm will also be evaluated. In addition, the problem studied here is static, in the way that a stable table of evacuee demand and number of buses during an evacuation period is given. The assignment of evacuees and routing of buses also use a static representation of the network condition. Extending the model to an explicitly dynamic setting, with time-varying demand generation rates and travel times, is another worthwhile direction for further work. From a computational standpoint, such extension further complicates an already complex problem, but the dynamic environment during evacuation requests this to be included.

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Emergency Management

Edited by Dr. Burak Eksioglu

After the large-scale disasters that we have witnessed in the recent past, it has become apparent that complex and coordinated emergency management systems are required for efficient and effective relief efforts. Such management systems can only be developed by involving many scientists and practitioners from multiple fields. Thus, this book on emergency management discusses various issues, such as the impact of human behavior, development of hardware and software architectures, cyber security concerns, dynamic process of guiding evacuees and routing vehicles, supply allocation, and vehicle routing problems in preparing for, and responding to large scale emergencies. The book is designed to be useful to students, researchers and engineers in all academic areas, but particularly for those in the fields of computer science, operations research, and human factor. We also hope that this book will become a useful reference for practitioners.

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