Safety Science 111 (2019) 167–178

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Operating strategies of buses for mass evacuation

Lakshay*, Nomesh B. Bolia

Department of Mechanical Engineering, Indian Institute of Technology Delhi, India

ARTICLE INFO

Keywords:
Evacuation
Bus-based evacuation planning
Radiological emergency
Uncertainty

ABSTRACT

Appropriate bus operating strategies are essential for mass bus dependent evacuation after a disaster strikes. Due to limited availability of buses, buses need to be run continuously, i.e., making multiple trips. It is important to find the efficient operating strategies of buses, including the number and sequence of trips. In order to find the optimal operating strategies, mathematical models have been developed. These models help the emergency manager in determining: (i) the minimum number of buses that must be available at respective depots in order to carry out the evacuation within the available time (ii) the optimal operating strategies of buses in order to minimize the overall evacuation time and (iii) perturbations required in these strategies on account of changes in the evacuation ecosystem due to uncertainties. To test the efficacy of these developed models, a case of a radiological accident is presented.

1. Introduction

Evacuation time estimate (ETE) is considered an important component in emergency resource planning. ETEs are required to develop efficient traffic management and the best response actions during emergencies. The evacuation time depends on many factors including traffic routing, signalization, population needing evacuation, weather condition and time of the day the emergency occurred (Urbanik, 2000). In order to reduce the evacuation time and thus, make the evacuation process effective, various traffic management strategies have been proposed in the literature. These strategies include contraflow, assigning traffic control personnel, and changing signal timings (Murray-Tuite and Wolshon, 2013). Generally, the models used in developing these strategies assume that personal vehicles are used as the mode of transport for evacuation. However, emergency transportation must also be provided to people who do not have access to personal vehicles during emergency. This aspect of evacuation planning has not been studied much (Nawaz et al., 2016). The importance of this aspect of evacuation planning was realized only after Hurricane Katrina (2005). During the hurricane it was observed that there was unnecessary delay in the evacuation process solely because personal vehicles were causing excess congestion on various road segments (Kulshrestha et al., 2011). It was also observed that a number of buses were flooded due to lack of well designed plan for buses during evacuation. Further, evacuation by personal vehicles is logistically complex and expensive (Deghdak, 2016). Therefore, public transit should be encouraged as the choice of transportation over personal vehicles during evacuation. In this paper, we develop a methodology for bus based evacuation plans.

Bus-based evacuation planning consists of a set of geographically scattered demand points i.e. pickup points from where people need to be transported in buses to a safe destination. These pickup points are subjected to time constraints, i.e., the time by which all people present at a given pickup point must be shifted to safe destinations within a specified time available for safe evacuation. Due to different geographical locations of these pickup points, they may have different values of the time available.

In case of limited availability of fleet of buses (which is generally the case), buses are required to run continuously, i.e., make multiple trips between pickup points and their respective safe destination (used interchangeably with shelter). Due to the requirement of multiple trips, it is important to develop optimal operation strategies of the buses in operation. Several deterministic models have been developed in the past (Bish, 2011; Dhingra and Roy, 2015; Kulshrestha et al., 2011) to make these strategies for sequencing bus trips. Various objective functions have been used to determine the optimal operating strategies. Table 1 lists the models developed by different authors and their respective objectives of the evacuation process.

Margulis et al. (2006) develop a deterministic model for evacuation using buses. They consider a scenario of flooding in which the objective is to maximize the number of people evacuated in a given time. However, the limitation of their model is that it can be applied to small areas only. Sayyady and Eksioglu (2010) formulated a similar model with an objective of minimizing the total evacuation time. However, the limitation of their model is that it takes initial trip assignment as an input,

* Corresponding author at: Department of Mechanical Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India.
E-mail address: lakshaytaneja01@gmail.com (Lakshay).

https://doi.org/10.1016/j.ssci.2018.07.007
Received 30 June 2017; Received in revised form 17 April 2018; Accepted 8 July 2018
Available online 17 July 2018
0925-7535/

Table 1
Objective considered in past for bus-based evacuation planning.

Objective for allocation	Paper
Minimize total evacuation time	Sayyady and Eksioglu (2010)
Maximize number of people evacuated	Margulis et al. (2006)
Minimize operational cost of evacuation	Dhingra and Roy (2015)
Handling Uncertainty in travel time, demand	Goerigk et al. (2015)

something not always justified.

In most of the models, evacuation problem is generally formulated from the perspective of transportation modelling and traffic assignment with no resource scarcity (Dhingra and Roy, 2015). These models do not incorporate factors related to constraints on available time, resource availability and variability of risk. Dhingra and Roy (2015) try to incorporate these aspects in their work and find the optimal allocation of limited resources with the given time constraint. However, their model mainly tries to minimize the operational cost of evacuation rather than minimizing exposure time to the disaster. Another limitation is that being probabilistic, their model may dispatch a bus to a pickup point that is already evacuated.

We believe what is needed instead is an integrated approach to find the optimum number of buses required, their deterministic sequencing operating strategies for different pickup points, given their respective time constraints. Overall, in this study, therefore, effort has been made to develop models for bus operating strategies for mass transit dependent people with resource and time constraints. These proposed models determine the schedule of buses from the depot and subsequent trips of those buses from the shelters to the pickup points. These models can provide the schedule of buses for both, small scale and large scale problems, and require acceptable computational times. To illustrate this, we consider a large scale evacuation problem that needs to be carried out by a fleet of buses. A case study of nuclear accident is used to test the efficacy of the developed model. However, the approach developed is general enough to be valid for cover other kinds of disasters where only a certain time window is available to complete the evacuation.

In case of an emergency, there are various types of uncertainties that arise and need to be incorporated while developing operating strategies for buses. As per Kulshrestha et al. (2011) there can be two types of uncertainties that may affect the schedule of buses: demand side uncertainty and supply side uncertainty. The former one includes uncertainty in the total number of evacuees, location of evacuees, and in the decision to evacuate or not. On the other hand, supply side uncertainties include reduction in link capacity, limited network connectivity, bus breakdown and availability of drivers. Goerigk et al. (2015) propose a robust optimization model to handle these kinds of uncertainties. However, they have not incorporated a constraint on the available time. Therefore, using that as a starting point, we develop a mathematical model to find the minimum change in schedule of the buses required to incorporate uncertainty.

Thus, the model developed in this study can help the emergency manager in the following ways:

- Determine the minimum number of transit vehicles required to evacuate all the transit dependent people.
- Determine the optimal operating strategies of buses in order to minimize the overall evacuation time.
- Calculate the maximum number of round trips any bus can make from pickup points to safe shelters within a given available time.
- Handle uncertainties and provide solutions in acceptable computational time.

The rest of this paper is structured as follows: Section 2 presents details about the bus-based evacuation problem. Mathematical modeling and formulation of bus operating strategies models has been presented in Section 3. The developed solution methodology has been applied to a case study of a nuclear accident in reactors of Kakrapar nuclear plant, Gujarat (India) in Section 4. Results and discussion are presented in Section 5. Section 6 provides a discussion on the insights and usefulness of the models. Section 7 concludes the paper along with some directions for possible future extension of this work.

2. Bus-based evacuation problem

Due to the warning of a disaster, authorities want an area to be evacuated. People present in the given area need to be evacuated to safe destinations. A transportation mode will be required in case the safe destination is far away. There may be people who rely on public transport to reach the safe destination. Therefore, evacuation planning for transit dependent people is required. The bus-based evacuation problem consists of finding the sequence of trips to be followed by the buses in order to evacuate endangered people within the available time. Bus-based evacuation consists of a set of bus yards (where buses are initially located), a set of pickup points and a set of safe destinations i.e. shelters. Buses go from the yard to the pickup points, where evacuees are gathered to board the buses. Buses take them to safe shelters from the pickup points. As stated in Section 1, due to high demand and limited number of buses, multiple trips of buses might be required. This means that once a bus reaches the shelter, it may have to come back to the same or any other pickup point in order to rescue more people. Fig. 1 shows the pictorial view of bus-based evacuation procedure. In the figure, a bus of yard 1 goes to the pickup point *P1*. From P1, it goes to shelter *S1*. Thereafter, it goes to *P3* from shelter *S1*. Likewise, other buses follow their own sequence of pickups. This process keeps on continuing until the demands from all pickup points are fulfilled.

The initial step in solving the bus-based evacuation problem is to know all the pickup points in the hazardous areas and the respective value of demand at those points. Once demand is known, possible shelter sites are identified, and the respective routes to those shelters should be computed. Afterwards, the number of buses available at different depots should be confirmed. By choosing an appropriate objective, the optimal operating strategies can be developed (more details in Section 3). Fig. 2 shows the various steps involved in the bus-based evacuation problem.

3. Mathematical modelling and formulation

Several inputs are required for developing the bus-based evacuation problem. Fig. 3 shows the inputs and outputs of bus-based evacuation models. Based on the scenario, an appropriate objective function should be considered. In order to determine optimal operating strategies for the buses, three mathematical models M1, M2, and M3 have been developed.

As stated earlier in Section 1, the purpose of these models is:

- Model M1 finds the minimum number of buses that must be available at different yards in order to carry out the evacuation in required time.
- Model M2 gives the required sequence of the trips of each bus in order to achieve the desired objective.
- Model M3 is for incorporating uncertainty related to bus failure and change in severity of accident.

The details of the models are explained below. The following assumptions have been made in developing these models:

- The initial locations of different yards (from where buses will be used for evacuation) are known.
- Buses with varying but known capacities will be used for evacuation.

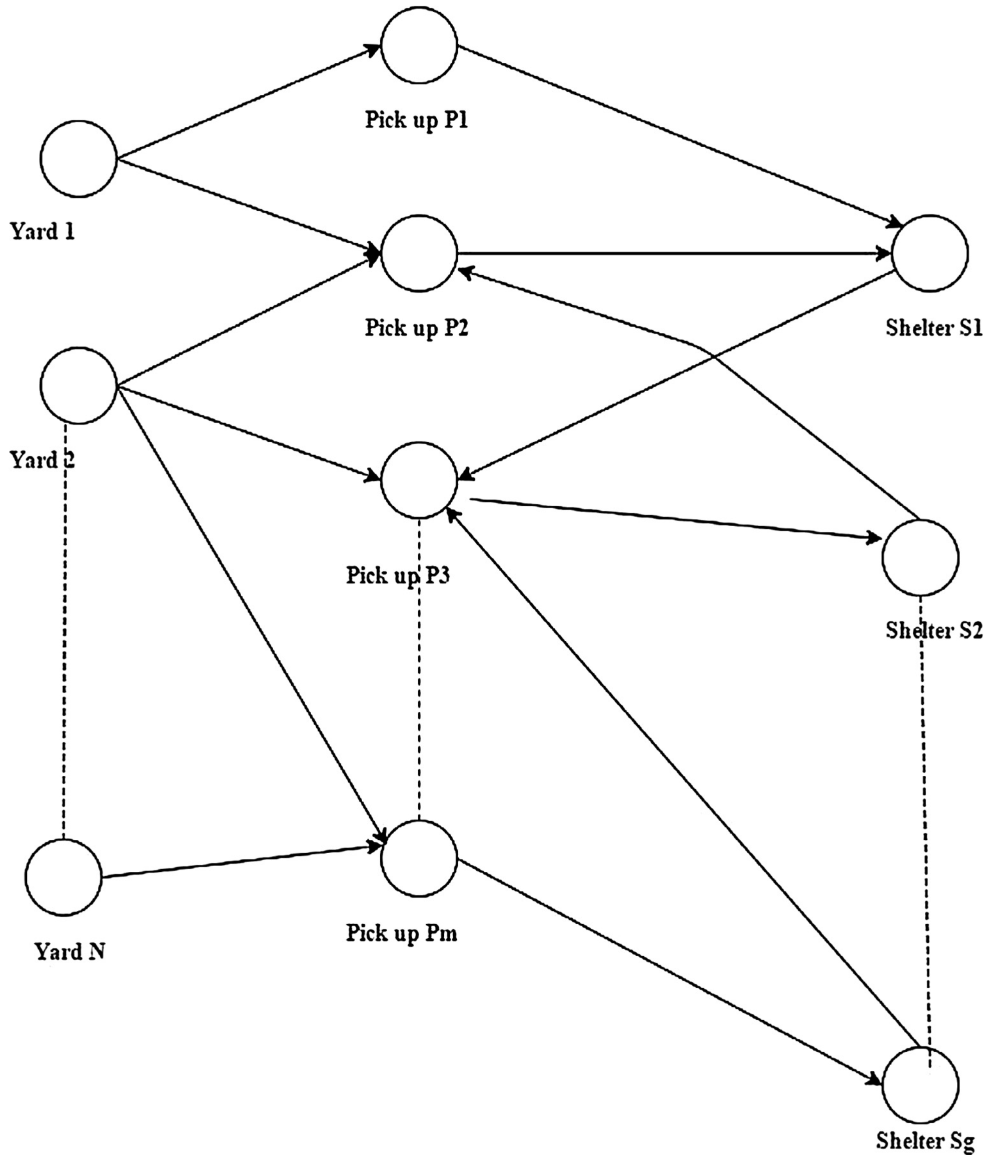

Fig. 1. Example of bus operating strategies.

- People know the location of their nearest pickup point where buses would come for transportation.
- Demands i.e. the number of people that need to be evacuated from respective pickup points are known.
- People are waiting at pickup points when bus arrives, i.e., the waiting time for a bus has been assumed to be zero. This assumption can be justified as in case of life threatening disasters people are willing to evacuate as soon as possible.
- Loading, rest stops and unloading time of buses for different pickup points and shelters are known. The loading, unloading time depends on factors such as number of children and population with special needs at respective points. Further, unloading time can also incorporate servicing time such as refilling and interior cleaning at a shelter before its next trip.
- For the scheduling problem, it has been assumed that inbound and outbound routes (routes from a particular yard to a particular pickup point and pickup point to shelters) are known. It implies that flexibility in route selection has not been considered. However, route flexibility can be easily considered in the model by adding additional route choice constraints that may add more complexity to the developed model (Goerigk et al., 2015).
- Roadway structure has been appropriately developed, which is reasonable considering that the analysis is for proactive planning for evacuation.
- Inbound and outbound travel time for buses are known and assumed to be constant.

The notation [N] is used throughout the article to represent the set {1, 2, …, N}. Let [P] be the set of pickup points in the endangered area (at different geographical locations). Let D_p be the estimated "effective" demand that needs to be transported from a pickup point p ∈[P]. D_p incorporates the presence of different types of people needing evacuation i.e., people with special needs, children, senior citizens, people with luggage, etc. It is important and possible to anticipate the population profile of pickup points. This is because the number of buses (of whatever capacity) required to completely evacuate any pickup point depends upon the population profile of that point. For instance, if a bus can take 80 regular persons, it will take lesser number of special needs people. Accordingly, effective estimated demand (i.e., D_p) can be estimated by decision makers using simulation based studies.

Let [Y] be the set of yards where buses are located initially, [K_y] the set of buses at yard y$\in[Y]$ and B_y the maximum number of buses that can be accommodated at yard *y*. The travel time from yard *y* to pickup point *p* is assumed to be constant and denoted by $d_{y,p.}$ As stated earlier,

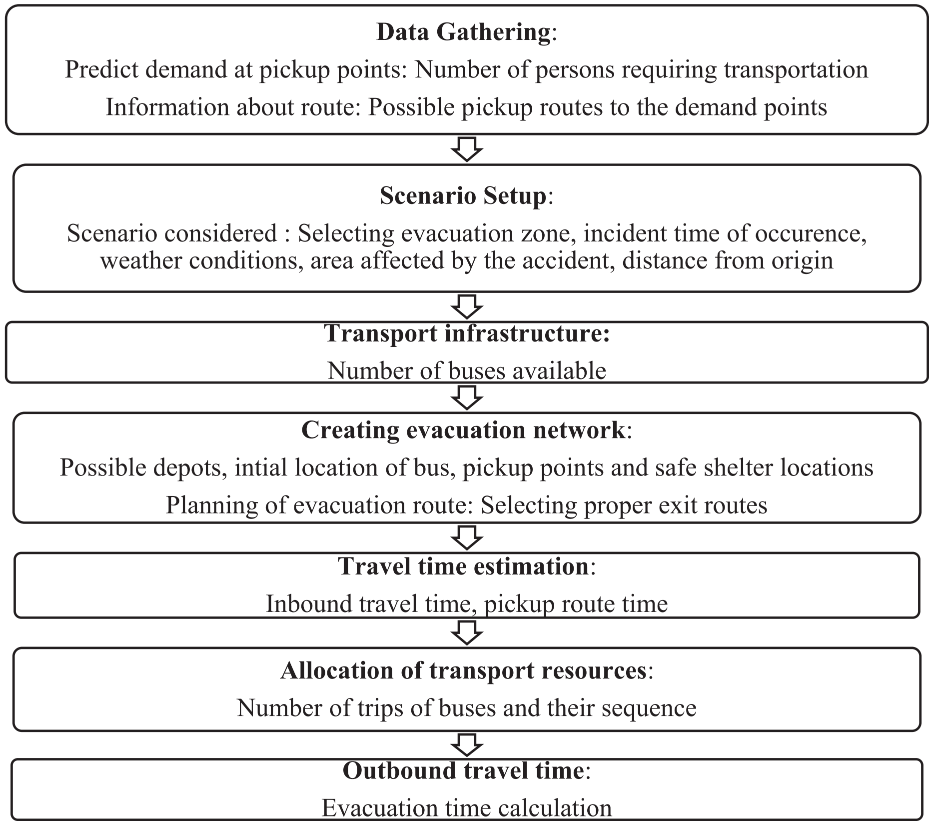

Fig. 2. Steps involved in bus-based evacuation problem (Urbanik II, 2000).

we have assumed that from a pickup point, the bus takes the evacuees to an assigned shelter. Let $C_{y,i}$ be the capacity of bus i of yard y and s_p be the shelter assigned to a particular pickup point p. Let r_p be the pickup point-shelter pair, i.e., $r_p = \{p, s_p\}$. The travel time from the pickup point p to its assigned shelter s_p is given bydf_{r_p}. Fig. 4 shows a pictorial representation of these parameters for better understanding.

We use the binary variable $x_{y,i,j}$ that takes value 1 if jth trip of a bus i that is initially located at yard y happens, and otherwise 0. Another binary variable s_{y,i,j,r_p}takes value 1 if that bus goes to pickup point p, and is otherwise 0. The bus reaches a pickup point p and takes l_p minutes to load the population. Once the bus is full, it departs to the assigned shelter. On reaching the assigned shelter, it takes u_{s_p}minutes to unload the bus. The bus then makes subsequent trips to different pickup points from the shelter.

Let $\tau_p$be the available time by which demand D_p must be satisfied and $L_{i,y}$be the maximum number of round trips a bus i of yard y can make in the available time. The expression for trip time (t_{y,i,j,r_p}) of a bus for its jth trip to point p can be given by the summation of three time components: travel time from the previous trip *(j-1)* shelter's to point p, travel time from point p to jth trip shelter and the loading, rest stop (r) and unloading time.

$$t_{y,i,j,r_p} = \begin{cases} (d_{y,p} + df_{r_p} + l_p + u_{s_p} + r).\ s_{y,i,j,r_p} & j = 1 \\ \left(\sum\limits_{g \in [P]} (df_{p-s_g}).\ s_{y,i,j,1,r_g} + (df_{r_p} + u_{s_p} + l_p + r) \right). & 2 \leqslant j \leqslant L_{i,y} \\ s_{y,i,j,r_p} & \end{cases} \tag{1}$$

Once the time for a particular trip is known, the *clock time* of a particular bus ($ct_{y,i,j}$), i.e., the cumulative travel time of a bus until the jth trip is given by:

$$ct_{y,i,j} = \sum_{z=1}^{j} \sum_{k \in [P]} t_{y,i,z,r_k} \tag{2}$$

3.1. Linearization of trip time

Clearly, Eq. (1) is nonlinear. Since the problem size can be large in this context, nonlinear programming may not give satisfactory results in reasonable time. Therefore we linearize Eq. (1). To do so, another binary decision variable $z_{y,i,j,r_p,r_g}$is introduced which takes value 1 if the bus has gone to the pair $\{g, s_g\}$ during the $(j-1)$th trip and it goes to

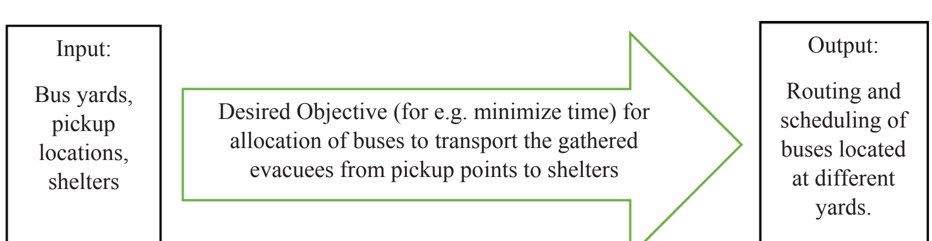

Fig. 3. Bus-based evacuation modelling components.

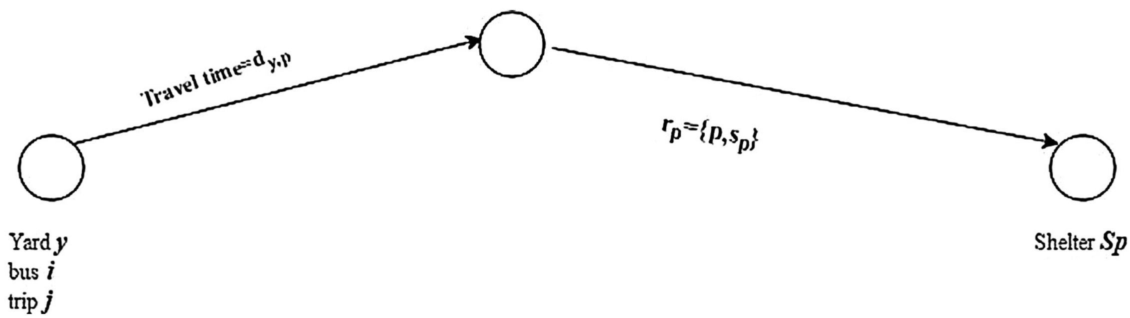

Fig. 4. Pictorial view of notation of parameter used.

pickup point p during jth trip. Then the trip time to pickup point p is given by:

$$t_{y,i,j,r_p} = \begin{cases} (d_{y,p} + df_{r_p} + l_p + u_{r_p} + r).\ s_{y,i,j,r_p} & j = 1 \\ \left(\sum_{g\in[P]} (df_{p-s_g}).\ z_{y,i,j,r_p,r_g} + (df_{r_p} + u_{s_p} + l_p + r).\ s_{y,i,j,r_p} \right) & 2 \leqslant j \leqslant L_{i,y} \end{cases} \tag{3}$$

3.2. Formulation

Mixed integer linear programming models are formulated to find the operating strategies of buses. In order to plan for bus-based evacuation, first and foremost, it is important to know the minimum number of buses required to evacuate all transit dependent people. To do so, a mathematical model M1 has been formulated that determines the minimum number of buses that must be available. Let B be the minimum number of buses required (at all depots put together) in order to perform evacuation within the available time and M be a large positive number. Then M1 can be formulated as:

3.2.1. Model M1

$$\min B \tag{4}$$

subject to

$$\sum_{i\in[B_y]} x_{y,i,1} \geqslant K_y \qquad y\in[Y] \tag{4a}$$

$$x_{y,i,j} \geqslant x_{y,i,j+1} \qquad y\in[Y],\ i\in[B_y],\ j\in[L_{i,y}] \tag{5}$$

$$\sum_{y\in[Y]}\sum_{i\in[B_y]}\sum_{j\in[L_i]} x_{y,i,j}.\ C_{y,i} \geqslant \sum_{p\in[P]} D_p \tag{6}$$

$$\sum_{p\in[P]} s_{y,i,j,r_p} \leqslant x_{y,i,j} \qquad y\in[Y],\ i\in[B_y],\ j\in[L_{i,y}] \tag{7}$$

$$\sum_{y\in[Y]}\sum_{i\in[B_y]}\sum_{j\in[L_i]} s_{y,i,j,r_p}.\ C_{y,i} \geqslant D_p \qquad p\in[P] \tag{8}$$

$$2.\ z_{y,i,j,r_p,r_g} \leqslant s_{y,i,j,r_p} + s_{y,i,j-1,r_g} \qquad y\in[Y],\ i\in[B_y],\ j\in[L_{i,y}],\ p\in[P] \tag{9}$$

$$z_{y,i,j,r_p,r_g} \geqslant s_{y,i,j,r_p} + s_{y,i,j-1,r_g} - 1 \qquad y\in[Y],\ i\in[B_y],\ j\in[L_{i,y}],\ p\in[P] \tag{10}$$

$$\left(1 - s_{y,i,j,r_p}\right).\ M \geqslant (ct_{y,i,j} - \tau_p) \qquad y\in[Y],\ i\in[B_y],\ j\in[L_{i,y}],\ p\in[P] \tag{11}$$

$$B \geqslant \sum_{y\in[Y]}\sum_{i\in[B_y]} x_{y,i,1} \tag{12}$$

The objective of model M1 is given by Eq. (4), i.e., to minimize B. The constraints of the model are given by Eqs. (4a)–(12). Eq. (4a) assures that every bus available at yard y is used for evacuation. Eq. (5) ensures that the subsequent trip of a bus can happen only when its current trip has been completed. Eq. (6) corresponds to the meeting of all demand, i.e., the total number of trips by all buses must be greater than or equal to the total demand at the pickup points. Eq. (7) ensures that only if the jth trip of a particular bus has happened, it go to a pickup point during its jth trip. Eq. (8) is to ensure that the number of trips of buses at each pickup point is greater than its required demand (D_p). Eqs. (9) and (10) are for consistency in the definition of variablez_{y,i,j,r_p,r_g}. Eq. (11) ensures that if a bus trip happens to a pickup point, its clock time must be less than the available time of that point. Eq. (12) is for calculating the minimum number of buses required for performing evacuation within the available time.

Model M1 gives the total number of buses that must kept to evacuate within the available time. However, the evacuation time can be reduced by changing the operating strategies of trips. Therefore, it is important for the decision maker to determine the optimal operating strategies of a given number of buses (greater than the one given by model M1) in order to minimize the overall evacuation time. To do so, a model M2 has been proposed. It finds the optimal schedule of the initial and the subsequent trips of all buses in order to minimize the exposure time to casualty from all pickup points. The variable T_{max} denotes the maximum overall evacuation time from all pickup locations. The mathematical model M2 can be formulated as:

3.2.2. Model M2

$$\min T_{\max} \tag{13}$$

subject to

$$x_{y,i,j} \geqslant x_{y,i,j+1} \qquad y\in[Y],\ i\in[K_y],\ j\in[L_{i,y}] \tag{14}$$

$$\sum_{y\in[Y]}\sum_{i\in[K_y]}\sum_{j\in[L_i]} x_{y,i,j}.\ C_{y,i} \geqslant \sum_{p\in[P]} D_p \tag{15}$$

$$\sum_{p\in[P]} s_{y,i,j,r_p} \leqslant x_{y,i,j} \qquad y\in[Y],\ i\in[K_y],\ j\in[L_{i,y}] \tag{16}$$

$$\sum_{y\in[Y]}\sum_{i\in[K_y]}\sum_{j\in[L_i]} s_{y,i,j,r_p}.\ C_{y,i} \geqslant D_p \qquad p\in[P] \tag{17}$$

$$2.\ z_{y,i,j,r_p,r_g} \leqslant s_{y,i,j,r_p} + s_{y,i,j-1,r_g} \qquad y\in[Y],\ i\in[K_y],\ j\in[L_{i,y}],\ p\in[P] \tag{18}$$

$$z_{y,i,j,r_p,r_g} \geqslant s_{y,i,j,r_p} + s_{y,i,j-1,r_g} - 1 \qquad y\in[Y],\ i\in[K_y],\ j\in[L_{i,y}],\ p\in[P] \tag{19}$$

$$\left(1 - s_{y,i,j,r_p}\right).\ M \geqslant (ct_{y,i,j} - \tau_p) \qquad y\in[Y],\ i\in[K_y],\ j\in[L_{i,y}],\ p\in[P] \tag{20}$$

$$T_{\max} \geqslant ct_{y,i,j} \qquad y\in[Y],\ i\in[K_y],\ j\in[L_{i,y}] \tag{21}$$

The objective of the model is given by Eq. (13) which aims to minimize $T_{\max}$. Constraints of the model are given by Eqs. (14)–(21). Constraints (14)–(20) are the same as constraints (6)–(11). Constraint (21) define the T_{max} as the maximum clock time across all trips among

Table 2
Past accidents involving mass scale evacuation of people (IFRC, 2015).

Year	Accident	Evacuation Decision
1979	Three mile island	10 mile radius needs to be evacuated
1986	Chernobyl	30 kms was evacuated, 115,000 people relocated
2011	Fukushima Daiichi	20 kms was evacuated, 78,000 people relocated

all buses.

The model M2 determines the optimal sequence of each bus. The bus driver can be trained to follow the sequence computed by the models. However, in an emergency, there can be various kinds of uncertainties involved (as stated in Section 1). These uncertainties change the value of parameters used in the above models. For example, due to a bus breakdown, the number of available buses can change. Or, due to increased severity of the emergency, the available time for evacuation τ_p could reduce. In such situations, since finding a new optimal solution could be both time consuming and difficult for drivers to learn, it is important for the emergency manager to get a feasible solution which is similar to the already planned optimal solution (the solution to which drivers are trained). It is clear, that the bigger the change in parameter values, the worse will be the solution quality. So, the new solution is not intended to be a universal response to any systematic change but only a quick response to a small perturbations. In order to find this new solution, the model M3 is proposed which finds the minimum change in sequence (optimal before the effect of changed conditions due to introduction of uncertainty) of buses required to get a feasible solution. Let s^*_{y,i,j,r_p} be the optimal solution for earlier scenario, i.e., before the introduction of uncertainty. Then, the mathematical model M3 can be formulated as:

3.2.3. Model M3

$$\min \sum_{y\in[Y]}\sum_{i\in[K_y]}\sum_{j\in[L_i]}\sum_{p\in[P]} |s_{y,i,j,r_p} - s^*_{y,i,j,r_p}| \tag{22}$$

$$\min \sum_{y\in[Y]}\sum_{i\in[K_y]}\sum_{j\in[L_i]}\sum_{p\in[P]} k_{y,i,j,r_p} + h_{y,i,j,r_p} \tag{22a}$$

subject to

$$k_{y,i,j,r_p} - h_{y,i,j,r_p} = s_{y,i,j,r_p} - s^*_{y,i,j,r_p} \tag{22b}$$

$$k_{y,i,j,r_p} \geqslant 0, \quad h_{y,i,j,r_p} \geqslant 0 \tag{22c}$$

$$x_{y,i,j} \geqslant x_{y,i,j+1} \qquad y\in[Y],\ i\in[K_y],\ j\in[L_{i,y}] \tag{23}$$

$$\sum_{y\in[Y]}\sum_{i\in[K_y]}\sum_{j\in[L_i]} x_{y,i,j}.\ C_{y,i} \geqslant \sum_{p\in[P]} D_p \tag{24}$$

$$\sum_{p\in[P]} s_{y,i,j,r_p} \leqslant x_{y,i,j} \qquad y\in[Y],\ i\in[K_y],\ j\in[L_{i,y}] \tag{25}$$

$$\sum_{y\in[Y]}\sum_{i\in[K_y]}\sum_{j\in[L_i]} s_{y,i,j,r_p}.\ C_{y,i} \geqslant D_p \qquad p\in[P] \tag{26}$$

$$2.\ z_{y,i,j,r_p,r_g} \leqslant s_{y,i,j,r_p} + s_{y,i,j-1,r_g} \qquad y\in[Y],\ i\in[K_y],\ j\in[L_{i,y}],\ p\in[P] \tag{27}$$

$$z_{y,i,j,r_p,r_g} \geqslant s_{y,i,j,r_p} + s_{y,i,j-1,r_g} - 1 \qquad y\in[Y],\ i\in[K_y],\ j\in[L_{i,y}],\ p\in[P] \tag{28}$$

$$\left(1 - s_{y,i,j,r_p}\right).\ M \geqslant (ct_{y,i,j} - \tau_p) \qquad y\in[Y],\ i\in[K_y],\ j\in[L_{i,y}],\ p\in[P] \tag{29}$$

Note that this apparently nonlinear model (due to presence of absolute value function in Eq. (22) can be easily linearized by: (i) Replacing Eq. (22) with Eq. (22a), (ii) adding the following 2 constraints: (22b), (22c). The objective of the model is given by Eq. (22) that tries to minimize the absolute change in sequence required for the changed conditions. Constraints of the model are given from Eqs. (23)–(29). This model is expected to be solved quickly (if perturbations values are small) due to the presence of a good starting point in the form of s^*_{y,i,j,r_p}.

4. Case study of radiological disaster

In this section, various response actions that can be used during a radiological emergency are presented. Once the correct response action is chosen for the given scenario, the steps required to perform the response action effectively are laid out.

4.1. Radiological emergency

Nowadays, many developing countries have embarked upon large nuclear reactors. However, the safety record of nuclear power plants is questionable as 99 accidents have been reported from 1959 to 2009 (Sovacool, 2010). There are many causes for nuclear accidents including human error, system failure, sabotage, cyclone, flood and earthquake (National Disaster Management Authority, 2009). The three major accidents in the past (listed in Table 2) led to a mass scale evacuation of people to save their lives. As per Nuclear Regularity Commission (NRC) guidelines (Kantor et al., 1996), it is mandatory for the nuclear business operator to prepare response measures in the case of a radiological emergency. As per guidelines, ETE for partial or total evacuation of population within a 10-mile radius, i.e., Evacuation Planning Zone (EPZ) of a facility should be predicted and proper evacuation planning is required.

4.2. Response

In case of an accident, if there is release of radioactive material in the environment, a correct response is required. The basic information needed before performing any response action includes (Glickman and Ujihara, 1990): type and properties of substance released, amount of substance released, health effect from short term exposure, distance from nuclear facility, time of release, medium by which it is released i.e. water, air.

The response action can be either to remove the population from the exposure zone, i.e., evacuation, or to shelter-in-place (Georgiadou et al., 2007). Fig. 5 shows the decision to be taken in different region of EPZ (Dhingra and Roy, 2015). If the pickup point is within a 5 km radius then it must be evacuated and beyond that either of the two can be chosen based on the concentration level of radiation and time available. As evacuation involves social disruption and huge amount of cost, evacuation should be done only in case:

- Dosage of radiation is above the threshold level (Georgiadou et al., 2007).
- Evacuation time of a region is less than the anticipated time in which radiation vapor cloud would reach the region (i.e. the available time)

In case of a nuclear accident, evacuation time depends upon a number of factors including number of people that need to be evacuated, condition of road network, effectiveness of evacuation planning, time of the day evacuation is to be carried out and weather conditions (Glickman and Ujihara, 1990). On the other hand, the available time for target evacuation (time by which vapor cloud will reach the area) depends upon the extent of the accident, wind speed and progression of the accident (Lee et al., 2016). Once target evacuation time of different regions in EPZ is known for a given scenario, action plan for different activities can be computed. Table 3 typically provides the time by which actions should be performed in case of an accident.

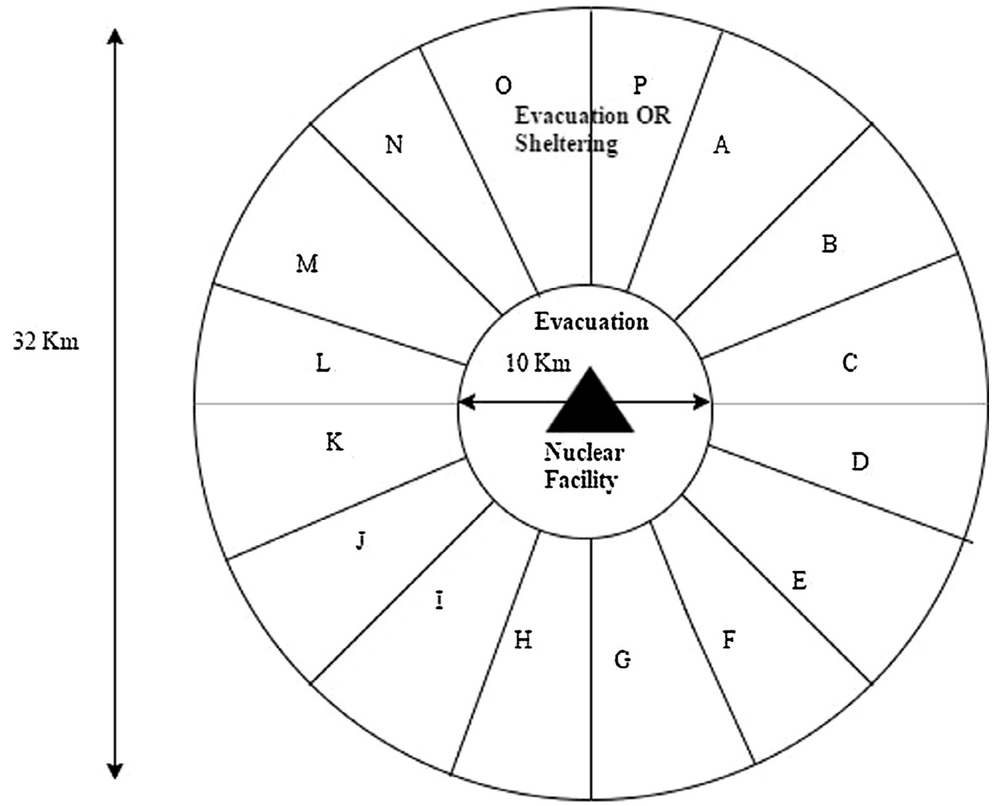

Fig. 5. Evacuation Planning Zone (EPZ).

Table 3
Typical timeline guidelines in case of nuclear accident (Lee et al., 2016).

Actions	Time
Alert message: Onsite Control provides warning to staff after verification	Within 15 min
Informing all off-site emergency center	Within 30 min
Informing local residents about the status of nuclear plant	Within 45 min
Protective action to be carried out	Within 1 h

4.3. Case study

The case for developing an evacuation plan near Kakrapar Atomic Power Station (KAPS), Gujarat, India is presented. In this study, the focus is on allocating the available resources optimally during the evacuation.

As stated earlier, an EPZ consists of a 10 mile radius around the nuclear facility. ETE should be known for the populated areas in the EPZ. To do so, the 10 mile radial area is divided into 16 segments as shown in Fig. 5. In each sector, there are several villages. Based on the scenario considered (wind condition, distance from nuclear facility, substance released, etc.) the villages that need to be evacuated can be decided. As there are mostly rural areas in the 10 mile radius of the facility, people will rely on public transport for evacuation. Thus, bus-based evacuation planning is required.

As stated in Section 2, bus-based evacuation planning consists of a set of bus yards ([y]), pickup points ([P]), and shelters ([F]). Roy et al. (2014) in their work have done extensive survey to find these input parameters for the evacuation plan development. The same parameters have been used in our study. However, they have not considered issues like planning for minimum resources that must be available, optimal allocation of the buses, multiple trips to different villages and uncertainty issues. The models developed in this paper address these issues.

4.3.1. Input parameters

Let there be 13 pickup points in sector L and M (Fig. 5) with a total population of around 3 million. Due to radiation release, the population needs to be evacuated to shelters. Roy et al. (2014) find temporary holding areas (like school, community center) outside the EPZ, where temporary shelter and medical facilities can be provided to victims. From the given possible shelters, a particular shelter is assigned to pickup points based on minimum travel time required to reach the shelter. There are two potential holding spaces areas near the villages of sector L and M and outside EPZ which can serve as temporary shelters for these pickup points. Fig. 6 shows the location of these shelters which can serve as temporary holding area for 13 pickup points.

As stated earlier, we are assuming that all the population will be evacuated with the help of buses. Hence, the developed models M1, M2, M3 (of bus-based evacuation planning) need to be applied in case of evacuation planning.

Table 4 shows the assigned shelters for different pickup points. It also shows the population of various villages that needs to be evacuated to the assigned shelter within a given available time, after which toxic radiation cloud will reach the village. The available time is calculated based on the climate and severity of the accident. Table 4 shows the time by which each village must be evacuated. There can be various routes for a bus to take from depot to pickup points and then from pickup point to its assigned shelter. It has been assumed that the bus takes the evacuees from the fastest route. To calculate the fastest route, the length of routes is calculated and by assuming a constant value of speed (given in Table 5) the fastest route travel time is calculated. Table 5 also presents the values of other parameters used in the case study. In the absence of detailed data of differential bus capacity, it is assumed to be the same for all buses. But clearly, the model can handle differential capacities as well. Table 4 shows the value of these parameters i.e. $d_{y,p}$ and df_{r_p}.

Once all the parameters and information are known, minimum buses that are required can be computed using model M1. Also, the bus

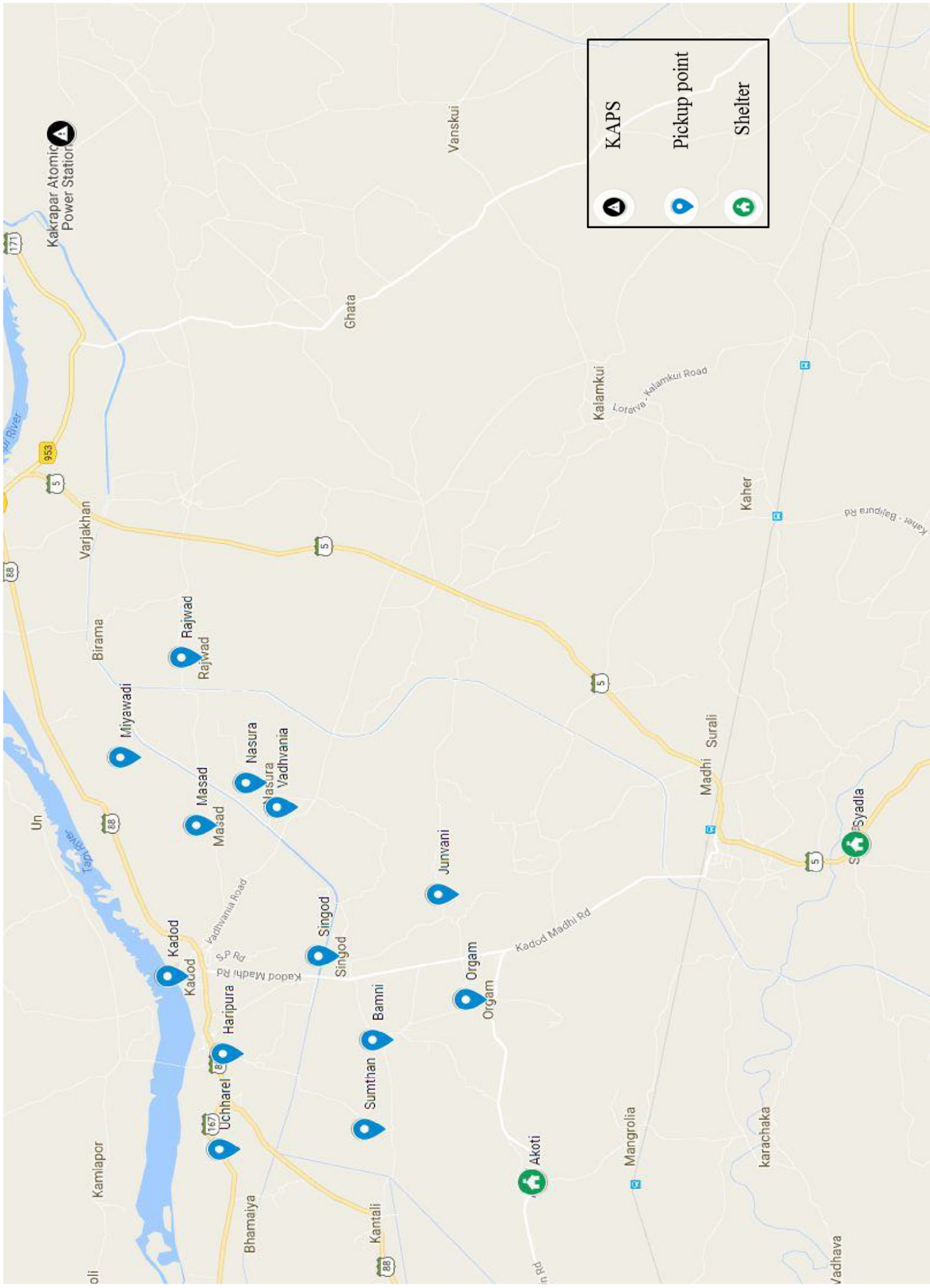

Fig. 6. Location of pickup points and shelter for scenario considered.

operating strategies can be computed solving model M2 in case of the availability of a given number of buses.

5. Results and discussion

In this section, the results of the case study of an accident at a nuclear facility requiring immediate evacuation of nearby regions are presented. The developed models will help the authorities to develop an evacuation plan for the disaster where sufficient time window is present to evacuate the victims after a disaster warning. Based on wind flow direction and wind speed, a scenario is considered in which sectors L and M need to be evacuated. The emergency manager will want to find out:

- Minimum number of buses that must be available in order to carry out the evacuation.
- The operating strategies, i.e., sequence of bus trips required to be carried out in order to minimize the evacuation time of the last village that will be evacuated.

5.1. Environment

All the models are linear in nature and have been coded in IBM CPLEX. All the scenarios are conducted on a machine with Intel core i7 and 32-GB of random access memory.

Table 4
Input parameters for the case study.

Village no.	Sector	Name	τ_p	D_p	$d_{y,p}$		$df_{p,s}$		Shelter assigned
					Bardoli	Surat	Syadla	Akoti	
1	L	Rajvad	90	19	36	83	20	34	Syadla
2	M	Miyawadi	120	7	33	105	17	31	Syadla
3	L	Nasura	120	12	31	75	16	30	Syadla
4	L	Masad	120	26	28	72	13	28	Syadla
5	L	Vadhvani	150	23	30	67	14	30	Syadla
6	L	Junvani	150	10	34	70	19	14	Akoti
7	M	Kadod	150	143	23	72	7	23	Syadla
8	L	Singod	150	28	38	88	14	18	Syadla
9	L	Haripura	150	22	22	67	8	24	Syadla
10	L	Bamni	150	18	30	67	16	10	Akoti
11	L	Uchhrel	150	17	21	86	6	26	Syadla
12	L	Orgam	150	21	29	65	21	9	Akoti
13	L	Samthan	150	14	35	79	19	15	Akoti

Table 5
Parameters to compute the evacuation time.

Parameter	Value
Bus speed (v)	Highway:50 km/h Rural road: 25 km/h
Loading and unloading time	8 min
Bus capacity	80 persons (same for all)
Maximum trips allowed (by heuristic)	4

5.2. Maximum number of trips allowed

In the models given in Section 3, it is important to find the range of variable j. Generally, models use the value of j equal to the total number of trips required (Goerigk et al., 2015). However, for this problem, if the range of j is {1…360}, it is not possible to find the solution even with a running time of 80hrs for this problem. Therefore, it is important to find the value of the parameter $L_{i,y}$. Then j can vary in {1…$L_{i,y}$}.

To determine the maximum number of trips allowed to the buses, we have proposed a heuristic. In this heuristic, a branching procedure is followed. Fig. 7 shows the way branching is done for the clock time of buses that may go to different villages. We have assumed that branching will be done until the clock time is less than the available time of the village to which a bus is going. Minimum clock time across all buses is recorded and further branching for the minimum clock time value is done. From the branching, it was observed that no bus from Bardoli depot or Surat depot could make more than four trips. Therefore, $L_{i,y}$ is set to be 4.

5.3. Model M1: minimum resources evacuation problem

Model M1 has been applied to find out the minimum number of buses required in order to evacuate all the 13 villages' population to their respective shelters within given amount of time. The Bardoli bus depot is near to sector L and M which can be used to evacuate these villages. The travel time of Bardoli depot to different pickup points is given in Table 4. Further, in this section, we let the capacity of each yard B_y equal 150.

The model M1 calculates that 101 buses must be available at Bardoli depot to carry out the evacuation (in 22 min 45 s). Table 6 shows the number of trips made by buses and their respective sequence. It can be inferred from the table that all buses are required to make at least three trips to different villages, and 57 buses are required to make the fourth trip. Further, the detailed sequence of the buses is given in Table 7. For instance, it can be seen from the table that six buses follows a sequence of $\{1 - s_1 - 3 - s_3 - 7 - s_7\}$.

However, practically it may not be possible to have these many buses at Bardoli depot (due to demand of buses for daily usage and budget constraint). In such cases, buses should come from the other depots as well. In this context, therefore, buses from next nearest depot, i.e. Surat depot need to be used to evacuate these villages.

In real life, the buses available at each of the 2 depots will be given. In this case study let each depot have 50 buses each. Note that 50 is a number chosen as an example and the method will work for all other cases.

If 50 buses are available at each depot, i.e., a total of 100, then M1 can be used to find the minimum additional number of buses to be placed at Bardoli depot. Using $K_1 = 50$, $K_2 = 50$, M1 computes that the total number of buses $B = 118$. This means that 18 additional buses need to be made available at Bardoli depot.

Recall that model M1 gives the minimum number of buses that must be kept to evacuate within available time. However, the evacuation time can be reduced by changing the sequence of trips. Therefore, model M2 has been applied to find the routing and sequence of buses in order to minimize the overall evacuation time.

5.4. Model M2: minimum evacuation time

The number of buses that should be available at depots (at a given time) must be greater than the one calculated from model M1. Therefore, we considered a scenario when the available number of buses at the time of evacuation is greater than the minimum number of buses. Let $K_1 = 70$ and $K_2 = 75$. Model M2 has been applied for this scenario to find the optimal sequence of buses.

The results indicate that all the 13 villages can be evacuated safely within 137 min. Table 8 shows the allocation and pattern of multiple trips to different villages required in order to carry out the evacuation. The column in table indicate the trip number and rows correspond to the 13 villages ($p = 1, 2…,13$). The entry in the pth row and jth column of the Table 8 indicates the number of buses that travelled to village p in their jth trip. The computational time for this scenario is 8 min 14 s.

5.5. Model M3: uncertainty in available time and bus availability

We consider two scenario for model M3.

(a) **Change in available time**

We consider scenarios in which the severity of accident changes the available evacuation time. The available time changes from the existing value to 0.93 times that value, for all the villages. It was found that only six trips of some buses need to be changed to get a new feasible solution. The computational time for the model less than 10 s.

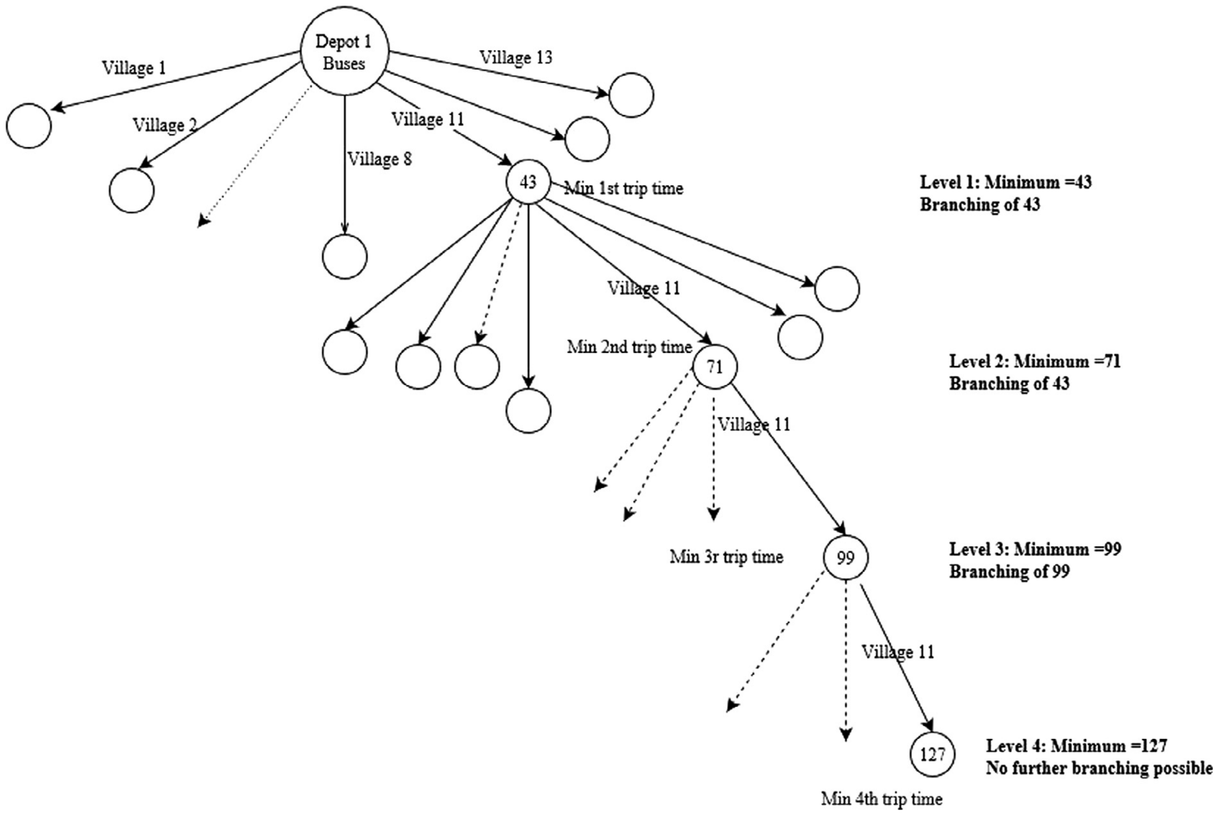

Fig. 7. Branching for finding the maximum number of trips allowed.

Table 6
Number of trips and their respective sequence in case Bardoli depot is used.

Village	Trip				Evac time (min)	Avlb. time (min)
	1	2	3	4		
1	19	0	0	0	72	90
2	6	1	0	0	107	120
3	4	8	0	0	120	120
4	12	14	0	0	114	120
5	7	6	10	0	146	150
6	2	3	5	0	150	150
7	28	32	38	45	150	150
8	0	11	17	0	148	150
9	12	0	5	5	150	150
10	0	8	10	0	150	150
11	4	7	3	3	149	150
12	1	3	13	4	150	150
13	6	8	0	0	112	150
Total Trips	101	101	101	57		

(b) **Change in availability of buses**

We consider scenarios in which the total available buses at depots reduces (due to either bus breakdown or non-availability of drivers). In the original scenario $K_1 = 70$, $K_2 = 75$. In the new scenario, K_1 and K_2 reduces by 2.5% each and become $K_1 = 68$, $K_2 = 73$. Model M3 results in a change for only 17 trips of some buses to yields a new solution within 16 s. This is much better compared to the computational time of 9 min 50 s that would be needed if the new problem was solved using model M2. Further, Table 9 presents the evacuation time of each village using the solution for M3.

6. Discussion

The results of the case study show that the models developed can help the emergency manager in determining the optimal bus operating strategies for efficient evacuation. These models provide proactive strategies to help decision makers with various strategic and tactical decisions. The decisions include the minimum number of buses that

Table 7
Trip-wise villages visited by Bardoli depot buses.

Sequence				No. of buses	Sequence				No. of buses
1	3	7		6	9	7	8	7	4
1	10	12		5	4	2	10		1
1	7	5		1	5	8	5		1
1	11	6		2	4	3	5		1
1	8	9		1	11	7	10	12	2
1	7	8		1	2	6	12		1
1	3	11		1	13	13	12		2
1	4	9		1	9	4	7	7	1
1	10	10		1	13	13	10		1
5	7	11	7	1	9	8	7	7	3
7	4	7	9	2	4	7	9	7	2
4	5	5		1	2	4	10		1
7	4	7	7	5	3	6	12		1
4	7	7	7	2	13	12	8		2
3	4	8		1	6	10	8		1
5	7	7	7	4	11	7	5	9	1
13	12	6		1	3	11	7	11	1
12	13	6		1	2	10	12		1
7	8	7	7	4	9	4	7	9	1
2	13	12		3	4	7	7	9	1
4	13	10		1	4	7	7	11	1
7	7	8	7	7	6	8	7		1
4	11	7	7	1	5	6	10		1
7	7	5	7	3	9	5	7	11	1
9	7	5	7	1	11	7	5	7	1
7	11	10	12	1	7	4	8		1
9	11	10	12	1	7	4	9	7	1
7	5	7	7	4	4	8	6		1
3	11	11	7	1					

Table 8
Allocation and pattern of multiple trips required to different villages in order to carry out the evacuation.

↓ Village trip	Bardoli depot				Surat depot			
	1	2	3	4	1	2	3	4
1	19	0	0	0	0	0	0	0
2	2	5	0	0	0	0	0	0
3	1	4	0	0	7	0	0	0
4	2	1	0	0	23	0	0	0
5	0	1	6	0	13	3	0	0
6	0	0	0	0	6	4	0	0
7	20	29	35	15	0	44	0	0
8	1	19	8	0	0	0	0	0
9	14	2	2	0	4	0	0	0
10	1	0	1	0	10	6	0	0
11	8	2	5	2	0	0	0	0
12	0	0	2	0	7	12	0	0
13	2	7	0	0	5	0	0	0
Trips total	70	70	59	17	75	69	0	0

Table 9
Evacuation time comparison for Model M3.

Village	EvacTime Model3	Village	EvacTime Model3
1	72	8	134
2	96	9	144
3	120	10	149
4	114	11	134
5	135	12	134
6	137	13	110
7	144		

must be available at various depots for evacuation. Once that is known, another model attempts to determine the optimal routes of buses which as seen in the results, reduce the overall evacuation time.

While computing the results, it has been assumed that all the shelters are known before the emergency and are active whenever needed. However, during an actual disaster, it may be the case that the number of evacuees present at the shelters is not known or even that the chosen shelters are not active. In such cases, the number of buses required may increase. In such cases, the emergency manager should make necessary changes in the planned operating strategies. However, the emergency manager will want to minimize such changes since drivers would have been proactively trained for the original plan. To address these requirements, a model similar to model M3 can be developed for such cases. This model will determine the number of planned trips whose patterns need to be changed to make the plan feasible for the changed scenario. Incorporating such uncertainties to develop new models can be a useful future extension of this work. Simulation based models can also help for such scenarios. These models can determine the effects of shelter activity level on evacuation dynamics. Further, during evacuation, the demand (i.e., pickup number) can be unpredictable. However, as stated earlier, when proactively planning for a disaster response, the emergency manager must have an idea of the number of transit vehicles (buses in particular) required to evacuate the population present in an endangered area. Similarly, the emergency manager needs some idea of the possible drop-off points to determine the lower bound of number of buses required to evacuate people in the endangered area.

In the case study presented, it has been assumed that the transport infrastructure i.e., route capacities are not affected by the disaster. It has also been assumed that the travel time from any route is known and constant. However, during disasters such as hurricanes, floods and forest fires, routes may be either inaccessible or their capacity may reduce due to the impact of the disaster. This will change the travel time from that route and in the worst case, it may happen that a particular route becomes inaccessible. Thus, the emergency manager should ideally plan for such (travel time) uncertainties as well. For that purpose, models need to be developed to determine the bus operating strategies for a given range of uncertainty in travel time. A model similar to model M3 can be formulated in which dynamic travel time is considered. Our models can be a starting point for such models that consider uncertainties and dynamic travel time.

We also re-emphasize the following: that it has been assumed, quite realistically, that for nuclear sites, the roadway structure will be appropriately developed. That is indeed the case for the considered case study, where access to highway is fairly good for such evacuations. When that is not the case, the parameter for speed (v) can be estimated incorporating the various constraints.

To make these models useful in practice, we have considered that buses can be of different capacities. However, it should also be noted that at any pickup point, there can be different type of people such as old people, child, and special need population. Therefore, it is important to anticipate the population profile of pickup points. The reason for such anticipation is that the number of buses required to completely evacuate any pickup point depends upon the population profile of that point. For instance, if a bus can take 80 normal persons, it will take less number of special needs population. Accordingly, effective estimated demand (i.e., D_p) at each pickup point should be known to decision makers. Even though D_p itself has uncertainties associated to it, for developing proactive strategies, it should be estimated as accurately as possible. Such estimation of demand at any pickup point is a complex process and can be made a good future extension by studying behavior and profile of the population. In the presented case study, we have assumed that effective demand of all the pickup points is known.

Overall, we would like to present our models as high level models for an optimal decision framework, to be used as inputs for detailed simulation models for minute-by minute evacuation plan.

7. Conclusion

In this paper, models and algorithms for bus-based evacuation planning have been presented. It consists of finding effective operating strategies for the buses to be used in evacuation in order to achieve a desired objective. Three mixed integer linear programming models are developed to find these optimal operating strategies. The models have been applied to a case of radiological emergency where evacuation of a defined area needs to be carried out by a fleet of buses.

The results demonstrate that these models can help in handling the evacuation situation effectively: they compute the minimum number of buses that must be available in order to carry out the evacuation for any given scenario, and determine the optimal trip sequence of each available bus. The bus driver can be trained beforehand to follow this sequence. However, during an emergency, there can be various uncertainties which may require a change in the *trained sequence* of buses. To minimize disruption due to such uncertainties, it is advisable for the new bus sequences to be as similar to the original as possible. Accordingly, the model M3 developed in the paper determines the minimum change in the original sequence required to get a feasible solution after incorporating the changes effected by uncertainties. Overall, it can be concluded from the case considered that these models can help decision makers not only in strategic planning but also in operational planning of handling emergencies effectively.

Future extension of the work includes developing robust models for different kinds of uncertainties involved. Examples of such uncertainties include the change in inbound and outbound travel time as in the case of a flood. Further, some hazards compromise the transportation infrastructure and the corresponding parameters may be dynamic throughout the event. As a result, considering route flexibility, i.e., choosing a route between a pickup point and available shelters that is different from the original plan, can be incorporated in these models. The models developed in this manuscript can be used as a base model for considering such route flexibility. Thus, route flexibility can also be considered as a future extension to the work. Furthermore, the effective estimation of demand at any pickup point is a future extension which requires study of population behavior and profile. Lastly, the effect of demand and shelter uncertainties can also be a possible future research direction.

On a slightly different rack, it will also be interesting to find the operating strategies of buses in cases, where congestion due to personal vehicles exists. Another interesting area is a study of the effect of availability of drivers and their behaviors on evacuation dynamics through agent based models will be required. All these studies, however, require very different models and datasets to be effective and can be a part of future work that aims to practically implement structured modeling to real life situations.

Acknowledgments

This project is partially supported by the Human Settlement Management Institute, Housing and Urban Development Corporation Limited (HUDCO) and Ministry of Human Resource Development (MHRD), GoI. The authors also would like to thank Dr. Amit Agarwal for his helpful comments. Lastly the authors would like to acknowledge the contribution of Prem Chand and Rama Shankar for carrying out several supporting tasks throughout the duration of the project.

References

Bish, D.R., 2011. Planning for a bus-based evacuation. OR Spectrum 33 (3), 629–654. https://doi.org/10.1007/s00291-011-0256-1.
Deghdak, K., T'kindt, V., Bouquard, J.L., 2016. Scheduling evacuation operations. J. Scheduling 19 (4), 467–478. https://doi.org/10.1007/s10951-015-0461-x.
Dhingra, V., Roy, D., 2015. Modeling emergency evacuation with time and resource constraints: a case study from Gujarat. Socio-Econ. Plan. Sci. 51, 23–33. https://doi.org/10.1016/j.seps.2015.06.001.
Georgiadou, P.S., Papazoglou, I.A., Kiranoudis, C.T., Markatos, N.C., 2007. Modeling emergency evacuation for major hazard industrial sites. Reliab. Eng. Syst. Saf. 92 (10), 1388–1402. https://doi.org/10.1016/j.ress.2006.09.009.
Glickman, T.S., Ujihara, A.M., 1990. Deciding between in-place protection and evacuation in toxic vapor cloud emergencies. J. Hazard. Mater. 23, 57–72.
Goerigk, M., Deghdak, K., T'Kindt, V., 2015. A two-stage robustness approach to evacuation planning with buses. Transport. Res. Part B: Methodol. 78, 66–82. https://doi.org/10.1016/j.trb.2015.04.008.
IFRC, 2015. Nuclear and Radiological Emergency Guidelines Preparedness, Response and Recovery. International Federation of Red Cross and Red Crescent Societies.
Kantor, F., Fox, E.F., Wingert, V.L., McNut, W.F., 1996. Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants Criteria for Emergency Planning in an Early Site Permit Application. United States Nuclear Regulatory Commission.
Kulshrestha, A., Lou, Y., Yin, Y., 2011. Pick-up locations and bus allocation for transit-based evacuation planning with demand uncertainty. J. Adv. Transport. 47 (June 2010), 512–525. https://doi.org/10.1002/atr.
Lee, J., Jeong, J.J., Wonki Shin, E.S., Cheolwoo, C., 2016. The estimated evacuation time for the emergency planning zone of the Kori nuclear site, with a focus on the precautionary action zone. J. Radiat. Protect. Res. 41 (3), 196–205.
Margulis, L., Charosky, P., Fernandez, J., Centeno, M., 2006. Hurricane Evacuation Decision-Support Model for Bus Dispatch. In: Fourth LACCEI International Latin American and Caribbean Conference for Engineering and Technology (LACCET '2006) Breaking Frontiers and Barriers in Engineering: Education, Research, and Practice, (June).
Murray-Tuite, P., Wolshon, B., 2013. Evacuation transportation modeling: an overview of research, development, and practice. Transport. Res. Part C: Emerging Technol. 27, 25–45. https://doi.org/10.1016/j.trc.2012.11.005.
National Disaster Management Authority, 2009. Management of Nuclear and Radiological Emergencies. Retrieved from. <http://nidm.gov.in/pdf/guidelines/new/managementofnuclearradiologicalemergencies.pdf>.
Nawaz, A., Okubo, K., Kubota, H., 2016. Short-notice bus-based evacuation under dynamic demand conditions. Asian Transp. Stud. 4 (1), 228–244.
Roy, D., Sharma, A., Kumar, A., Vivek, S., 2014. Location Identification for Rapid Evacuation from a Disaster Site : A Case Study from KAPS. Indian Institute of Management, Ahmedabad. Retrieved from < https://web.iima.ac.in/assets/snippets/workingpaperpdf/1375022182014-09-01.pdf > .
Sayyady, F., Eksioglu, S.D., 2010. Optimizing the use of public transit system during no-notice evacuation of urban areas. Comput. Ind. Eng. 59 (4), 488–495. https://doi.org/10.1016/j.cie.2010.06.001.
Sovacool, B.K., 2010. A critical evaluation of nuclear power and renewable electricity in Asia. J. Contemp. Asia 40 (3), 369–400. https://doi.org/10.1080/00472331003798350.
Urbanik II, T., 2000. Evacuation time estimates for nuclear power plants. J. Hazard. Mater. 75, 165–180.