A Stochastic Multi-Agent Transportation Network Model for Evacuation Planning

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Abstract

A popular definition of disaster is a sudden, calamitous event and causes human, material, and economic or environmental losses that exceed the community's or society's ability to cope using its own resources (IFRC). Potential consequences of disasters include human and economic loss, as well as economic damages[1]. Efficient evacuation planning gains more and more popularity in researchers because of the frequently happened disaster recently. A transportation network model of evacuation planning with stochastic components is introduced in the paper. This study provides a comprehensive classification of existing works regarding model approaches and formulations, and it provides a stochastic model of multi-agent Minimum Total Evacuation Time (MTET) problem approach to the evacuation problem. Additionally, a heuristic algorithm is discussed as a potential approach to solving this problem.

1. Introduction

The aftermath of disasters includes tremendous human and economic loss, as well as environmental damages. Apart from the disasters mentioned by Galindo and Batta in their review[1], such as 2004 tsunami in the Indian Ocean and 9/11 World Trade Center, a large number of disasters happened after 2015. Examples are the massive earthquake in Nepal in 2015, Syria refugee crisis 2016, and Heidi Hurricane 2016 etc. As a result, there is an increasing number of research cast lights on evacuation planning.

The efficiency of evacuation is critical during the disasters. Numerous study, formulation, and approach has been presented in the recent years to save the evacuation time, and therefore, reduce the human, economic and environmental loss. Existing methods to improve the evacuation efficiency include reserving lanes for evacuation, staging evacuation plan, optimal controlling traffic, and providing guidance to evacuees[2].

This study mainly focuses on the evacuation planning and attaches special importance to evacuation planning as a network design problem (NDP), because many evacuation problems can be generalized as NDPs[2]. Additionally, as the extent of the disaster is hard to predict in advance, stochastic components are necessary to be considered in the model formulation.

This rest parts are organized as follows: it begins with a literature review analyzing the classification of research in the field of evacuation planning. Classification is mainly based on the model type, formulation, and algorithm. In the main body of this study, a multi-agent transportation network model of evacuation planning with stochastic components is introduced with the objective to minimum total evacuation time. Based on the model, further analysis is provided concerning possible algorithm to solve the problem.

2. Literature review

2.1 Classification

The classifications of works are based on five classifications proposed Altay and Green[3]. However, I find the author's affiliation is with little contribution to the study and should be removed. The remaining four classifications are, disaster type, solution methodology, operational stage, and research contribution, respectively.

2.1.1 Disaster operations life cycle

Generally, the disasters can be classified into four stages: mitigation, preparedness, response, recovery[1]. Mitigation refers to the approaches to reduce the risk of disaster and diminish the potential of destructive consequences. Preparedness refers to the approaches for more efficient responses before the disaster. The response involves activities upon the occurrence of the disaster. The recovery stage involves the activities to restore the functioning of the community. Most works done at this stage fall within the mitigation stage and the response stage. For instance, Tuydes et al. propose a heuristic method to solve contraflow evacuation after the occurrence of disaster[4].

2.1.2 Disaster type

There are three types of disasters in our discussion, namely, natural, man-made, humanitarian. Natural disasters are most commonly discussed in the research works, probably because of the high occurrence of natural disasters. However, a growing trend in studying all types of disasters has been identified. This kind of research possesses a strong universality and of great value, because it can be applied to an all-hazard condition.

2.1.3 Methodology

Among the literature in evacuation planning, mathematical programming is the most popular methodology used, like Tuydes et al[4]. Apart from that, simulation, decision theory, and queueing theory are also widely used. Stochastic programming method has recently gained its popularity after 2006[1]. Therefore, we can predict that mathematical programming will still maintain its dominant position in the few years. Among the works adopting mathematical programming, various intelligent approaches are used to solve them, such as tabu search(TS), simulated annealing (SA) and genetic algorithm (GA).

2.1.4 Research contribution

Altay and Green classified the articles into three categories according to the contribution. The three categories are theory, model, and application. The first category includes works provides a framework, test a hypothesis and describe the behavior of a system. The second category groups the article which analyzes the current status of the study. And the products which developed using the state of arts are grouped in the third category. In the study, most of the papers fall within the first category.

2.2 Mathematical Models

2.2.1 Model Representation

The evacuation planning model usually can be represented as a transportation network $G\ (N, A)$ with N denoting Nodes and A denoting the Arcs. Typically, the graph is with limited capacity arcs, single source, and a single destination. The model can be generalized as a simple network problem such as min-cost flow problem and max-flow problem. Usually, the cost is the evacuation time or the evacuation distance that it required from source *s* to destination *d*.

Conventionally, the evacuation planning models are considered to have only one single objective function. However, the literature after 2006 begin to adopt a new iterative Bi-Level framework where the upper level is the decision-maker and the lower level to solve network design problem (See figure 1)[2]. Usually, Bi-Level can be modeled as shown in figure 1.

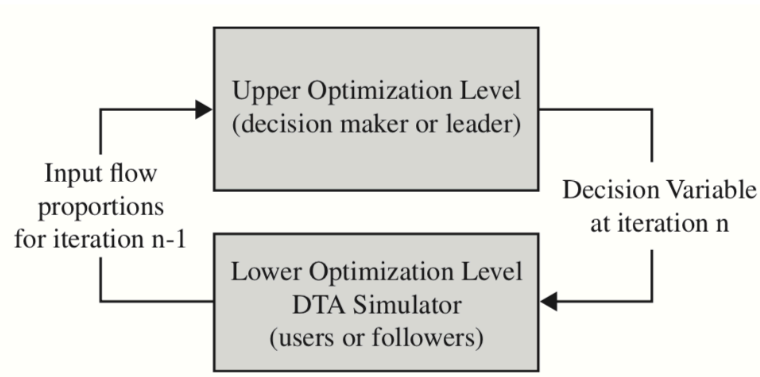

Figure 1 Bi-Level iterative framework

In the bi-level model, it can be regarded as a game played by the decision-maker and the followers. The objective of upper level should the minimize the total cost in the equilibrium, while the objective of the lower level is to minimize the cost traveling between the origin and destination.

It should be noted that because of the computational difficulty of the problem, metaheuristic approach seems to be the best choice to tackle the large-scale evacuation planning problem.

2.2.2 Objective Function

According to the objective of the mathematical model introduced by different works, three major types can be identified, namely, Minimum Total Evacuation Time (MTET), Maximum Dynamic Flow (MDF), Minimum Total Evacuation Distance (MTED). Most of the related works in this review use MTET as an objective function, examples are Sbayti and Mahmassani[5], Huydes and Ziliaskopoulos[4].

Miller-Hooks' MDEF model adopts Maximum Dynamic Flow as objective[6]. Maximum Flow $\mathrm{V(T)}$ is defined as the cumulative number of evacuees from the source S over the time. It is worthy to note that, in order to model the uncertainty of different scenarios, an expected maximum flow is set as the objective function, given the probability of scenario i as $\mathrm{p(i)}$.

Several works focus on MTED as well. Cova and Johnson[7] adopt a lane-based network model which minimize the total travel distance of all evacuees. The model is an integer-extension of the min-cost flow problem. Additionally, as a lane-based approach, this model also set minimizing the merge-conflicts and cross-conflicts as the secondary objective.

2.2.3 Constraints

Generally, the constraints of a min-cost flow problem would include followings: Flow constraints of nodes, capacity constraints of arcs, and binary variable or nonnegative constraints. However, additional constraints are included regarding specific problems considering different evacuation planning classification. For instance, in Tuydes et al.[4], the demand of each network cell and limitation on the flow in the travel time are considered because the model is in a transportation cell representation. In Kim's contraflow configuration[8], additional constraints regarding the reversibility of each arc are included. Wang et al.[9] add randomness constraints on capacity because of the uncertainty of disaster's damage on the transportation network.

2.2.4 Stochastic Components

The degree of the disasters, such as hurricane and earthquake, cannot be predicted in advance. As a result, the destructions it will bring is undetermined before it really happens. However, some existing works adopt a determined model, which neglects the importance of stochastic components when the model is built. Common stochastic parameters include disaster occurrence uncertainty, location uncertainty, human behavior uncertainty, damage uncertainty and trafficability of transportation network.

For instance, as discussed in above section 2.3.2, because the randomness of trafficability of routes, Miller-Hooks [6] use random variables to represent the traverse time and capacity of the network. Therefore, the model is a time-varying extension of MDF. And the expected maximum flow is defined in that circumstance.

To model the randomness of human behavior, a multi-agent optimization formulation is introduced by Edrissi et al in 2013[10]. The travel time of different agents of evacuees along the same link is different in this model considering the different car condition and human behavior in driving. Therefore, the decision making in building renovation, shelter allocation, and network improvement is a dependent in this scope. The optimization solution in the three sub-problems has to be revised.

2.2.5 Solution Algorithm

Multiple algorithms are applied to solve evacuation planning problem. These algorithms can be classified into exact algorithms and heuristic algorithms, or evolutionary algorithms. A growing trend has been identified in evolutionary algorithms such as metaheuristic approach. Only algorithms for solving mathematical programming problems are discussed in the following section.

Yamada[11] use Dijkstra algorithm to solve the modified min-cost flow problem. Cova et al.[7] used commercial solver (CPLEX) to solve medium-size network flow problems. However, the computational complexity of the real-world problem is far larger than the size. A proportion of Literature after 2006 began to use a metaheuristic approach. Tuydes et al.[4] implemented a tabu-based metaheuristic approach for the contraflow problem. A local search among the neighbor reversibility schemas is adopted first and the decision is made based on the dual problem. Finally, optimum is reached if the termination criteria are met. Goerigk et al. applied a genetic approach algorithm to solve the comprehensive mix-integer programming[12]. New solutions are randomly mutated in the neighborhood and local search is used to find the local optimum iteratively within a time constraint.

3. Problem Statements

The minimum total travel time problem can be modeled by different agents from origin to destination in a graph. Let graph $G = (N,A)$ where N is the nodes and A is the set of connected arcs. Suppose S is the set of scenarios, where each arc $(i,j) \in A$ has a capacity c_{ij}^{s}. The probability of scenario s happen is $p(s)$. Each scenario can be modeled as a min-cost flow problem with multi-agents.

3.1 Notations

The following notations and definitions are used in the formulation:

G = transportation network

A = the set of arcs in the network

i, j = connected nodes

O_k = origin of agent *k*

D_k = destination of agent *k*

k = agent which has single origin and destination

K = set of agent *k*

s = scenario where capacities of arcs are different

S = set of scenario *s*

d_k = total number of evacuees in agent *k*

= capacity of arc *(i,j)* in scenario *s*

x_{ij}^{ks} = decision represent the number of evacuees in agent *k* travels on arc *(i,j)* in scenario *s*

t_{ij}^{ks} = travel time of agent *k* along arc *(i,j)* in scenario *s*

3.2 Mathematical formulation

$$\text{minimize } Z = \mathrm{E}[T(s)] \tag{1}$$

subject to

$$\sum_{i,j \in A} x_{ij}^{ks} - \sum_{j,i \in G} x_{ji}^{ks} = 0, \qquad k = 1,2,\dots,K, s = 1,2,\dots,S \tag{2}$$

$$\sum_{i \in A} x_{O_k i}^{ks} = d_k\ , \qquad k = 1,2,\dots,K, s = 1,2,\dots,S \tag{3}$$

$$\sum_{i \in A} x_{iD_k}^{ks} = d_k, \qquad k = 1,2,\dots,K, s = 1,2,\dots,S \tag{4}$$

$$\sum_{k=1}^{K} x_{ij}^{ks} \leq\ c_{ij}^{s}, \quad \forall (i,j) \in A, s = 1,2,\dots,S \tag{5}$$

$$x_{ij}^{ks} - x_{ij}^{ks'} = 0, \qquad \forall s, s' \in \{1,2,\dots,S\}, k = 1,2,\dots,K \tag{6}$$

$$x_{ij}^{ks} \geq 0, \qquad \forall (i,j) \in A, k = 1,2,\dots,K, s = 1,2,\dots,S \tag{7}$$

The objective function (1) is minimizing expectation of total travel time $T(s)$ over *S*. The total travel time is calculated as the individual time multiplied by decision variable.

$$T(s) = \sum_{k}^{K} \sum_{(i,j) \in A} t_{ij}^{ks} x_{ij}^{ks}$$

While the expectation of $T(s)$ is the sum product of $T(s)$ and probability $p(s)$.

$$\mathrm{E}(\,T(s)\,) = \sum_{s}^{S} T(s) \cdot p(s)$$

(2) - (4) are flow constraints. Note that for different agent k, the original, destination and demand might be different. (5) is the capacity constraints based on scenario s. (6) is the unique constraint, which shows the optimal path is unique over different scenarios. (7) is the non-negative constraint.

4. Proposed Solution Algorithm

Considering large number of evacue*k*es in real life, the size of the problem can be considerable. Therefore, a tabu-based heuristic approach is introduced as a possible algorithm to efficiently solve the problem.

4.1 The Heuristic Algorithm

The heuristic algorithm searches for the optimal more efficiently than the other algorithms. In particular, tabu search(TS) is an effective heuristic algorithm which searches for the potential optimal solution among the neighborhoods and moves forward from the local optimal.
The basic structure of heuristic approach, in this case, is set to be: 1) The original network 2) Search for the local neighborhoods 3) Reach the optimality of the objective function.

4.1.1 Initial Solution

An initial solution to the problem is chosen. All the information of the network set up including the arc capacity in different scenarios.

4.1.2 Neighborhood Search

The neighbor is defined as the modified solution by adding an additional number of evacuees on arcs which still haven't reached the capacity. Obliged solutions are put on Search List. Next step is the tabu move by choosing an available solution in the Search List.

4.1.3 Decision Criteria

The effectiveness of new solution is tested. If the evacuation time is shorter than the current optimum, the current best is updated. However, moves with no improvement still can be accepted, during some circumstances, as a diversification action. However, the current optimum is still kept in this situation until next improvement is made.

4.1.4 Tabu List

After the tabu move is accepted, the solution is temporarily put into tabu list for a certain number of iterations to avoid being chosen again. After that, the solution will be removed from the tabu list.

4.1.5 Stopping Rule

The tabu search can be stopped if the optimal is reached or no improvement has been made in a certain number of iterations. The tabu search can also be terminated after a predetermined search time.

5. Conclusion

Current research on evacuation planning varies in terms of various attributes, including disaster type, lifecycle, methodology and research contribution. A stochastic model is reasonable because the real-life disaster is uncertain in terms of type, location, damage etc. This work introduces a stochastic multi-agent model of the transportation network in evacuation planning. A tabu search-based algorithm is introduced as a possible approach to solving the problem. However, there are several limitations of this work. For instance, the model doesn't consider the time delay, travel congestion and uncertainty of individual decision making. Additionally, the stochastic model only adds the uncertain parameter of route capacity, but it doesn't consider the human behavior. Further study can be done in building a more comprehensive model with more stochastic components.

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