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Simulation of Occupant Exit Selection Behavior during Emergency Evacuation using a Game Theory Model

H.C. HUANG, S.M. LO, C.M. ZHAO, P. WANG
Building and Construction Department
City University of Hong Kong
Tat Chee Avenue, Kowloon Tong, Kowloon, Hong Kong
Hong Kong (S.A.R.)

Abstract: - Choice of exit is one of the most important aspects impact on the evacuation of occupants from the dangerous situation. In general, a building consists of enclosure areas such as rooms, walkways, stairs and so on. When occupants face with a multi-exit area, the principal problem in wayfinding is to select the way out. This article presents a game theory based exit choice model for evacuation. The choice of exits will be depended on how groups of evacuees interact. Evacuees perceive the actions of other evacuees and the environmental situations, and interact with their cognition to decide their escape route. Non-cooperative game theory deals largely with how intelligent individuals interact with one another in an effort to achieve their own goals – to leave the fire zone as fast as possible. Game theory route choice model has been integrated in our evacuation model. The simulation results demonstrate that the evacuees' interaction can affect the evacuation pattern and clearance time of a multi-exit zone.

Key-Words: - Simulation, Evacuation, Game theory, Human behavior;

1 Introduction

Evacuation of occupants from the hazardous region(s) is *per se* a way to reduce the ill effects of a fire disaster in a building and predicting evacuation pattern is useful in emergency management. In the circumstance, many evacuation models, such as EXODUS [1], SIMULX [2, 3], EGRESS [4, 5], SGEM [6 – 8] and *etc* have been developed to assist building designers to predict the evacuation pattern. Most of the models have focused on modeling the flow of evacuees and the behavior of crowd flow has not been comprehensively studied, especially the behavioral reaction of the evacuees during their movement.

One of the critical behavioral reactions of people that may affect the escape process is the choice of exit. Choice of exit is one of the most complex aspects of people's movement. Generally, a building consists of enclosure areas such rooms, walkways and stairs. Here 'exit' does not mean the final exit to safety destination or outside of the building. Besides the final exits, the term 'exit' here also refers to the openings of an area through which people can escape from one area to another inside the building(see Fig.1). The principal problem in wayfinding is to select the way out when occupants egress from a multi-exit area. Therefore, choice of exit is the selection of routes from one point to another.

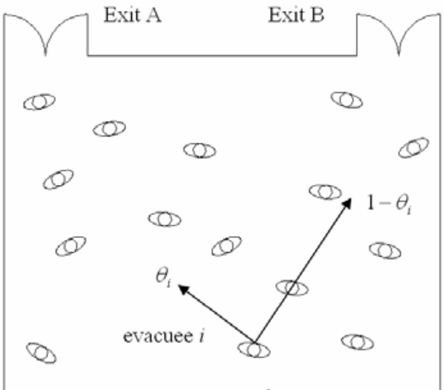

Fig.1 N evacuees evacuate from an enclosure

Under emergency situation, each evacuee is supposed to strive to leave the building as soon as possible. Obviously, congestion will occur at the exits of one zone to another one. The egress system including all the passages and exits can be regarded as resources. Thus, evacuees will compete for the resources for his/her own goal. If they act in rational way, competition among evacuees will affect each one's judgment on exit choice. An individual's choice of escape route can be regarded as a wayfinding which involves perception and cognition. His or her decision will be affected by what has been seen in the environment and what has been formulated in his or her mind – the cognitive map. When a group of people are finding their ways to leave a hazardous zone, other people's action may affect an individual's decision. In other word, interaction of people will be a process that should be considered in modeling the evacuation pattern in a zone of multi-exits. Non-cooperative game theory [9, 10] deals largely with how intelligent individuals interact with one another in an effort to achieve their own goals – to leave the fire zone as fast as possible. This article presents a game theory based method that can be incorporated within an evacuation model and effectively model the exit selection process in an evacuation process.

2 Previous Studies

Early engineering models used to predict people's movement, such as EVACNET [11], applied no behavioral rules. They relied on the physical movement of the population, and the physical representation of the building geometry to influence and determine occupant egress. Recently, social/ architectural scientists, such as Passini [12], Ozel [13], Proulx [14, 15], Sime [16] and Canter [17] have pointed out that one of the dominant factors affecting evacuation patterns is the evacuees' behavioral reactions accompanying their movement. Their studies have identified the contributing factors and provided valuable information for studying wayfinding process. On the basis of these studies, some engineering models incorporate psychological rules to model the response pattern of evacuees. However, how the rules can be applied in a dynamic process, especially when the reaction of an individual is affected dynamically by others, has rarely been discussed.

Garbrecht [18, 19] studied the difference between random walk and random path selection strategies in normal situations. The first describes a movement in a labyrinth where a person makes a random choice at each intersection. The latter refers to an initial random choice of a complete path from origin to destination. It has been shown that the two ways of route selection will lead to different result even the random mechanism is assumed to be uniform amongst all alternatives. This indicates that an individual has pre-select a route based on his or her knowledge of the environment, the final destination may be altered if he or she has changed the choice during the movement. The transient change of route choice is critical to the escape process under emergency situation; an individual may endeavor to achieve his or her own goal – to leave the hazardous zone as fast as possible. One of the interim goals to achieve the final goal will be to avoid congestion. This phenomenon can be noticed in a space with large population, such as stadium, auditorium or etc.

Gwynne and Schneider [20, 21] have also proposed exit selection behavior models. The models concern the response of occupants to exit selection and re-direction. The occupants' decision-making is adapted according to their familiarity with the structure, the exit's visibility and the length of queues at the exits. The exit selection behavior is mainly modeled as the passive response to the extent of the crowding and only final exits of the building is considered. However, in the real situations the occupants will predict their evacuation efficiency based on others' walking direction and then decide which route will be the better. Besides the final exits, the selection of exits will also occur whenever occupants egress from any enclosure inside a building.

In most evacuation models, the exit choice of an individual may be modeled by a pre-selection process on the basis of some wayfinding rules. Checking the shortest distance and the inter-person distance dynamically will be an approach to manipulate the transient situations. However, modeling the dynamic interaction of people with respect to the congestion state of the exits and the actions of other evacuees during the process is rare.

3 Use of Game Theory

If the interactive decision process of the evacuees is rational, game theory can be adopted to describe the interactive behavior. Game theory is a branch of mathematics devoted to the logic of decision making in social interactions. The principal objective of game theory is to determine, through formal reasoning alone, what strategies the players ought to choose in order to pursue their own interests rationally and what outcomes will result if they do so. All players are advisable and do not know what strategies the other side players choose. In other words, it is not possible to increase a player's own benefit using the erroneous strategies of others and an optimal strategy will be found to all players at *Nash Equilibrium*.

In a game, several agents (the evacuees) strive to maximize their (expected) utility index by choosing particular courses of action (selecting particular route), and each agent's final utility payoffs will depend on the profile of courses of action chosen by all agents. The interactive situation, specified by the set of participants, the possible courses of action of each agent, and the set of all possible utility payoffs, is called a *game*. When evacuees and the congestion state of a route achieve a *Nash Equilibrium* [22], the strategy is optimal, i.e. all evacuees select exits based on the strategy in that the clearance time is the shortest.

Primary assumptions for a game theory model are list as follows:

- Each evacuee is selfish, that is, concerned only with himself.
- All the evacuees make a decision simultaneously at the beginning of evacuation.
- Within the persons, evacuees are rational and make a decision based on his persona goal (minimizing egress time).
- The left evacuees make no decision and just select the exit closer to them.
- This problem is modeled as a static game with complete information.

4 Model Descriptions

Many modern buildings will comprise rooms, walkway and stairs forming a multi-zone complex. Such building layout can be represented by a network system and the evacuation problem can be resolved as a network flow problem with nodes and links representing rooms and communication paths. O'Neill has commented that the network structure of nodes and their activity links is analogous to the topological paths between choice points within a building layout [23]. Choice points can occur at route (e.g. corridor) intersections and route turns [24]. An individual will select his or her route ‘step by step’ with the route choice point taken at every node of his evacuation path. This idea originates from research area of traffic assignment problem [25]. Then we can extend the sample in section 3 into a generic model.

The process of an evacuee’s evacuation is mainly influenced by his or her interaction with the environment and other evacuees. At each decision point, they will not know what strategies the other side evacuees choose. An estimation of evacuation cost must be taken into account with expectation to the reaction of other evacuees at other exits.

It is reasonable to assume that the evacuees will be rational, that it, their behavior will be based on the observed situation and logical reasoning. When all evacuees are advisable and each individual will always choose his or her maximum utility (or minimum cost) route with respect to the states of the exits so as to minimize the escape time.

We know that the maximum flow rate (the number of persons walking through an exit in unit time) of an exit is limited and in proportion to the width of the exit. Therefore, when the number of evacuees who decide to egress through an exit increase to a certain amount, they must queue at the exit. Thus, the crowding is formed neighboring the exit and congestion may occur due to possible conflicts among evacuees. It is obvious that the expected travel time of an evacuee depends on both the queue length and the distance to the exit L. The queue length is related to the crowd density D and the width of the exit B.

There are two steps incorporated in the model. In the first step, we treat all the evacuees as a “whole entity” and assign them to the exits. A game is envisaged between the crowd of evacuees seeking an exit to minimize the expected travel time and a “virtual entity” imposing the blockage influence on the evacuees to maximize the expected travel time. It is assumed to be a two-player, non-cooperative, zero sum game. In this game, the evacuees will guess which exit will be congested and the “virtual entity” will guess which exit will be chosen. According to the spirit of game theory, the mixed strategy *Nash equilibrium* for this game gives a reasonable probability-based result of exit selection. Actually, the result of this step indicates the attraction of all the exits to the crowd. In the second step, we need to determine the decision of each evacuee. The factor of distance to the exits is considered. This information is used to adjust the probability values obtained in step one.

As a general case, we consider an example that there are N persons anxious to evacuate from an enclosure (e.g. a room). The enclosure has M exits leading to other enclosures or the outside of the building. The initial positions of the evacuees are distributed randomly at the start of evacuation. Pure strategies $S_1 = \{\alpha_i\}(1 \le i \le m)$ of the crowd will be formed when all evacuees choose the exit i. A pure strategy is a completely deterministic strategy occurs when a player assigns probability 1 to a specific action. The pure strategies of the “virtual entity” are $S_2 = \{\beta_j\}(1 \le j \le m)$ representing that exit j is imposed capacity restriction. The payoff matrix $\mathbf{A}$ of the evacuees can be expressed as follows:

$$\mathbf{A} = \begin{array}{c} \\ \beta_1 \\ \beta_2 \\ \vdots \\ \beta_m \end{array} \begin{array}{c} \begin{array}{cccc} \alpha_1 & \alpha_2 & \cdots & \alpha_m \end{array} \\ \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix} \end{array} \qquad (5)$$

where $\{\alpha_1, \alpha_2, \cdots \alpha_m\}$, $\{\beta_1, \beta_2, \cdots \beta_m\}$ are the strategies of the two players respectively. The expected payoff a_{ij} is the cost representing the total evacuation time of evacuees under scenario (α_i, β_j) with all evacuees moving toward the exit i.

aij may be computed on the basis of the crowd density at the exit i, the width of exit i, the distance to exit i and the strategy β_j.

According to game theory, if the matrix (5) satisfies the following condition:

$$\max_i \min_j a_{ij} = \min_j \max_i a_{ij} = a_{kl} \qquad (6)$$

an optimal pure strategy situation (α_k, β_l) will exist. It should be noted that "optimal" here means "equilibrium" not "best" when players are extremely pessimistic and choose their own best strategy from the worst ones. The optimal pure strategies may be more than one or do not exist.

When formula (6) can not be satisfied, there will be no solution for pure strategies but a mixed strategy solution will then exist. In game theory, a mixed strategy is used to describe a strategy compromising of possible moves and a probability distribution which corresponds to how frequently each move is chosen[22]. A player adopts a mixed strategy by choosing his actions randomly, using fixed probabilities. In other words, players may instead randomly select from among these pure strategies with certain probabilities. Randomizing one's own choice in this way is called a mixed strategy. Nash showed in 1951 [22] that any finite strategic-form game has equilibrium if mixed strategies are allowed.

For the above exit selection process, a mixed strategy is considered as the probability of exit choice. To seek the equilibrium (optimal) solution, we consider the following couple of mathematical linear programming problems:

$$\max\ z = \sum_i x_i$$

$$\begin{cases} \sum_i a_{ij} x_i \le 1 & j = 1, \Lambda, m \\ x_i \ge 0 & i = 1, \Lambda, m \end{cases} \qquad (7)$$

$$\min\ w = \sum_j y_i$$

$$\begin{cases} \sum_i a_{ij} y_j \ge 1 & i = 1, \Lambda, m \\ y_j \ge 0 & j = 1, \Lambda, m \end{cases} \qquad (8)$$

where z, w are the objective functions, $z = w = 1/v$; v is the value of the games, i.e. the expected evacuation time of the evacuees (or the expected earned value of the virtual entity); aij are elements of the payoff (lose) matrix. If $\bar{\mathbf{x}}$, $\bar{\mathbf{y}}$ are the optimal solutions of the problem (3) and (4) respectively, then the value of the game is

$$v = \frac{1}{\sum_{i=1}^{m} \bar{x}_i}$$

The optimal solution of the game is $(\mathbf{x}^*, \mathbf{y}^*)$, where $\mathbf{x}^* = v\bar{\mathbf{x}}$, $\mathbf{y}^* = v\bar{\mathbf{y}}$, x_i^* is the probability that the evacuees choose exit i; y_j^* is the probability that the virtual entity choose exit j to impose blockage.

For the above couple of problems (7) and (8) only one of them needs to be solved because the solution of one problem can be derived from another. In this paper, we aim to find the probability of exit choice, so the problem (7) is solved. As the classical method, we adopt simplex method to solve the linear programming problem and obtain the probability distribution $\mathbf{x}^*$ assigning the crowd to the exits.

In the step one, the above game-based algorithm only consider the relation between the congestion situation near the exits and the egress time. As the common sense, we understand that an evacuee will not choose the farther exit unless the closer exit is congested. Because the distances to the exits also influence the exit choice process, we should modify $\mathbf{x}^*$ by the location information in the step two. The final probabilities of exit choice should be:

$$p_i^* = \frac{x_i^*}{l_i \cdot \sum_{j=1}^{m} \frac{x_j^*}{l_j}} \qquad (9)$$

where $l_i (1 \le i \le m)$ is the distance to the exit i.

5 Model Implementation

The aforesaid conditions can be implemented in a fine grid evacuation model such as the SGEM [8]. The current version of SGEM adopts a simple exit choice model, namely shortest-path model or familiar-path model. Then we added the proposed model as a new feature into SGEM. Figure 2 shows the outline algorithm of the computation at each time step. The computation of exit choice is dynamic during the simulation.