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Incorporation of decision, game, and Bayesian game theory in an emergency evacuation exit decision model

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ABSTRACT

This paper explores the use of utility and game theory to model egress decisions for exit choices found in evacuations. These mathematically rigorous theories serve as a basis for individual exit decision making that captures interactions between evacuees. The model presented in this paper is fundamentally different from traditional evacuation simulators that capture the exit selection behaviour through simple heuristics or objective functions. A utility function based on energy consumption of exit alternatives is created that captures evacuee risk preferences and beliefs. Multiple game forms are created to allow for trade-offs between model fidelity and computational complexity. These models range from Bayesian games to simplified normal games. Multiple examples and validations are used to show that the decision analysis model developed here captures natural human tendencies and characteristics. This enables creation of a high fidelity exit decision model that simulates exit selection of evacuees.

1. Introduction

An egress scenario can be viewed as a series of decision making processes by the individuals involved. Many decisions are made by evacuees during an egress situation. Evacuees interpret information from multiple sources, which provides new knowledge on which to base their decisions. This knowledge contributes to evacuees' beliefs on their exit alternatives. Evacuees determine their best course of action based on their beliefs and preferences. ESM [1], Exodus [2], SGEM [3] and SIMULEX [4] are well known evacuation programs that use heuristics or simple objective functions associated with exit alternatives to determine an evacuee's destination goal. While these methods attempt to capture the decision making process, the key component of evacuee interactions is missing. Vacate [5–7] is a non-nodal based egress model that uses driving forces to simulate the individual's wants and needs. While the driving force approach captures some human to human interactions, a method with a proven mathematical foundation for solving human interaction problems is still needed. This paper presents a novel method to model the decisions evacuees make concerning egress alternatives, with a focus on the effects of evacuee interactions. The mathematically rigorous method of this paper captures the exit selection of the individual through simulation of the decision analysis process rather than a heuristic-based simulation of the evacuee's behaviour.

Past research [8] has examined the use of utility theory [9,10], game theory [10] and the velocity-obstacle method [11] in maneuvering decision analysis. Maneuvering decision analysis provides a mathematical representation for the decisions and interactions involved in determining the optimum velocity magnitudes and directions for maneuvering in a crowded room. Maneuvering decision analysis uses a separate decision process from that of selecting the best exit alternative. Past research focused on the movement decisions evacuees ought to make to avoid obstacles and other individuals in getting to a *specific* exit. In this paper, a method is presented to determine the decisions evacuees ought to make to identify the best exit from a set of alternative exits. While closely related, these papers offer the needed mathematical techniques to simulate two separate decision processes inherent to evacuations. Validations presented in past research [12–14] and in this paper show the usefulness of decision analysis in capturing the decision making process of individuals in egress situations.

Both the structural environment and other individuals in that environment are considerations when individuals decide between egress alternatives. Current evacuation simulators incorporate people in the environment as a variable in the alternative's objective function. For example, if an evacuee is a follower personality, then an alternative with a larger the crowd would be more attractive than one with less. These simulators do not take into account the interactions that occur between evacuees during the actual decision making process, but only capture the

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end effect. The method presented in this paper simulates the decision making process that determine the evacuee's behaviour in exit selection—not the behaviours directly.

Decision theory and game theory [9,10,15] provide attractive approaches to properly simulate the decision making process of the evacuees' exit alternative selections. The evacuee's environment dictates the type of game that is played. Decision theory is used when there are no interactions occurring with other evacuees. In this case, the decision is based only on the evacuee's beliefs about the alternatives and the evacuee's preference. This situation can occur if no one else is in the vicinity to interact with. Alternatively, game theory is used when the evacuees' interactions with others affect their alternative selection. For example, for two evacuees in a room, each evacuee's decision may impact the other's decision. In the language of game theory, they are playing a game with one another. These two theories provide a mathematically rigorous basis for modelling the decision making processes people should make.

A limited amount of research has been conducted in using decision or game theory principles to determine which egress alternative a person should choose. A literary review [16] concludes that the incorporation of evacuee interactions in simulations is very rare. One study [16] focuses on a zero sum 2-player game in which one of the game's players is the population and the other player is an ambiguous capacity restricting entity. This approximation for the evacuee interactions does not capture the true complexity of individual player interactions. Hoogendoorn and Bovy [17] have examined the formation of a utility function and the use of differential games to examine the decisions associated with crowd flow. Other studies [18–21] focused on the nature of crowd flow using game theory principles. These studies incorporate an objective function that approximates the evacuee's desires. In this paper, a value function that captures a single preference of the decision-maker is used as an objective function.

This paper presents the incorporation of game theory based evacuee interactions in Vacate-GT (Game Theory), a decision-based evacuation simulator. The interactions examined focus on games played between evacuees during exit alternative selection. This research is novel in modelling exit selection games where the players are the individual evacuees and the utility functions are based on a value function. The value function is formed from the energy consumption associated with each egress alternative. The preference is to minimize the anticipated energy consumption. The games are played in certain time intervals, usually related to the amount of time a player takes to complete a walking step. In this paper, decision, Bayesian and normal games are used to model different evacuee situations. These games represent the actual decision making process more realistically than a pseudo-game with a crowd playing against a restriction entity. Furthermore, the use of different games allows for varying degrees of model fidelity.

As previously stated, the research presented in this paper deviates from traditional large-scale evacuation simulators, in which heuristics or simple objective functions are used to approximate the general crowd flow and evacuee exit decisions. This paper models the decision behind an evacuee's choice of one exit alternative over another. Instead of modelling behaviours directly, this paper offers methods that model the decision process of the individuals that result in behaviours. This is an important distinction. The research focuses on forming a high fidelity decision model at the individual evacuee level. The fidelity of the decision model varies according to the number of players (i.e. evacuees) being modelled. The process of using decision and game theory to determine the choices of each individual is currently more computationally expensive than traditional simulators. However, as computational power increases, the ability to use decision-based higher fidelity models on a large-scale becomes less burdensome.

2. Environment and egress alternatives

In this study, an entire floor of a building is used as the test environment, with multiple rooms, hallways, etc., forming sections within the environment. The passable barriers between the section and non-section areas (e.g. stairways, doors, windows or any area not encapsulated by the section) are considered exits. Egress alternatives are any invisible or visible barrier that, when passed, allows the evacuee to see into a region that was previously visually obstructed. In this definition, an egress alternative is not limited to a section exit. For example, in a section with multiple rooms, an egress alternative may be a door that leads to another room in a section (i.e. a door between rooms of the section). Current alternatives are egress alternatives that an individual is presently deciding upon due to their current location.

Fig. 1A shows an evacuee (represented by an “X”) with two current egress alternatives in the black outlined section. The decision region (represented by the checker pattern) is the area made of walls and alternatives surrounding the evacuee. The current egress alternatives are represented by blue dotted lines while the exits for the section are represented by red dashed lines. The blue dotted line egress alternatives of Fig. 1A represent the barriers which, if passed, would allow for the individual to view a different area of the section. Fig. 1B shows the egress alternatives

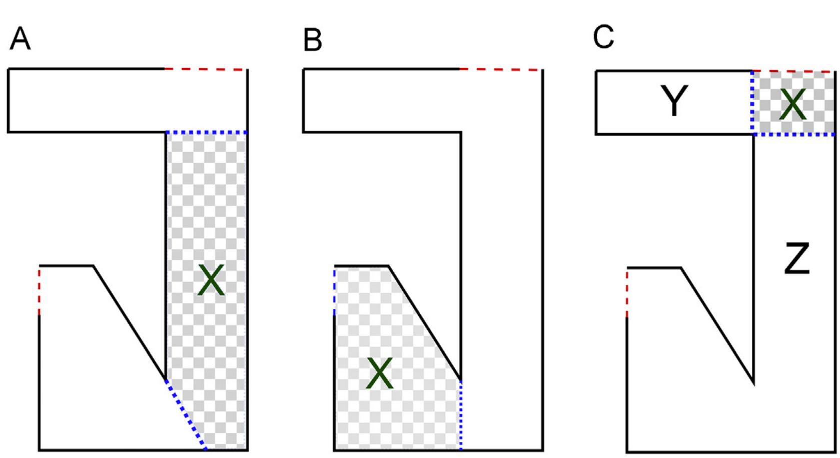

Fig. 1. Examples of decision regions and egress alternatives. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)