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Dynamic crowd evacuation approach for the emergency route planning problem: Application to case studies

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ABSTRACT

Disastrous situations, either natural or man-made, have claimed countless lives. In a planning context, this triggers the need for an evacuation situation that involves the emergency route planning (ERP) problem. ERP emphasizes the effectiveness of the evacuation plan to mitigate risk and ensure crowd safety. Reviews on previous ERP works have elicited a plethora of approaches, such as decision support, exact, heuristic, and metaheuristic approaches. However, previous works on ERP focused on either crowd modeling techniques or routing approaches, but not both. This elicits the need to bridge modeling and routing approaches by means of a dynamic concept. To capture this dynamism concept, group cohesiveness and flexible routing approaches have been proposed, namely as an integrated evacuation planning with dynamism (iEvaP+). Group cohesiveness is utilized by considering group structure and intra-group compliance. Meanwhile, an artificial immune system (AIS) algorithm is adopted as the route optimizer. The iEvaP+ approach is applied to three case studies in order to identify the impact of crowd dynamism in the ERP problem. The result indicates that dynamism has direct influence on the evacuation plan performance. Besides the group cohesiveness, the properties of the evacuation network (such as exit) are also important in mitigating risks and crowd survivability.

1. Introduction

An emergency can be defined as a situation requiring time-critical response that is induced by a disastrous phenomena, be it naturally (i.e. hurricane, flood, earthquake) or man-made (i.e. hazard material release, fire), that could put human lives at risks (Alsnih and Stopher, 2004). When an emergency response is elicited, evacuation is the typical strategy employed to mitigate risks which require immediate mobilization and time-critical actions involving efficient coordination, space capacity utilization, and availability of emergency resources. In the context of planning, emergency evacuation is also known as emergency route planning (ERP) problem, encompassing two interrelated problems (Chiu et al., 2007): routing of the crowd and regulating the crowd flow.

Crowds can be formed by several or thousands of people that move in a bounded environment, either in group or individually, with respect to their individual goals in space such as avoiding obstacles, and remaining close to friends or family (Yersin et al., 2008). The definition of crowd is dependent on three co-related aspects (Sharma, 2009): (1) goals and needs; (2) social and physical attributes (e.g. level of interaction); and (3) psychological and situational aspects (stress levels at a respective time or place). The crowd model considered in this study is tuned towards fulfilling the first two aspects, which is typically known as group cohesion.

Meanwhile, the perceived environment is utilized by crowds to choose the shortest path in time and space that leads to their goal (Yersin et al., 2008). The need for evacuation is crucial for residents in a bounded environment (within a structure or enclosed area) as opposed to those in an open space, due to the possible risks that are associated with it. As such, the attributes that can be associated with the bounded environment include the layout design (Shukla, 2009), its relation to risk factors (e.g. space capacity) (Park et al., 2007), and the available exit choices (e.g. exit's width) (Pu and Zlatanova, 2005).

In the context of crowd evacuation modeling and routing, dynamic concepts are important characteristics that aim to fulfill either level-of-service, design elements of pedestrian facilities, or planning guidelines (Helbing and Johansson, 2011). In a more specific term, a dynamic concept is an instance of synthetic human behavior when compared to actual human behavior (Fridman et al., 2011). In our study, the dynamic concept refers to the cohesiveness of groups in a crowd, particularly the grouping phenomenon (group formation) within the crowd and the level of interaction within the groups (intra-group compliance).

Crowds tend to propagate in a chaotic way during an emergency situation due to the uncertainty of the perceived situation (Wang et al.,

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2009). In addition, a crowd which moves in groups may affect the groups' flow of egression, their behavior toward others, and the estimated evacuation time (Wang et al., 2009). Additionally, environmental properties, such as exit choices, may have crucial impact on the life and death of people in the crowd during an emergency evacuation (Pu and Zlatanova, 2005). Understanding these underlying problems is crucial for crowd safety and can help emergency management agencies (EMAs) to prepare for and prevent an actual crisis.

Therefore, the objective of this study is twofold. Firstly, this study focuses on identifying the impact of the dynamic concepts (group cohesion) toward the crowd egression. Secondly, this study focuses on identifying the relationship between the exit properties (e.g. exit width and number) and the ability of the crowd egression. By achieving these objectives, the expected evacuation plan may help mitigate risks and ensure crowd safety prior to the occurrence of a disastrous situation.

2. Literature review

The cognition of the ERP approach involves three distinct and interrelated components: (1) crowd modeling, (2) route assignment, and (3) emergency's scenario modeling. However, our study is tuned towards fulfilling the first two aspects: crowd modeling and route assignment.

Crowd is generally modeled based on theoretical models, ranging from analytical ones to those based on matrices or cells (Bandini et al., 2005), generally categorized into microscopic, macroscopic, and mesoscopic (Radianti et al., 2013). Microscopic models treat every individual in the crowd as a separate "particle". Several variants of the microscopic approach include the encoding of human desires in the form of physics-based force, such as social force model (Helbing et al., 2000), and representing each pedestrian as a node that occupies a cell, such as cellular automata (Yuan and Tan, 2011). Macroscopic models describe crowds through their average flow and density. Fluid dynamic model (Helbing, 1998), flow tiles (Chenney, 2004), and non-local crowd dynamics (Colombo and Lécureux-Mercier, 2012) are variations of microscopic models. The hybrid of the two former models, namely the mesoscopic model, combines the key concepts of the relationship between local inter-individual interactions (micro) and collective patterns (macro) (Wang et al., 2009). Among these three categories of crowd models, the mesoscopic model is distinguished as the modeling approach that is able to capture crowd behavior realistically. Indirectly, adoption of this model helps in making an effective decision, improving response capability towards disaster, and reducing any adverse impacts on both human beings and surroundings (Lv et al., 2012).

The network or route is a logical layout which is used to model the perceived environments in time and space (Yersin et al., 2008). An actual building or structure layout is approximated by a continuous model. This is accomplished by means of networking a set of destination points that represents the real roadways for utilization by the crowd during emergency evacuation. Graph-based method is the most popular method adopted for approximating information of the enclosed region of a structure through a network of nodes and edges (Kemloh Wagoum et al., 2012). This is because the destination points can be predetermined (i.e. exits) or adjustable (i.e. crossings, turning point at the end of a corridor). Also, the visibility of the graph of a minimal network at any location is ensured based on the range of at least one node. Consequentially, both logical approximations of the perceived environments and crowd modeling are interdependent and equally important in ERP. Unfortunately, research employing both these methods simultaneously is scarce.

Employing crowd modeling and graph-based layout representation, simultaneously, would help to efficiently move a crowd in a building. This is especially true in large and complex structures (Hajibabai et al., 2007), where actual agglomeration of the crowd is reflected. In a sociological sense, people who have social ties and intentionally walk together, such as family members and friends, are commonly known as "group" (Qiu and Hu, 2010; Moussaïd et al., 2010). In an emergency context, the group characteristics (e.g. group size and influences among group members) may also influence the crowd egress flow as well as the efficiency of an evacuation plan (Qiu and Hu, 2010; Moussaïd et al., 2010; Moreland et al., 2013). This group characteristic is generally known as the group cohesion, which is defined as the tendency for a group to be in unity while working towards a goal or to fulfill the demands of its members (Carron and Brawley, 2000). A group's cohesive properties such as group size and influences among group members, are vital due to the following reasons: (1) The group size determines the group's physical structure and composition of the group; (2) Individual compliance influences the group's interaction in terms of their flow rate.

The dynamism concept has previously been adopted in the decision support system (DSS), where timely decision making before and during a disastrous situation is provided. Some examples include: Dynamic crowd navigation in a multi-storey building (Kwan and Lee, 2005); topological support and analysis of crowd distribution and simulation (Castle and Longley, 2005); route search and interactive evacuation instructions (Pu and Zlatanova, 2005); and dynamic route generation for both rescue and evacuation operations (Chang et al., 2009). Although the dynamism concept is captured, the focus of the studies is more on decision dynamics of the crowd egress route and not the dynamism of the crowd itself. In addition, DSS approaches are dependent on information availability, data security, and privacy compliances (Kwan and Lee, 2005).

ERP approaches that capture the dynamic concept using exact approaches have also been proposed. Examples of such approaches include: the panic reactions that attenuate the egress of a crowd (Wang et al., 2009); variable travel times and demand of crowd (Hui et al., 2010); crowd egress in reaction to their injury level (Amaldi et al., 2010); crowd with special needs (e.g. elderly and children) (Kaisar et al., 2012); network flow with reorganization of traffic routing during an evacuation (Bretschneider and Kimms, 2011); and dynamic crowd flow distribution during an evacuation (Lv et al., 2012). These approaches introduced dynamism in the form of crowd reactivity towards danger which impedes the overall evacuation process. Therefore, the dynamic nature of the approaches is limited towards the one that affects the formulated crowd model while not considering the dynamism of their route layout.

Meanwhile, heuristic is another popular and emerging ERP approach in the field of computational optimization. Examples of heuristic approaches are: capacity constrained route planner (CCRP) which dynamically utilizes spatial information for crowd routing (Lu et al., 2005; Kim et al., 2007; Zeng and Wang, 2009; Shekhar et al., 2012); an adaptive evacuation route algorithm (AERA) utilizing a dynamic network during the event of a flood (Liu et al., 2006); and an event-driven way-finding approach which combines the shortest and quickest path heuristics (Kemloh Wagoum et al., 2012). The dynamic nature of the heuristic approaches are bounded with the decision complex of the crowd when exposed to certain measurable levels of danger. This motivates the initiation of the crowd dynamic routing. Nevertheless, dynamic interaction between the crowd model and their respective routing mechanisms is limited such that the crowd model may influence the routing mechanism but not otherwise.

Studies employing the ERP approach by means of a meta-heuristic algorithm have been proposed by several researchers. Examples of the approaches include: a simulated annealing algorithm embedded in dynamic network loading of crowd egress (Cepolina, 2005); an ant colony algorithm to optimize the dynamic network flow of a crowd with respect to disaster extension (Yuan and Wang, 2007; Zong et al., 2010); and a tabu search for dynamic network optimization considering crossing and lane reversal strategies (Xie et al., 2010; Jiang et al., 2013). These approaches have demonstrated the dynamism of a crowd in network utilization, where adjustments of the crowd flow and changes in route selection are illustrated. Consequentially, the meta-heuristic approaches are limited towards achieving optimum