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Simulation-based evacuation planning using state-of-the-art sensitivity analysis techniques

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ABSTRACT

With the continuous growth of cities and the issues of insufficient space, indoor parking garages have become a vital component of transportation systems. Since emergencies will occur sooner or later, planning and organizing a successful evacuation plan for parking garages, with the aim of reducing the evacuation time and improving the driver's behavior during evacuations, is needed. This research presents a systematic approach for the development and evaluation of evacuation strategies in such environments, through state-of-the-art sensitivity analysis that provides faster convergence and lower computational burden. To demonstrate the proposed methodology, a simulation model is developed using AIMSUN for a three-level indoor parking garage located in Athens, Greece. Four scenarios with different evacuation strategies and plans are considered. A multi-step sensitivity analysis framework is implemented to overcome the uncertainties that emerge from the model assumptions, model inaccuracy and shortage of data. Sensitivity analysis is used to evaluate the consequences of the proposed scenarios and estimate the total time to evacuate the parking garage. The full experimental design resulted in the automated execution of more than 80 thousand simulations, corresponding to approximately 65 processor-days. The results of this research show that the developed methodology provides significant reduction in evacuation time (from 35% to over 40%). This process provides useful and credible ranges of expected evacuation times under all plausible outcomes.

1. Introduction

Successful emergency management depends on the early preparation actions that must be taken before the disaster [45] and on the capability of reducing evacuation time as much as possible. Human behavior, during emergency situations, has proven to be unpredictable. Evacuation situations have been the topic of extensive research investigation. Wang et al. [49] and Lammel et al. [31] considered tsunami evacuation situations, Yin et al. [50] studied a hurricane evacuation case, while Simonovic and Ahmad [45] examined the human behavior during flood emergency, to name a few. However, to the authors' knowledge, indoor parking facilities have not been the subject of intensive investigation so far, even though they tend to be extremely dangerous in case of a disaster, as indoor parking garages are closed environments with limited access.

Microscopic traffic simulators are traditionally useful tools for designing, evaluating and optimizing transportation systems, for evacuation procedures and for accurately reproducing reality. However, the capability of a model to properly replicate the actual

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situation, evaluate the consequences of a new strategy or compute outputs of a transportation system, is significantly influenced by the value of the model input parameters [13]. Hence, traffic models must be calibrated in order to precisely describe reality [2,5].

The topic of this research is related to the modeling and simulation of the evacuation of large indoor parking facilities. The evacuation process leverages microscopic traffic simulation software [8]; while intended for the modeling of regular road networks, it was possible to apply such software to accurately model indoor parking garages, where special maneuvers are performed. Besides modeling the "do nothing" reference case, the microscopic traffic simulation model was used to also evaluate different strategies to improve evacuation time.

Since data for evacuation cases are from scarce to non-existent, we employ sensitivity analysis to analyze these scenarios. State-of-the-art sensitivity analysis techniques are used to determine which parameters most influence the output and to obtain distributions of the expected values of the evacuation times.

Input and output scatter plots technique, possibly the simplest method to perform sensitivity analysis, was used initially to identify the most influential parameters. Then, a variance-based method was used to compute and compare sensitivity indices of the main parameters, based on Sobol's decomposition of variance [46], which is considered as one of the most recent and effective global sensitivity analysis techniques. An exploration of pseudo-random and quasi-random numbers has been performed in the context of the experimental design of the variance-based method to obtain a faster rate of convergence. Naturally, as this task involved running thousands of simulations, a programmatic framework (based on Matlab and Python) has been developed to execute the sensitivity analysis.

While this methodology is applied to the field of evacuation of underground facilities, in this research, there is nothing domain-specific about it. In fact, it is absolutely general and can be applied to any problem, perhaps with minor modifications or extensions.

The remainder of the paper is structured as follows. A literature review is presented in Section 2, followed by a presentation of the methodological and simulation framework in Section 3. Section 4 presents the sensitivity analysis techniques used in this research. The case study setup and results are presented in the Sections 5 and 6 respectively, followed by a discussion of the results and the computational effort required in Section 7. Finally, conclusions are drawn and directions for future research are outlined in Section 8.

2. Literature review

Evacuations are not rare events, they can be needed anywhere, anytime and must be executed according to pre-planned strategies and advanced warning time in order to effectively implement the needed management policies [35]. Therefore, evacuation situations have been the subject of extensive research investigation activities during the past decades, with the majority focusing on evacuation planning, evacuation optimization and evacuation simulation of areas imposed because of an emergency incident. Jha et al. [28] used the microscopic simulator MITSIMLab to evaluate an emergency evacuation planning of Los Alamos National Laboratory, New Mexico. Five different scenarios were developed, each with a different strategy, as a full or partial closure of various roads or a limited access to some facilities in order to improve the total evacuation time and the needed time to only evacuate the population within the most dangerous areas. Balakrishna et al. [6] developed a dynamic traffic assignment-based tool for the support of emergency situations, with a particular emphasis on behavioral aspects.

Bae et al. [4] developed an evacuation agent-based model to describe an evacuation process of a metropolis imposed during a bombardment. Duanmu et al. [18] studied the effects of re-routing, demand rates and active control measures on the evacuation process and found that an active traffic control management can lead to a significant decrease in the total evacuation time.

A multi-objective evolutionary algorithm and a geographical information system (GIS) have been proposed [41] to assist in evacuation planning by guiding people to safe areas through suitable route patterns, while Fang et al. [19] utilized a modified ant colony optimization algorithm and applied it on a large scale stadium in China to solve the evacuation routing problem with the aims of minimizing the total evacuation time and the total evacuation distance. A distributed building evacuation simulator (DBES) has been designed by Dimakis et al. [16] to evaluate the success rate of different evacuation strategies in confined environments. The tool is capable of simulating different types of entities/agents that may need to be evacuated and different evacuation strategies for each type simultaneously. In addition, DBES can be run on different servers to minimize the execution time. Other studies relied on opportunistic networks [37], where mobile nodes are able to communicate and share data with each other. Such technology enables each pocket device (e.g. mobile phones) to broadcast emergency information and messages to other devices based on its local view and understanding of its environment which is updated via opportunistic communication systems [25,27]. Moreover, Gelenbe and Huiobo [22] proposed a cloud-enabled indoor emergency response system, used in environment without proper infrastructure (e.g. sensors are not pre-installed and WiFi access points are out of service due to hazards) to alarm and guide evacuees. Results show that the proposed system can improve the evacuation process and guide civilians with depleted mobile phones towards other evacuees rather than roaming randomly in the building.

The concept of hierarchical decision making has been also adapted to guide different types of evacuees based on their capabilities, age, mobility etc. Doing so can enhance the effectiveness of the evacuation process significantly Akinwande et al. [1]. Simulation-based pedestrian evacuation has seen a lot of interested recently. For example, Chen et al. [10] explicitly incorporate collision avoidance during evacuation in classrooms (with aisles) in a cellular automaton model, while Liu et al. [33] propose a social force model for simulating crowd evacuation, using real video data to steer the model parameters in a way that minimizes congestion. Gan et al. [20] combine optimization and simulation to determine optimal evacuation plans for individual evacuees. Simulation of evacuation from restricted environments (e.g. high-rise buildings) is the topic of several recent articles (e.g. [9,17,29]).

Traffic simulation aims to reproduce real traffic situations, but the modeling process will always involve a number of uncertainties, due to basic modeling assumptions, structural equations, level of discretization, numerical resolution method and data inaccuracy or data shortage [40].