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An optimization method for the distance between exits of buildings considering uncertainties based on arbitrary polynomial chaos expansion

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ABSTRACT

The distance between exits is an important design parameter in fire safety design of buildings. In order to find the optimal distance between exits under uncertainties with a low computational cost, the surrogate model (i.e. approximation model) of evacuation time is constructed by the arbitrary polynomial chaos expansion. Through a two-stage nested Monte Carlo simulation of this surrogate model, the optimal distance between exits under uncertainty is found efficiently. In order to demonstrate the proposed method, a single room with two exits is presented as a fire compartment and uncertainties of occupant density and child-occupant load ratio are also considered. In this case, the results showed that the optimal distance between exits changes with the level of probability of evacuation time, and there is a critical level of probability for the transition of the optimal value of the distance between exits. Furthermore, the traditional Monte Carlo simulation method is used to compare the accuracy of the surrogate model with the computer evacuation model FDS+Evac developed by the VTT Technical Research Center of Finland [1]. The results indicate that the proposed surrogate-based optimization method can achieve a similar accuracy with a much lower computational cost.

1. Introduction

The distance between exits is a critical issue in fire protection design of buildings, which is generally determined within a certain range according to the current prescriptive-based fire protection codes of buildings. For example, the distance between adjacent exits should be larger than 5 m in a fire compartment of public buildings according to the Chinese code GB50016-2014 [2]. However, for larger distance between exits, the travel distance of some occupants may be increased, which may reduce evacuation efficiency of crowds. Moreover, once available safe egress time (*ASET*) is larger than required safe egress time (*RSET*), buildings are regarded as safe enough without the consideration of the optimal value of the distance between exits in performance-based fire protection design of buildings [3]. Besides, due to the randomness of the fire and occupant characteristics [4], there may be a high degree of uncertainty in initial conditions and processes of occupant evacuation. Hence, in order to carry out a cost-effective fire protection design of buildings, the distance between exits need to be optimized with consideration of uncertainties.

Great attention has been paid to uncertainties in evacuation modeling by many researchers. Sources of uncertainty in evacuation modeling are generally classified into 4 types: model input uncertainty; measure uncertainty; intrinsic uncertainty and behavioral uncertainty [5]. Based on a lattice-gas model, Song et al. [6] adopted the mean field theory to develop an evacuation model considering uncertainty in the number of pedestrians. Averill et al. [7] employed a Modified-Markov Modeling approach to propose a grid-based evacuation model, which can be used to deal with uncertainty in the number of occupants. Xie et al. [8] utilized the polynomial chaos expansion to solve uncertainties in input parameters with the purpose of reducing the computational cost of uncertainty analysis of evacuation time. To address the randomness of occupant characteristics, distributions of stochastic variables (e.g. pre-movement time, walking speed, body diameter) are embedded in more computer evacuation models, such as building EXODUS [9], Simulex [10,11], FDS+Evac [1] and Pathfinder [12]. Moreover, random numbers/seeds are used in evacuation modeling to deal with the space conflict, exit choice, queuing behavior, etc. [13]. With the aim of accurately evaluating the performance capability of passenger evacuation, Vassalos et al. [14] adopted the Monte Carlo simulation approach to obtain the cumulative

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probability distribution (CDF) of evacuation time under uncertainties regarding to human behavior. In order to address the impact of human behavior on evacuation model prediction, based on functional analysis Ronchi et al. [13] proposed a quantitative method to determine the appropriate number of repeated simulations for a certain evacuation scenario.

Recently, the distance between exits has been widely studied by some researchers. Based on a two-dimensional cellular automaton model, Zhao et al. [15] investigated the effect of the distance between exits on evacuation time under deterministic evacuation scenarios, and suggested that the layout of exits should be symmetrical for a higher crowd evacuation efficiency and the optimal value of the distance between exits is approximately equal to 3/10 of the total length of the wall, which is independent of exit width. Moreover, in order to save the computational cost of fire protection design of buildings, Tavares et al. [16] proposed a surrogate model-based optimization method to find the optimal location of exits under deterministic evacuation scenarios, which couples numerical optimization techniques to a deterministic response surface method with the building EXODUS evacuation model. In addition, based on evacuation simulations using the computer model Simulex, Tavares et al. [17] showed that the efficiency of crowd evacuation is significantly affected by the relative distance between exits, which can be used to determine the suitable exit locations for evacuation design of buildings. Zhou et al. [18] adopted a cellular automation model to explore occupant evacuation dynamics, and indicated that the efficiency of crowd evacuation will be reduced by the improper distance between exits. Besides, Jiang [19] also investigated the impact of the configuration of exits on the efficiency of crowd evacuation, and showed that the optimal value of the distance between exits is 1/5 of the length of the wall. Furthermore, Rao et al. [20] examined the importance of the distance between exits in occupant evacuation time based on a cellular automation model, and indicated that the distance between exits can have a more significant impact on occupant evacuation than exit width in complex buildings.

As discussed above, it can be seen that previous research focused on the optimal design of the distance between exits under deterministic evacuation scenarios. However, occupant evacuation is extremely complex and highly uncertain, which is affected by various uncertain factors such as pre-movement time, occupant density, crowd type, etc. Thus, the optimal distance between exits under uncertain evacuation scenarios is an important and interesting topic.

2. Optimization method for the distance between exits under uncertainties

Occupant evacuation under fire emergency is extremely complex. Therefore, the treatment of uncertainties a very important aspect in evacuation modeling. To address this problem, Tavares et al. [21] presented different solutions, e.g. Design of Experiments (DoE) techniques and functional analysis. For the optimization of the distance between exits under uncertainties, the most straightforward method is the two-stage nested Monte Carlo simulation of computer evacuation models. However, this method is highly time-consuming due to the complexity of occupant evacuation process. In order to save the computational cost of optimization under uncertainties, the most obvious approach is directly coupling numerical optimization techniques to the Monte Carlo simulation of computer evacuation models, but it still requires a numerous computer evacuation simulations. To significantly reduce the computational cost, a surrogate model-based optimization method is proposed to determine the optimal distance between exits under uncertainties. The arbitrary polynomial chaos expansion, which is one of stochastic response surface methods, can be used to construct the surrogate model of the output with fewer computer simulations [22]. In this work, given uncertainties in evacuation scenarios (i.e. model input uncertainty), the computer evacuation model coupled with the arbitrary polynomial chaos expansion is used to construct the surrogate model of evacuation time, which can represent the relationship between evacuation time and input parameters. Subsequently, the two-stage nested Monte Carlo simulation for the surrogate model of evacuation time can be performed, whose results can be used to determine the optimal value of the distance between exits for a certain level of probability of evacuation time. To achieve the minimum evacuation time at a certain acceptable level of probability over the design space of the distance between exits, a surrogate model-based optimization method is proposed in this paper, which can be summarized in a 4-step procedure, as shown in Fig. 1.

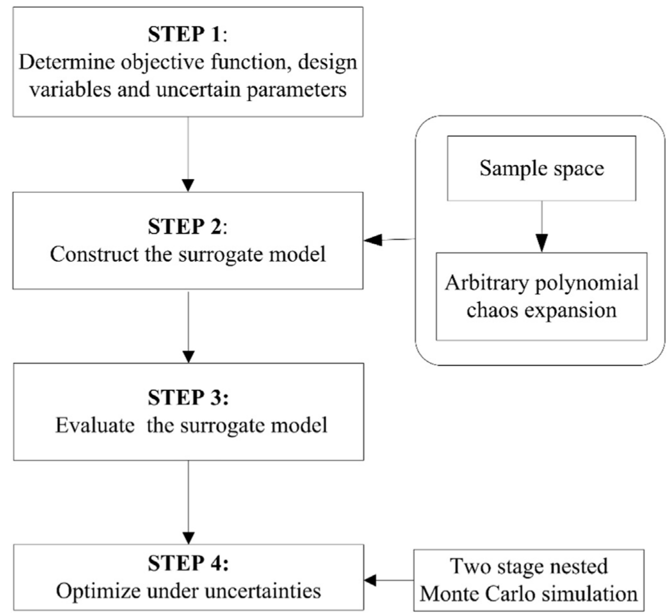

Fig. 1. Illustration of a 4-step procedure for the optimization method considering uncertainties.

2.1. Objective function and design variables

Due to the randomness of fire occurrence and human behavior, in general, it is difficult to pre-determine initial values of some parameters related to occupant evacuation under fires, such as occupant density, crowd type, pre-movement time etc., which are called as uncertain parameters. Meanwhile, geometric parameters of buildings, such as exit width, exit location, the distance between exits, etc., are generally unchanged for occupant evacuation under fires. They are referred to as design variables. Evacuation time is dominated by design variables and effected by uncertain parameters. We denote evacuation time as follows.

$$T_e = f\left(x_{i_1}, x_{i_2}, \cdots, x_{i_{n_1}}, x_{j_1}, x_{j_2}, \cdots, x_{j_{n_2}}\right) \quad (1)$$

where T_e is evacuation time; n_1 is the number of design variables associated with evacuation time; $x_{i_1}, x_{i_2}, \cdots, x_{i_{n_1}}$ are design variables, e.g. exit location, exit width, the distance between exits; n_2 is the number of uncertain parameters related to evacuation time; $x_{j_1}, x_{j_2}, \cdots, x_{j_{n_2}}$ are uncertain parameters, such as occupant density, crowd type and pre-movement times, etc.

In this paper, our purpose is to minimize evacuation time at a