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Sensitivity and Uncertainty Analysis of a Fire Spread Model with Correlated Inputs

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Abstract

Sensitivity and uncertainty analysis is a very important tool to identify and treat model uncertainties in quantitative fire risk analysis. An existing Fire Spread model with correlated input variables are presented for sampling-based sensitivity analysis, and selected input variables include fire growth rate, fire resistance rating and its standard deviation, fire load density and its standard deviation. A sampling approach is proposed to deal with the correlated structure of input variables, which introduces a noise term and can transform correlated input variable structure into an independent one. Furthermore, sensitivity analysis of input variables of fire spread model is performed and an order of variable sensitivity is given. Results show that fire resistance rating and its standard deviation are two very important input variables while standard deviation of fire load density is the least sensitive parameter. Further discussions are provided on the effectiveness of the sampling technique and the use the results of the analysis.

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Keywords: risk assessment; modeling; fire growth, statistics

Nomenclature

α	fire growth rate (kW/s^2)
nS	number of samples
t_{sp}	fire spread time (minute)
$FLD\mu$	mean of Fire Load Density (kg/m^2)
$FRR\mu$	mean of Fire Resistance Rating (minute)
$FLD\sigma$	standard deviation of Fire Load Density (kg/m^2)
$FRR\sigma$	standard deviation of Fire Resistance Rating (minute)
NF_{FLD}	noise Factor of Fire Load Density
NF_{FRR}	noise Factor of Fire Resistance Rating

1. Introduction

Quantitative fire risk assessment models have been frequently proposed to predict fire risks, especially with the shift from prescriptive to performance-based fire safety design. Generally those fire models are used to estimate results and consequences of assigned fire scenarios with certain amount of input variables and outputs, presuming that the model is valid to solve the given problems. However, the uncertainty of the input variables propagates through the model and makes the uncertainty of the results unpredictable, specifically when the model is a submodel of large system.

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Sensitivity and uncertainty analysis are becoming increasingly widespread in many fields of engineering and science. Hamby [1] explained some reasons for sensitivity and uncertainty analysis, including determining which parameters require additional research for strengthening the knowledge base, which parameters are insignificant and which inputs contribute most to output variability. Cacuci et al. [2] stated that the methods of sensitivity and uncertainty analysis are based on deterministic and statistical methods, which can be further categorized as follows: sampling-based methods (simple random sampling, stratified importance sampling, and Latin Hypercube sampling), first and second-order reliability algorithms, variance-based methods, and screening design methods.

The most popular uncertainty analysis technique is sampling based methods (also called Monte Carlo method) [3,4]. Such methods involve the generation and exploration of a mapping from uncertain analysis inputs to uncertain analysis results. Among the sampling based methods, the simple random sampling approach is the simplest but it needs a large amount of samples to effectively cover the distribution range, and it becomes non-feasible to conduct uncertainty analysis when the inputs are multivariate and the system takes time to generate outputs. Most designs use Stratified Sampling to improve the rate at which estimated quantities converge to the true quantities [5]. The principle behind stratified sampling with a single variate is to partition the sample space into non-overlapping regions and to guarantee sampling from each region. The purpose for Stratified Sampling is to ensure that all parts of the sample space are represented, for improved (i.e. less uncertain) mean and variance estimates. The idea of fully covering the range of each parameter is further extended in the Latin Hypercube sampling procedure [6], which is a frequently used method and many applications exist in the fire safety engineering area [7-10]. For Latin hypercube sampling, the range of all the input variables are exhaustively divided into same number of disjoint intervals of equal probability and one set of input values is selected at random from each interval. This requires that the investigated input variables should have clear and continual distributions, such as normal distribution, but practically these are sometimes hard to define. Furthermore, if a correlation structure exists among the input variables, but the actual sampling takes place as if the input variables were independent, the theoretical properties of the statistics formed from the output may no longer be valid [11]. A detailed illustration of differences of the Random Sampling, Stratified Sampling and Latin hypercube sampling can be found in [12].

Until now, only a few studies were done to deal with the sensitivity analysis of correlated variables [11,13-16]. A method for inducing a desired rank correlation matrix on multivariate input vectors for simulation studies was developed by Iman and Conover [11,13]. The primary intention of this procedure is to produce correlated input variables for use with computer models. Xu [16] used a regression-based method to quantitatively decompose the variances in the model output into partial variances contributed by the correlated and uncorrelated variations of parameters. Mara et.al [15] created a procedure that generalizes Xu's [16] approach to the case of conditionally dependent inputs by an ANOVA decomposition of the original model. Jacques et.al [14] proposed a variance-based application of the multidimensional generalization of classical sensitivity indices, and applied group sensitivities for models with correlated inputs. Sebastien [17] considered a method based on local polynomial approximations for conditional moments to deal with correlated inputs. Xu [18] extended Fourier amplitude sensitivity test (FAST) to models with correlated parameters. All the above studies except the work of Iman were variance-based methods and actually do not involved with sampling of input variables.

In this study, uncertainty and sensitivity analysis of a fire spread model with dependent input variables and discrete distributions is investigated. A sampling method adapted to this specific model is proposed and parameter sensitivity analysis is performed.

2. Description of Fire Spread Model

The Fire Spread model is a probabilistic model using Bayesian Network approach and probability theory [19,20]. It is one of the submodels of CUrisk, which is a Fire Risk Analysis computer model being developed at Carleton University. This sub-model is used to calculate the probability of fire spread across rooms throughout a building at different simulation times. The results reflect the combination of the fire development process and the boundary failure process. The probability of fire spread from room B to room A, *P(a|b)*, is written as,

$$P(a \mid b) = P(a|a')P_{ig}(a'|b) \tag{1}$$

And,

$$P_{ig}(a' \mid b) = P(a'|b)P(b) \tag{2}$$

If a room has several adjacent fire rooms, heat could be transferred to this room simultaneously from all adjacent fire rooms; Assuming the room A has two adjacent fire rooms B and C, the probability of fire spread to room A due to fire rooms B and C is,

$$P(a \mid b,c) = P(a \mid a')P_{ig}(a' \mid b,c) \tag{3}$$