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Numerical Optimisation Techniques Applied to Evacuation Analysis

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Summary. A common problem faced by fire safety engineers in the field of evacuation analysis concerns the optimal design of an arbitrarily complex structure in order to minimise evacuation times. How does the engineer determine the best solution? In this study we introduce the concept of numerical optimisation techniques to address this problem. The study makes use of the buildingEXODUS evacuation model coupled with classical optimisation theory including Design of Experiments (DoE) and Response Surface Models (RSM). We demonstrate the technique using a relatively simple problem of determining the optimal location for a single exit in a square room.

1 Introduction

In attempting to find the optimal design which minimises egress time for an arbitrarily complex structure the engineer typically identifies several design variables and associated constraints which may be adjusted to modify the egress time. In practise the engineer would select several scenarios covering the allowable range of the design variables, run the simulations and select the scenario which produces the shortest evacuation time. But how does the engineer know that the solution is optimal or near optimal? The more cases the engineer runs the more likely they will be to have identified the optimal solution however, the more cases that are run, the longer the design time. Indeed, to be certain of finding a near optimal solution many hundreds of scenarios may need to be run and analysed to ensure that the entire design space is covered.

To address this problem we propose to use classical optimisation theory including Design of Experiments (DoE) and Response Surface Models (RSM) coupled to evacuation simulation using the buildingEXODUS evacuation software [1, 2].

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2 The Methodology

The methodology uses four main steps:

- **STEP 1: Identify the Objective Function (OF)**
  The OF is the function that is to be optimised, in these problems the OF is the Total Evacuation Time (ET). The main objective is to minimise ET.
- **STEP 2: Define Design Variables (DV) and constraints**
  For an OF there may be many DV (DV1, DV2, DV3, ...) e.g. number of exits, exit location, exit width, shape of the enclosure, number of occupants, etc. Thus the OF may be multi-dimensional.
- **STEP 3: Construct Response Surface (RS) describing OF**
  The RS is a multi-dimensional surface in DV space. Each point on the RS is determined by running the evacuation software for each unique set of DV. This requires many hundreds of evacuation scenarios to be simulated ensuring that the entire design space is covered. As this is impractical, an approximation to the RS is developed by running only a handful of scenarios for selected KEY values of the DV. The KEY values for the DV required to produce a "reasonable" approximation to the RS are determined using DoE techniques. These techniques identify strategic combinations of DV which provide a good coverage of the design space and which hopefully will produce a reasonable approximation to the RS. Examples of DoE techniques are the *Latin Hypercube* and *Central Composite Design* (CCD) [3, 4]. DoE techniques can only be used in unconstrained problems. In constrained problems, random selection procedures must be used.
  Each strategic combination of DV identified by the DoE technique defines a scenario which is then run using the evacuation model. The RSM is determined by fitting a mathematical function to the surface of points (ET, DV1, DV2, ...) in the design space. Examples of RSM which were used in this study are the *full-quadratic* and *high order polynomial* approximations [5].
- **STEP 4: Determine the minimum of the RSM**
  Numerical optimisation techniques are used to find the minimum of the multi-dimensional RSM. There are many optimisation algorithms [6] which can broadly be categorised into two families, the classical gradient-based methods and the stochastic-based methods. Examples of optimisation techniques include: *Fletcher–Reeves*—a gradient method and *Particle Swarm Optimisation (PSO)*—a stochastic method [6].
  The Fletcher–Reeves method can be used for constrained and unconstrained problems and its algorithm is based on the first derivatives of the OF and is considered to be very robust [6]. The technique does not use information obtained from matrix operations which also makes it numerically efficient. The main advantages of this method are: the gradient is linearly independent of all previous direction vectors; the searching process makes good progress because it is based on gradients and the formula to

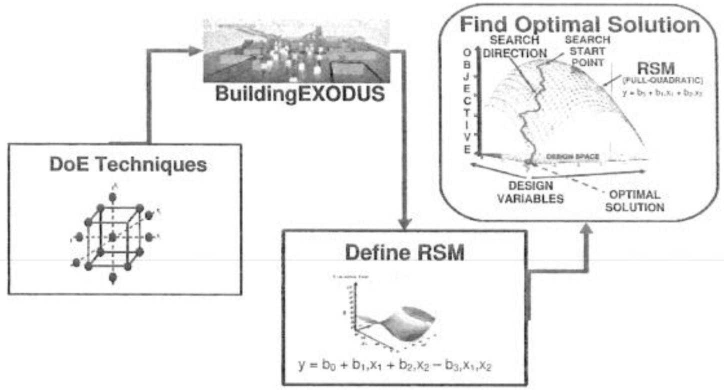

Fig. 1. The proposed optimisation methodology.

determine the new direction is simple. The Particle Swarm Optimisation (PSO), is based on a simplified social model that is closely tied to swarming theory [7]. It was developed by Dr. Eberhart and Dr. Kennedy in 1995 and it is inspired by social behaviour of bird flocking or fish schooling [8, 9]. The principle is that the design variables are understood as particles with associated velocities. The method is analogous to the Fletcher–Reeves, however instead of using the gradients of the objective function to insert the searching algorithm, the vectors are represented by uniform random numbers between 0 and 1.

In the work presented in this paper both these techniques were used. Once the minimum of the RSM is found it represents the set of DV required to produce the OPTIMAL solution. The proposed methodology is summarised in Fig. 1.

3 Demonstration Problem

The problem to be investigated can be stated very simply as follows, for a room of given size, containing an arbitrarily large population and a single exit, is there an optimal location for the exit that will minimise egress times? The square room used in the analysis has an area of 100 m^2 and an exit of width 1.0 m is considered. The population of the room consists of 200 people producing a population density of 2 people/m^2.

Our specific problem involves the determination of the optimal location of a single exit in a square room that results in the minimum evacuation time for the room. Here the Evacuation Time (ET) is the Objective Function (OF) and the exit location, measured from an arbitrary point on the perimeter is the single Design Variable (DV). As the exit can be placed anywhere on the perimeter of the room, the problem is considered unconstrained.

4 The Solution

The approach adopted involves the use of the buildingEXODUS evacuation software to simulate the evacuation of the compartment for each relevant exit configuration. The egress simulations were conducted assuming ideal conditions of zero response times and population behaviour such that occupants would move to their nearest exits. Both assumptions are made to simplify the analysis and to focus on issues associated with exit location. The population was randomly generated with a maximum travel speed varying between 1.2 m/s and 1.5 m/s. The unit flow rate of the exit was capped to a maximum value of 1.33 occupants/m/sec. The simulations were repeated a total of 600 times for each scenario. Thus all the numerical predictions represent an average over 600 simulations. For each repeat simulation the starting location of the population was also randomised. This ensured that the population was distributed throughout the confines of the geometry with little bias resulting from population starting position contributing significantly to the overall results.

4.1 The Design Variables

The geometry is defined by a 10 m × 10 m room with a single 1 m wide exit. The DV is the exit position (EP) which is measured from the bottom left corner of the room to the leading edge of the door. Given the symmetry of the room, the domain of the DV is $0 \leq EP \leq 4.5$. For instance, when $EP = 0$ the exit is located in the bottom left corner while when $EP = 4.5$ the exit is located 4.5 m from the left corner and is located within the centre of the wall.

Fig. 2. Exit locations for single exit cases with 1.0 m wide door.

4.2 Results and Discussion

The solution to this problem was determined by "brute force" by defining seven unique exit locations and performing 4,200 simulations using building EXODUS [10]. The seven exit locations were selected by attempting to cover as many unique locations in the DV domain as was thought to be practical. The results of this "brute force" approach (or traditional approach) suggested that an exit located in the corner of the room would produce a minimum evacuation time of 165.4 sec as shown in Fig. 3.

The problem was also solved using the Optimisation Method described in this paper. Two different approaches were used. In the first case all seven design points were used to define the RSM while in the second case a DoE technique was used to define the number and location of the DV. The solution found based on the seven different values of the DV used a forth order polynomial function to define the RSM and two optimisation techniques, Fletcher–Reeves and PSO. The forth order polynomial function defined the RSM with an R^2 of 0.95 producing a good fit. Using the optimisation techniques and the RSM defined using seven values of the DV the same optimal solution was found as using the brute force technique i.e. (0; 165.4). This suggests that if a sufficiently accurate RSM is used, these optimisation techniques are capable of accurately determining the optimal solution. However, we have gained little advantage as we have used as many design points as was used in the brute force method to locate the optimal solution.

For the second approach DoE techniques were used to identify the number and value for the DV. The Latin Hypercube DoE technique suggests that six design points must be used resulting in 3,600 simulations. Using the CCD DoE technique only three design points are required resulting in 1,800 simulations. In both cases a Full-Quadratic polynomial was used to define the RSM, pro-

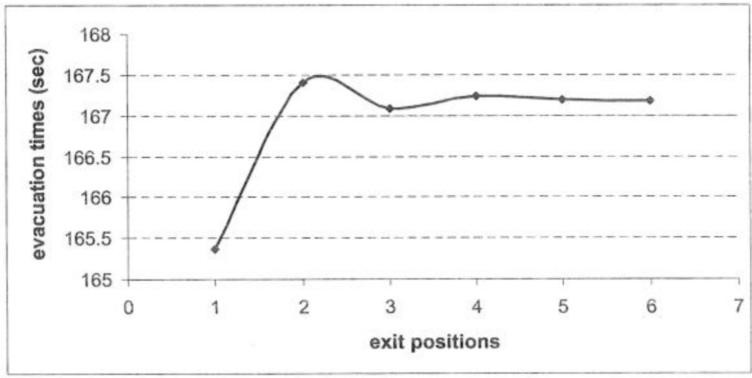

Fig. 3. Average ET for the single exit cases.

ducing a R^2 of 0.99. In both cases, both optimisation techniques were again used and in all four cases the correct optimal solution was obtained.

Thus using the DoE techniques combined with optimisation methods we have been able to identify the optimal egress solution using considerably less computational effort, and hence time than the brute force method.

5 Concluding Comments

In this paper we have presented a method to reduce the effort involved in determining optimal design to minimise evacuation time. The method is based on classical DoE, RSM and Numerical Optimisation techniques. The technique was demonstrated using a simple square room with a single exit. The optimisation method correctly identified the location of the exit that results in producing the minimum evacuation time for the structure.

Using the CCD DoE technique to identify three unique values of the DV, the Full Quadratic Smooth technique to define the RSM and two optimisation techniques, a gradient-based technique, the Fletcher–Reeves and a stochastic technique, the PSO, the correct solution was found and, most importantly, required 57% less effort than the brute force method of finding the optimal solution.

While the example application is considered quite simply, the authors have also successfully applied the technique to more complex problems involving rooms with two exits. In this case the problem is constrained as the location of the exits cannot overlap and non-square shaped rooms. In all these cases the technique is capable of identifying reasonable solutions to these problems. Further testing of the method continues to determine its robustness.

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