CASE STUDY // PROCESS ENGINEERING

SENSITIVITY ANALYSIS OF EVACUATION SIMULATIONS

Simulation of evacuations is an efficient way to find the best escape concepts and to increase the safety of buildings. The importance of different input parameters for the result is investigated by stochastic sensitivity analyses and evaluated by the Model of Optimal Prognosis (MOP).

Introduction

Safe evacuation of persons from buildings in cases of fire or other emergency situations is getting an increasing public attention. There are many sad examples in history where inadequate escape routes in the case of fire have caused the death of many people. The "Iroquois Theatre Fire" in Chicago with about 605 victims or the "Karlslust Dance Hall Fire" in Berlin with about 88 victims are only two examples. By evacuation simulations it is possible to discover critical parts of escape concepts in order to optimize the safety of buildings.

As evacuation simulation is a relatively young discipline, there is a strong need to develop knowledge and expertise on the sensitivity of the results on statistic or deterministic variation of input parameters. The probability distributions of most input parameters are not sufficiently known. To find out for which of them it is worth to carry out detailed investigations and experiments, probabilistic sensitivity studies are an efficient method. Typical simulation times are very short, even for big models – for less than 1000 occupants often below one minute. From the cost point of view, this makes evacuation simulation an ideal application area for stochastic methods where high numbers of samples are needed to find reliable results.

Evacuation simulation models are employed to simulate crowd movement in emergency situations. These models can be divided into four different groups: flow-based models, cellular automata, agent-based and activity-based models.

The sensitivity study was carried out with Pathfinder and optiSLang. Pathfinder is an agent-based model that individualises the movement of groups. Every evacuee is defined by a set of attributes like for example walking speed, shoulder width or comfort distance.

Numerical Model of Evacuation

Input Parameters

Whether an escape route is considered safe or not strongly depends on the amount of people using it in case of an emergency. The capacity of every section of a path is limited by its length and width as well as by obstructions and restrictions (doors) along its way. The movement of the crowd depends on physical factors like the area occupied by the bodies and the density of the group. The behaviour of the crowd also depends on many other properties of the individuals in the group like, for example, prior knowledge, knowledge of the place and leadership behaviour.

Pathfinder offers two modes of occupant movement: SFPE mode and steering mode. This study was made using the steering mode. The steering system in Pathfinder moves occupants so that they roughly follow their current seek curve and can respond to a changing environment.

Geometry

In Pathfinder, floors are divided into an irregular triangular navigation mesh. The mesh can be divided in multiple rooms on multiple floors in 3D. Floors with different heights can be connected by stairs, ramps or elevators. Occupants can only move on the navigation mesh while obstacles, like furniture or closed interior rooms, are simply represented by holes in the navigation mesh.

Solution Procedure

The numerical solution to determine occupant movements is discretised in time and uses an explicit integration scheme. In each time step the following procedure is carried out:

1. **Update targets:** Determine the current target for each occupant, taking into account different exits and individual properties and plan a path to reach the target.
2. **Calculate the movement of occupants** by explicit Euler integration, taking into account the current velocity of each occupant and individual acceleration to normal walking speed at start of the simulation and after passing obstacles.
3. **Modify escape paths** in order to account for other occupants who represent dynamic obstacles in their way and allow decisions for other exits and paths according to the local situation.

Path Generation

Escape paths along the navigation mesh are defined by a search algorithm along points on the edges of the mesh triangles. As there are often different paths on which a destination can be reached, a decision needs to be made on the most appropriate one. The solution algorithm selects the "locally quickest" path to the final destination. For this decision, it is assumed that the occupant knows about the doors in the local room and the queues at those doors as well as the distances to them. This evaluation is made by help of a weighted cost function of four steering behaviours (seek, separate, avoid walls and avoid occupants). Having determined the lowest cost direction, the maximum distance that should be travelled along this direction will be calculated. As the occupant moves, he has to account for dynamic obstacles like other occupants and, therefore, has to adjust his way by idling or seeking. Depending on the state and speed of the occupant, different sample directions are tested.

Sensitivity Analysis

Three sensitivity studies were carried out, each with a different objective:

1. Determine which of the parameters describing occupant properties are most important. For this purpose, a study with constant geometric parameters was made.
2. Investigate the influence of different geometric parameters. In this study, occupant properties are constant.
3. Evaluate the importance of geometric parameters versus occupant properties. In this study, all input parameters are varied stochastically.

Input and output parameters

Input parameters are divided into two groups: occupant properties and room geometry (Table 1 and 2).

Input Parameter	Unit	min	max
accelFactor	s	0.50	1.10
radius	m	0.14	0.25
maxVel	m/s	0.36	1.58
reacTime	s	0.09	0.11
minSqueezeFactor	-	0.50	1.00
persistTime	s	0.50	1.50
collisionResponseTime	s	0.50	2.00
comfortDist	m	0.00	0.50
slowFactor	-	0.05	0.15
localQueueTimeFactor	-	0.80	1.00
localTravelTimeFactor	-	0.80	1.00
tailTimeFactor	-	0.80	1.00

Table 1: Input parameters for occupant properties

Input Parameter	Unit	min	max
exit_west	m	1.00	1.40
exit_south	m	1.00	1.40
exit_east	m	1.00	1.40
door1	m	1.00	1.80
door2	m	1.00	1.80
door3	m	1.00	1.80

Table 2: Input parameters for room geometry

Parameters in Table 1 are assumed to have a normal probability distribution. Input parameters for the room geometry are shown in Table 2. They describe the width of the interior doors and emergency exits (see Fig. 1 next page). Parameters in Table 2 are assumed to have a uniform probability distribution. The input parameters of the occupants vary in ranges that correspond to typical properties of healthy people. The maximum speed of an occupant, for example, varies in a range

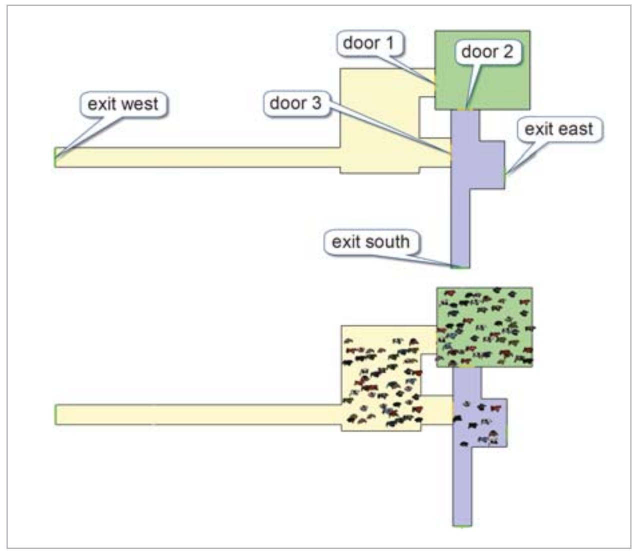

Fig. 1: Room geometry (top) and initial distribution of occupants (bottom)

that is typical for people who can move without mobility aids like crutches, walkers or wheel chairs. The input parameters for occupant properties are shown in Table 1. The most important ones are:

- Radius: radius of the moving cylinder by which occupants are represented. Its range corresponds to the range of human shoulder width
- Maximum velocity (maxVel): maximum velocity at which an occupant can move
- Comfort distance (comfort_Dist): specifies the desired distance one occupant will try to maintain with others nearby such as when waiting in queues
- Collision Response Time: when multiplied by an occupant's current speed, this parameter controls the distance at which an occupant will start recording a cost for colliding with other occupants when steering,
- Acceleration time (accel_Factor): specifies the amount of time it takes for the occupant to reach maximum speed from rest or to reach rest from maximum speed.

The most important output parameter for evacuation simulations is the time until the last evacuee has left the building. This evacuation time (maxTime) is measured in seconds. Other output parameters that evaluate the distribution of occupants to the different exits and the flow through the exits could be important for a subsequent optimization based on the sensitivity results.

Room Geometry

The fictive room geometry was set up with the objective to provoke changes of the "locally quickest" path during the simulation. There are multiple ways with similar length to the exits. The building has a total area of 110 m² consisting of three rooms on one floor connected by three doors with one long corridor and 3 exits. 110 occupants were chosen for escape scenario.

Sampling method

For all analyses, optiSLang's Advanced Latin Hypercube Sampling was applied to generate 500 or 1000 stochastic samples. The results were evaluated after calculation of the Metamodel of Optimal Prognosis (MOP) that allows to assess the quality of prognosis for the simulation model and is used to characterise the influence of each input parameter on each output parameter by evaluation of their ability to predict results. Simulation time for 500 samples was 35 min on an office PC with 4-core-CPU.

Study 1: Sensitivity to Occupant Properties

In this study, only occupant properties were used as stochastically varying input parameters. All geometric parameters of the building were held constant. The result shows that walking speed (maxVel) and outer dimensions (radius) of the occupants have highest influence on the evacuation time. Further, the acceleration time (accel_Factor) and the comfort distance (comfort_Dist) are important for the result.

The graph in Fig. 2 shows the Coefficients of Prognosis (CoP). The CoPs are calculated with the MOP. This metamodel is based on the results of the sensitivity analysis and uses approximation algorithms to provide a response surface which is applied to evaluate the quality of prognoses that can be made with the simulation model. The results in Fig. 2 read as follows: 54% of the variations in the results of the output parameter maxTime (evacuation time) can be explained by the variations of the input parameter maxVel (maximum velocity of an occupant). Input parameters with contribution of <1% are not displayed in this graph. The CoP is an appropriate measure to evaluate the quality of a model. Low CoP values are generally an indicator of an error in the model, for example, due to input errors committed by the user or in the simulation software. In this example, a high CoP of 96% was calculated.

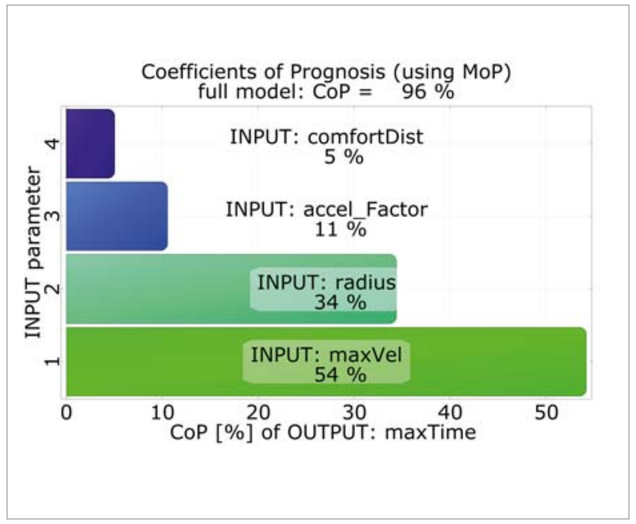

Fig. 2: Study 1 (only properties of occupants vary), Coefficients of Prognosis for evacuation time (maxTime)

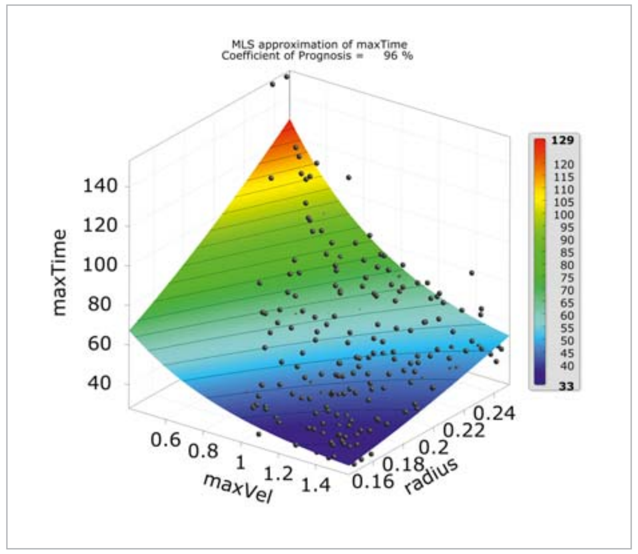

Fig. 3: Study 1 (only properties of occupants vary), 3D response surface for evacuation time (MOP)

Study 2: Sensitivity to Geometric Parameters

In real projects, a typical task for evacuation simulations is, for example, to prove that replacement of existing doors against wider ones is not required because safe egress is possible without expensive modifications. In study 2 of the investigated example, the interior door 3 has the highest importance: 32% of the variation of the evacuation time can be explained by the variations of the width of this door. This result is interesting because this door is not an emergency exit and therefore not considered to have such high importance for the result. Because of the queue at door 2 many occupants decide to take the second rescue path through door 1 (Fig. 4). But instead of following the crowd to the exit west (green arrow) they decide to take the "shortcut" through door 3 to the exit east (blue dotted arrow). To avoid this bottle-neck situation, escape route signs at door 3 have to show to exit west and not to door 3.

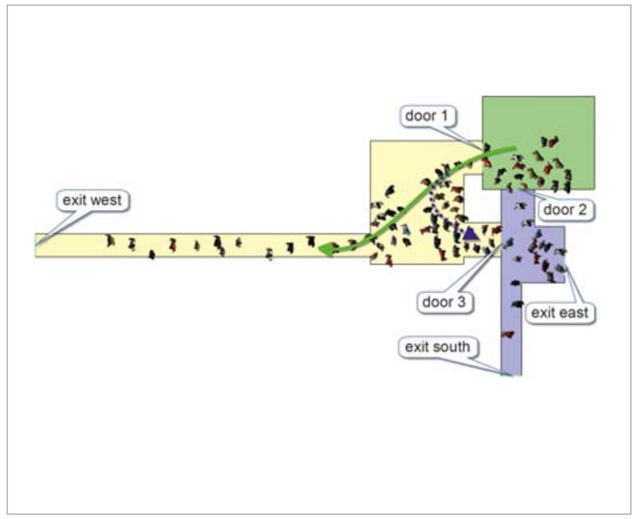

Fig. 4: Simulation sample of study 2, illustrating the importance of door 3

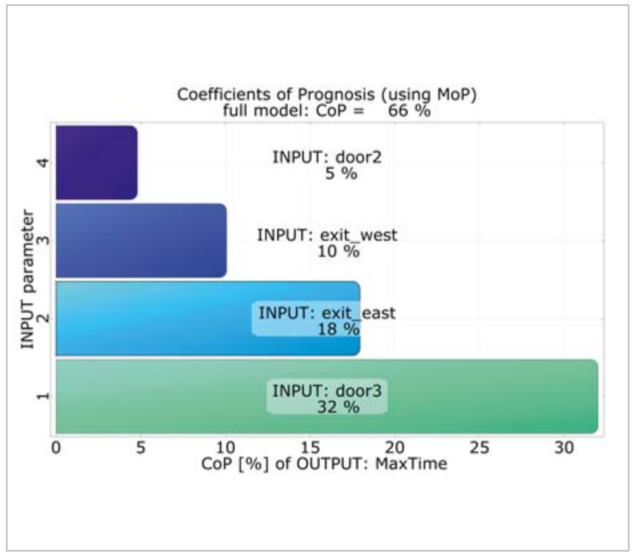

Fig. 5: Study 2 (only geometric parameters vary), Coefficients of Prognosis

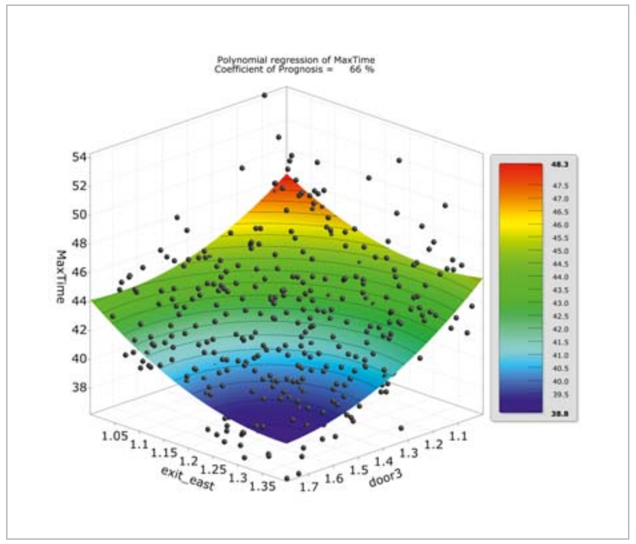

Fig. 6: Study 2 (only geometric parameters vary), 3D response surface, door 3 and exit east vs. evacuation time (MOP)

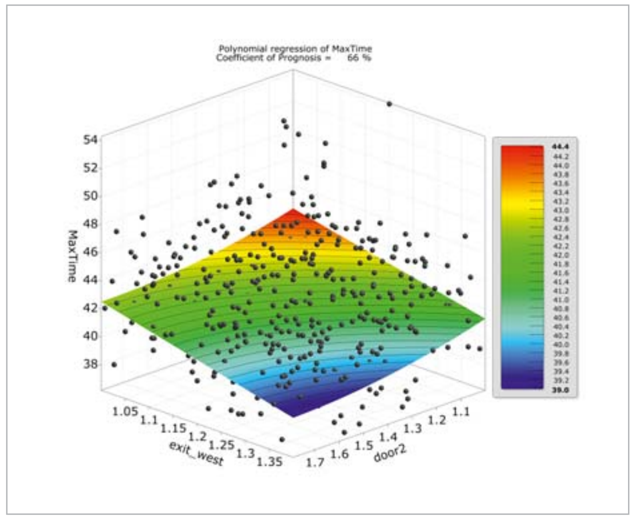

Fig. 7: Study 2: (only geometric parameters vary), 3D response surface, door 2 and exit west vs. evacuation time (MOP)

Study 3: Relationship of Sensitivities to Geometric Parameters and Occupant Properties

In this study, both groups of input parameters – occupant properties and room geometry – are varied. As in study 1 and 2, the probability distribution of geometric parameters is uniform, whereas the occupant properties follow a normal distribution. An interesting result is that the occupant properties radius, maximum velocity and acceleration time are much more important for the evacuation time than the width of interior doors and emergency exits in this example (Fig. 9).

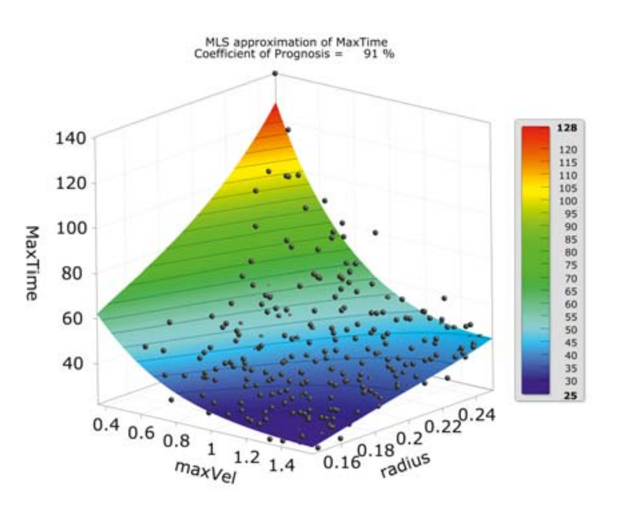

Fig. 8: Study 3 (Geometric Parameters and Occupant Properties vary), 3D response surface for evacuation time (MOP)

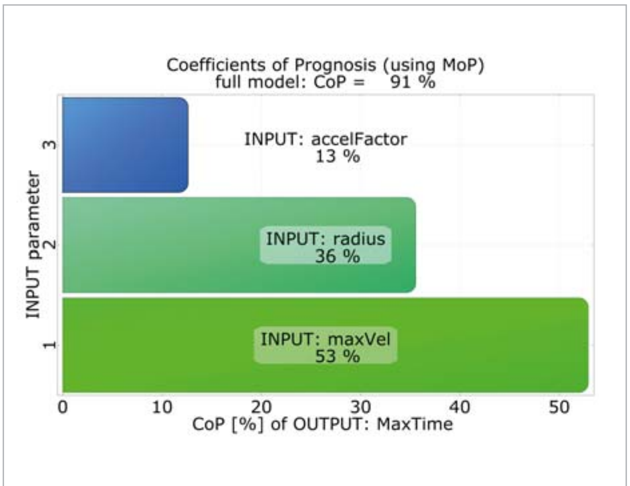

Fig. 9: Study 3 (Geometric Parameters and Occupant Properties vary), Coefficients of Prognosis

Conclusions

By stochastic sensitivity analyses of evacuation simulations with an example building consisting of three connected rooms with 3 emergency exits it could be shown that:

- Only a few input parameters that describe occupant properties have significant influence on the evacuation time, mainly the radius and the walking speed are important.
- If both geometric and occupant parameters are varied, the variation of occupant parameters has bigger influence on the variation of results.

The percentage of people who walk at reduced speed and also require more floor space is increasing due to the current trend of an aging population. The results show that the presence of people with physical impairments who are using walking frames or other mobility aids among the evacuees would have a strong influence on the entire evacuation process and not only on the total evacuation time.

The results can be applied to increase the reliability of simulations by more precise determination of the most important input parameters. It is recommended to verify particularly the input data for occupant shoulder width, maximum walking speed and acceleration time.

The results were produced by use of one arbitrary example for the basic geometry. Further investigations should be made to find out if this result is valid on other geometries as well. Simulation-based optimization and robust design analysis can follow the sensitivity analyses to improve designs for evacuation.

Authors // Dr. Gerald Grewolls (SIMTEGO GmbH) / Prof. Dr. Kathrin Grewolls (Ingenieurbüro für Brandschutz Grewolls)
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