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Probabilistic assessment of the occupant load density in retail buildings

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ABSTRACT

The occupant load density is a crucial parameter for the design of the means of egress in buildings. In retail buildings the occupant load density is highly influenced by the individual's choice and the necessity of a person to visit the store. This causes a high variability of the occupant load density in time. An accurate representation of this variability will provide a basis for enhancing fire safety design. In this paper, a probabilistic approach is used to describe the variability of the occupant load density over a year, based on long-term data of customer frequencies in combination with methods from the queuing theory the distribution of the occupant load density is derived for four different types of retail chains. It is shown that the type of a retail chain has a large influence on the distribution of the occupant load density and that the exceedance probability of current design values in different standards is very small. A method is proposed to derive design values for a performance based design on the basis of probabilistic models for the occupant load density. In addition, the developed probabilistic models describing the number of occupants in a store, allow the assessment of the occupant load density for other types of retail chains, even with incomplete data.

1. Introduction

By an accurate design of escaping routes the risk of human losses in fires can be reduced. The design of the means of egress implies a reasonable estimation of the number of occupants to be evacuated. To assess the total number of occupants in a compartment the occupant load density is used. In many countries the local codes [1–4] specify the occupant load density (also known as occupant load factor) for different occupancies to assess the total number of persons that have to be evacuated.

On one hand, the occupant load density is used in prescriptive fire safety codes to set additional fire safety measures like smoke alarms, sprinklers, smoke extraction or evacuation systems. On the other hand, the level of safety in a performance based design is usually evaluated by assessing the required safe egress time. There, the occupant load density is used to assess the number of persons that have to be evacuated. Last but not least, in a risk based approach the occupant load can be used to assess the probability of a fatality [5,6] or the expected fatality rate in a fire [7]. Albrecht [6] showed that the occupant load density is – besides the pre-travel activity time – the most influential parameter for assessing the required safe egress time. Magnusson et al. [5] applied a risk based approach to derive a safety factor for a characteristic value of the occupant load density (see Section 5.6), which may be used in a performance based design approach. All of the authors used a rough estimation of the distribution of the occupant load density due to the lack of data.

Independent of the application field an accurate knowledge about a realistic value of the occupant load density is necessary to ensure a safe design and to avoid an over-design of escaping routes which might lead to a non-optimal allocation of social recourses. Therefore, numerous surveys have been conducted in the past for office buildings [8–11]. Most of the studies are based on walk-through investigation, e.g. counting the actual number of building occupants or the number of working places. A similar methodology can be applied in buildings where the number of occupants is highly influenced by the occupant capacity of the building, e.g. in residential buildings [12], hotels, hospitals, school buildings, theatres, cinemas, etc. Courtney et al. [8] conducted surveys for the most of the listed types of occupancy.

In contrast to this, the number of persons in retail stores is usually not influenced by the occupant capacity of a store. The number of persons is highly influenced by the individual's choice and the necessity of a person to visit the store. This leads to a high variability of the number of occupants in time. Therefore,

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walk-through investigations are not suitable for the surveys in retail buildings. Only survey methods that include the number of persons in time should be used.

A common approach is to assess the occupant load density during peak days of a year [13,14]. Then, the derived occupant load density is used as a design value. The drawback of this approach is that the whole variability of the occupant load density remains unknown. Therefore, the occupant load can hardly be used in a probabilistic approach used for risk assessment.

Here, the occupant load density is assessed probabilistically based on a long-term survey for different types of retail chains. The data consists of frequency measurement of customers. The data has been provided from different major retail chains in Switzerland. Based on these data, a probabilistic model is developed to represent the distribution of the occupant load density over one year. Methods from the queuing theory are used because the data cannot directly be used to develop the probabilistic model. Such a probabilistic assessment of the occupant load meets the requirements of all the mentioned application fields.

2. Definitions

2.1. The occupant load density

The occupant load density d can be defined by the ratio of the number of persons p that are present in a compartment and its net floor area a_f (Eq. (1)). Here, the occupant load density is measured in persons per square meter [pers./m^2].

$$d = \frac{p}{a_f} \tag{1}$$

The number of persons in a room p [pers.] varies in time, while the net floor area a_f [m^2] of a building remains constant. Hence, the number of persons in a room p can be represented as random process $P(t)$. For definition and notation of random variables it is referred to Appendix A.1. The reference period for this random process is set to one year assuming stationarity and ergodicity over this period.

Usually, the number of persons in a room cannot directly be measured. Based on the number of arrivals respectively the departures and the time per customer spend in the store (dwell time) the number of persons can be assessed.

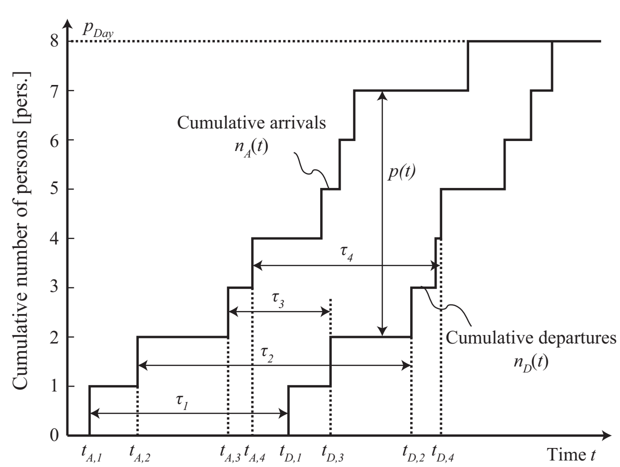

Fig. 1. Cumulative arrivals and departure to and from a system; adapted from [15].

2.2. Number of arrivals and departures

The random process for the number of person $P(t)$ in a compartment can be described by two underling processes, one for the arrivals and the other for the departures of persons [15]. The first process is represented by the cumulative number of arrivals $N_A(t)$ and the second process by the cumulative number of departures of the persons $N_D(t)$ over a day. Two realization of the processes $n_A(t)$ and $n_D(t)$ are illustrated in Fig. 1 for eight customers per day $p_{Day}=8$ as an example. The number of persons present in a store $P(t)$ at any time t can be assessed by Eq. (2).

$$P(t) = N_A(t) - N_D(t) \tag{2}$$

2.3. Dwell time

A realization of the cumulative number of arrivals $n_A(t)$ depends on the arrival time $t_{A,i}$ of the ith customer. This time can be considered as uncertain and is represented by a random variable $T_{A,i}$. At each realization of this time $t_{A,i}$ the cumulative number of arrivals $n_A(t_{A,i})$ increases by one. Customers will spend some time in the room until they leave. This time is denoted as the dwell time τ_i and represents the time from the arrival of a customer until the time of departure of the same customer. This time is individual and varies from customer to customer. Therefore, a random variable Τ (upper case letter of Greek letters are non-italic) is introduced to describe the variability associated with the dwell time. For each customer i the departure time $t_{D,i}$ is assessed by Eq. (3).

$$t_{D,i} = t_{A,i} + \tau_i \tag{3}$$

By reordering the departure times $t_{D,i}$ in ascending order the cumulative number of departures $n_D(t)$ is increased by one at each

Table 1
Overview of the provided data.

Retail chains		Customers per Hour	Customers per Day	Customers per Week	Other data on customer frequency[2]	Floor area for each store	Number of stores
Super-markets	A1				○[2a,b]	□[3)]	819
	A2	○[1b]	○[1b]	○[1b]		□	9
Furniture stores	B	●[1a]	●[1c]	●[1c]		□	10
Hardware stores	C1				○[2a]	□	73
	C2				○[2a]	□	95
Department stores	D1			●[1c]		□	24
	D2	○[1b]	○[1b]	○[1b]		□	4

[1] Over a survey period of (a) a few days/(b) few weeks/(c) a year.
[2] Sample statistics of frequency measurements over a year, e.g. (a) mean value and (b) standard deviation and quantile values.
[3] Divided in different categories of the net floor area (sales area), see Table 4 for categories.