Evacuation and Life Safety Assessment in Germany

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INTRODUCTION

In Germany, performance-based design methods are not explicitly embedded in national building codes. Accordingly, the major knowledge, guidance as well as material and product performance is closely linked to the prescriptive design approach. This approach has provided a substantial improvement of fire safety, resulting in a quite safe situation within the built environment at the present time. However, the increasing individuality and complexity of modern buildings or questions related to the conversion of existing buildings may conflict with the applicability or fulfilment of those deemed-to-satisfy requirements. Thus, the performance-based fire safety design has established in Germany as well.

All over the world, many countries and organisations have advanced standardisation of Fire Safety Engineering (FSE) well in the past [16]. Consequently, international standards are implicitly incorporated in the German day-to-day business of FSE. The current work on the DIN 18009 framework is supposed to ensure an adequate and uniform application of the variety of internationally available knowledge and methodologies [17].

Performance-based Fire Safety Design in Germany

Fire safety design is traditionally satisfactory if the building complies with the requirements in building codes. The accordance with the requirements leads to a "safe" building by definition. The codes are very constrictive to the layout and the material requirements.

Since 1978, the directive for industrial buildings in conjunction with DIN 18230 is the only native performance-based design approach in Germany. It regulates the determination of the required fire resistance time of components and the acceptable fire compartment area for industrial buildings. Basic principles for fire safety engineering are solely published in sub-statutory reports, guidelines and specifications.

The goal of the German Fire Protection Association (GFPA) (Vereinigung zur Förderung des Deutschen Brandschutzes e. V. – vfdb) Section 4 "Fire Protection Engineering" is to upgrade the modern fire protection engineering methods developed in the last years. Further-on it is the aim to make this upgrade available for daily applications in terms of of a guideline [7]. In the scope of fire protection concepts, this guideline is intended to contribute to harmonise disjointed approaches and assumptions and to avoid erroneous measures in the application of engineering methods.

Standardisation Activities in Germany

In the year 2008, the DIN working committee NA 005-52-21 AA „Brandschutzingenieurverfahren“ started its work to standardise fire safety engineering methods in Germany. The committee is also the national mirror committee for the international respectively European committees ISO/TC 92/SC 4 and CEN/TC 127/WG 8. In spring 2015, a first normative draft of DIN 18009 Part 1 [5] was released to the review process. After minor revisions had been included, it will be published in Summer 2016. Currently, two working groups are framing the technical sub documents "Evacuation and Life Safety" and "Fire Scenarios".

DIN 18009-1 – Fire Safety Engineering: Basic Principles and Codes of Practice

DIN 18009 Part 1 is intended as basis document to standardise the methodology in Fire Safety Engineering. It describes all characteristic steps and necessary terms and definitions related to the design process. In this respect, it is intended to serve as a guideline for both the design and the inspection process. In accordance with the basic principles of DIN 18009 Part 1, it is explicitly allowed to use other national or international standards in order to supplement the framework. In principal, DIN 18009 Part 1 comprises the following engineering methodologies: performance-based, argumentative and experimental; the emphasis is placed on the performance-based line. Irrespective of the question and the chosen method, the fundamental proof is based on the question if the system's resistance is greater than the minimal required resistance for a specific influence. To encourage this concept, guidelines for the identification of protection goals, performance criteria and acceptance criteria are provided. Further on, the framework regulates a classification of scenarios as well as the setup and selection of the latter. Finally, a concept for the inclusion of safety margins and guidelines for the documentation are provided to the practitioners [17].

DIN 18009-2 – Fire Safety Engineering: Evacuation and Life Safety

The first sub document DIN 18009 Part 2 covers evacuation modeling and the life safety assessment during fire and is currently in a first draft state. A special focus of the draft is the identification of representative scenarios and the related translation into parameter samples. With regards to requirements and related performance criteria, not only time magnitudes by means of the ASET/RSET concept shall be considered. Furthermore, the degree of safety related to the observed pedestrian dynamics e.g. the occurrence of jamming shall be addressed as well. In this respect, the quantification of dedicated acceptance criteria is very challenging. Regarding the established model classes to describe pedestrian dynamics, the methodology is designated to cope with different extends of data input and output. This covers the applicability of hydraulic models and agent-based models as well. Finally, a variety of recommendations for data analyses, visualisation and documentation are addressed. Selected insights related to methodology, requirements and scenario-based design are presented in the next section.

DIN 18009-2

Methodology and Requirements

To ensure a safe evacuation, the performance-based design and evaluation of the escape routes is predominantly focussed on the comparison of the available safe evacuation time (ASET) and the required safe evacuation time (RSET). The RSET has to be lower than the ASET:

$$\text{RSET} < \text{ASET} \tag{1}$$

The RSET is made up of the detection time $t_{\text{detection}}$, the alarm time t_{alarm} and the escape time t_{escape}, see equation 2:

$$\text{RSET} = t_{\text{detection}} + t_{\text{alarm}} + t_{\text{escape}} \tag{2}$$

The escape time is the sum of the pre-movement time t_{pre} and movement time t_{move} of the occupants, see equation 3:

$$t_{\text{escape}} = \max\left[t_{\text{pre},i} + t_{\text{move},i}\right] \tag{3}$$

The ASET/RSET comparison has to be proved within the whole built environment considering all significant respectively design scenarios. This also applies to the partial loss of escape routes. In addition to the fire safety-relevant analysis, the expected pedestrian dynamics have to be included in the assessment as well.

The application and quantification of safety margins for single performance criteria is currently under discussion. The whole design process shall be understood as a control loop.

Performance Criteria

DIN 18009 Part 2 will provide performance criteria and associated thresholds for a variety of magnitudes. In this respect, the life safety assessment is based on the evaluation of both ASET and RSET. For the determination of ASET, classical criteria such as *visibility, temperatures, gas concentrations* (CO_2, CO, HCN, O_2, etc.)and *radiation* will be incorporated. Furthermore, the height and the quality of the smoke-free layer is frequently used for life safety assessment. To evaluate the possible hazards to the occupants, Table 8.3 in [7, p. 253] provides some reference values depending on the exposure time.

In addition to the criteria related to ASET, it is the aim to define requirements for RSET as well. For that purpose, performance criteria like *evacuation time*, *jam density*, *jam time* or *waiting time* and associated thresholds shall be issued. The commitment and quantification of the latter is one of the big challenges. Hence, many documents and opinions have been collected during the past months. One example is a position paper published by the conference of German building ministers (ARGEBAU) [1] which clarified that the fire safety objective “rescue of occupants” can be achieved solely by fulfilling the prescriptive requirements for the design and dimensioning of escape routes. Especially in special occupancy buildings, the fire brigade can not ensure the rescue of occupants. Hence, the self-rescue has to be completed by the fire brigade’s arrival at the scene. The public fire brigade has an intervention time of about 8.5 to 15 minutes which may be an orientation for a threshold for assessing evacuation times.

Scenario-based Design

The centrepiece of DIN 18009 Part 2 is the identification of representative occupant scenarios regarding the pre-movement time, the movement time and the estimation of the required safe evacuation time. According to the basis document DIN 18009 Part 1, a comprehensive scenario systematisation has been introduced and incorporated into Part 2. In principal, the totality of possible occupant scenarios are grouped into relevant and non-relevant scenarios. By means of risk, non-relevant scenarios can be differentiated in bagatelle and worst-case scenarios. Additionally, a trial design may also result in unacceptable scenarios with high risk potentials, which categorically requires a redesign. Relevant scenarios are the centrepiece of the design process. They comprise a set of significant scenarios which are supposed to be represented by design scenarios. The outlined classification is illustrated in Figure 1.

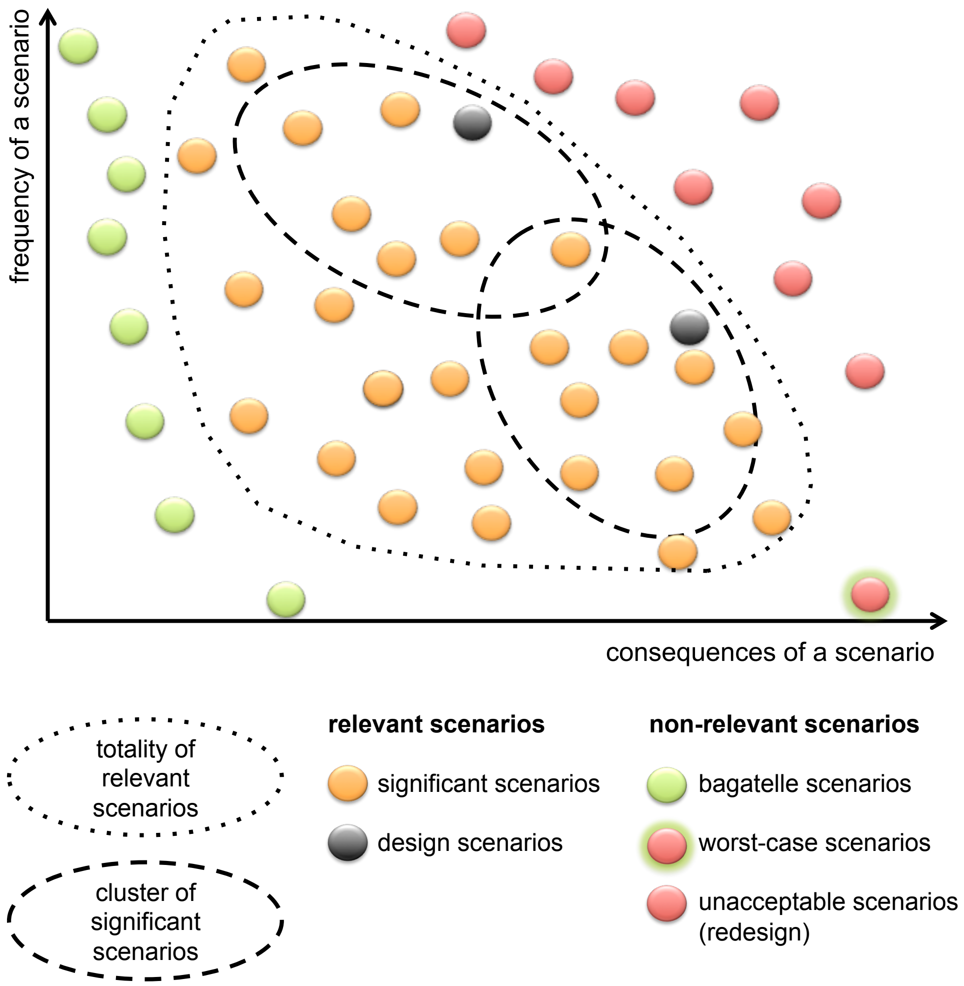


Figure 1: Scenario classification consisting of relevant scenarios (significant scenarios and design scenarios) and non-relevant scenarios (bagatelle scenarios, worst-case scenarios and unacceptable scenarios, which require a redesign).

Principles for the Description of Occupant Scenarios

On the basis of [8], occupant scenarios can be described by the categories *building, occupancy, hazard* and *safety measures* as shown in Figure 2.

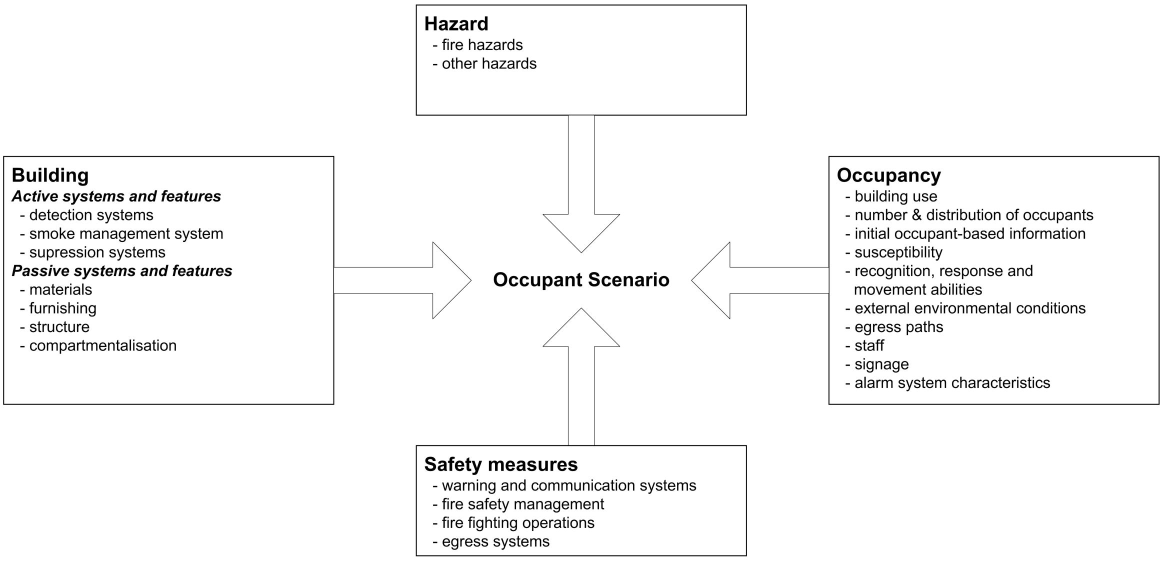


Figure 2: Categories for the description of occupant scenarios

Building

Building characteristics have a profound impact on potential occupant scenarios. The building layout plays major roles. The proposed layout, the construction of compartments and the interconnection have to be known. Events of active systems that change an occupant scenario, e. g. warning and communication systems, have be also known as well.

Occupancy

Evacuation strategies provide systems and features to allow people to exit structures safely, to reach a place of safety or to remain safely in a place during emergency conditions. These strategies have to be geared to the overall life safety goals and objectives and be have to be developed in accordance to the the overall fire protection and life safety program.

Assumptions must be made about the characteristics of the occupants in a way that the formulation of a scenario will challenge the fire safety design.

The estimate of the number of occupants and their locations are important for the egress path system and the evacuation strategies.

The occupant characteristics can also be the evacuation variables that should be the variables included in a sensitivity analysis.

Hazard

Hazard is the third component of the description of occupant scenarios. It is intended to cover a variety of causes that require a building evacuation. In the context of FSE, the occurrence of a fire in conjunction with the resulting effects is the most obvious cause. The interface to fire scenarios (future DIN 18009 Part 3) is considered by the understanding that a certain set of fire scenarios is one of the degrees of freedom of an occupant scenario. However, in the context of this article, this point is excluded.

Safety Measures

Finally, the possible influences associated to safety measures have to be included into the assessment. The performance and reliability of each of the fire safety measures are parameters of the design process. In concrete terms, this covers all technical, organisational and defensive prevention measures.

Workflow

The exploration of occupant scenarios and the determination of significant and design occupant scenarios requires a structured approach. A uniform approach does not exist in Germany so far. Current considerations provide the workflow presented in Figure 3.

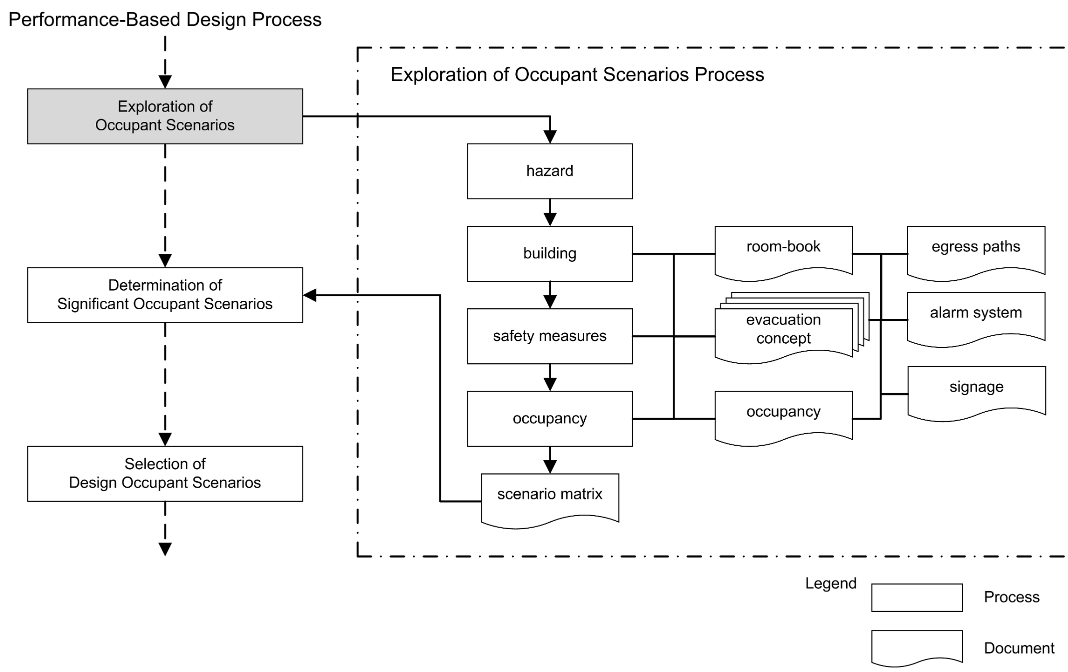


Figure 3: Occupant scenario workflow

APPLICATION EXAMPLE

Description of the Building

The example shows a three-storey building with multiple options of occupancies. The ground floor includes a lobby, a restaurant and offices. The floors are connected by an atrium and open stairs. All floors above the ground floor have a similar layout and include offices, meeting rooms and two independent stairwells. The floor plans can be found in figure 4.

(a) Ground Floor

(b) 1st/2nd Floor

Figure 4: Floor plans of the application example consisting of the ground floor and the two overlying floors.

Project Scope, Goals and Objectives

Prescriptive codes provide evacuation design guidance for a broad range of building types, occupancy and use groups and allow for many common arrangements. The codes include requirements for the layout of the building, the fire resistance of structural components, the fire safety system and the fire management. The level of safety achieved by those codes is unquantified. The compliance can be shown easily. For large buildings with modern architecture, the limits of prescriptive design become obvious.

According to the German Model Building Code (MBO) [2], the structure shall be designed, constructed and maintained to protect occupants who are not familiar to the hazard throughout the time required to evacuate, relocate to or remain in a safe area. The structural integrity shall be also maintained for this time. Active and passive systems shall be effective in mitigating possible hazardous conditions.

Exploration of Occupant Scenarios

The exploration of potential occupant scenarios is based on the four afore-mentioned categories building, occupancy, hazard and safety measures. Regarding the category building, two evacuation concepts via two stairwells or via the atrium are considered. Based on the occupant loads stated in [3, 7], six different building uses have been specified. As a start, the building evacuation will be considered without the occurrence of fire. Finally, the trial design consists of an automatic alarm system. Table 1 gives an overview about the considered degrees of freedom.

Table 1: Data collection for the description of occupant scenarios

Category				
Building	**Occupancy**		**Hazard**	**Safety measures**
	Number and distribution of occupants			
Escape route	Office+Conference I	Office+Conference III	No fire	Automatic
via 2 Staircases	E00: 48	E00: 64		alarm system
via Atrium	E01: 0	E01: 250		
	E02: 134	E02: 134		
	Total: 182	Total: 448		
	Office+Conference II	Office+Conference IV		
	E00: 48	E00: 48		
	E01: 59	E01: 334		
	E02: 134	E02: 134		
	Total: 241	Total: 516		
	Office	Conference+Exhibition		
	E00: 64	E00: 89		
	E01: 134	E01: 500		
	E02: 134	E02: 134		
	Total: 332	Total: 723		
	Occupant characteristics			
	Agent type:	ADULT		
	Walking speed (m/s)	$\mu = 1.3$; $\sigma = 0.26$		
	t_{pre} rapid (s)	$[0, 60]$		
	t_{pre} familiar (s)	$[60, 180]$		
	t_{pre} unfamiliar (s)	$[60, 240]$		

Determination of Occupant Scenarios

Currently, the determination of occupant scenarios is possible by combining systematic sampling methods and engineering judgement. The latter is particularly inevitable for scenarios "where data are not available to support these calculations [...] [which moreover] should be documented and based on the most reliable and appropriate information." However, especially for more complex tasks, "the examination of different scenarios is critical in providing a reasonable understanding of the conditions that might arise" [6, p. 2142]. For that purpose, an event tree as partially shown in Figure 5 might be a helpful tool for a well-structured design of experiment. Relating to the application example, the components given in Table 1 comprise six different building uses, two evacuation concepts and three different assumptions for the characterisation of the pre-evacuation phase. By applying a full-factorial sampling approach, this results in 36 different scenarios.

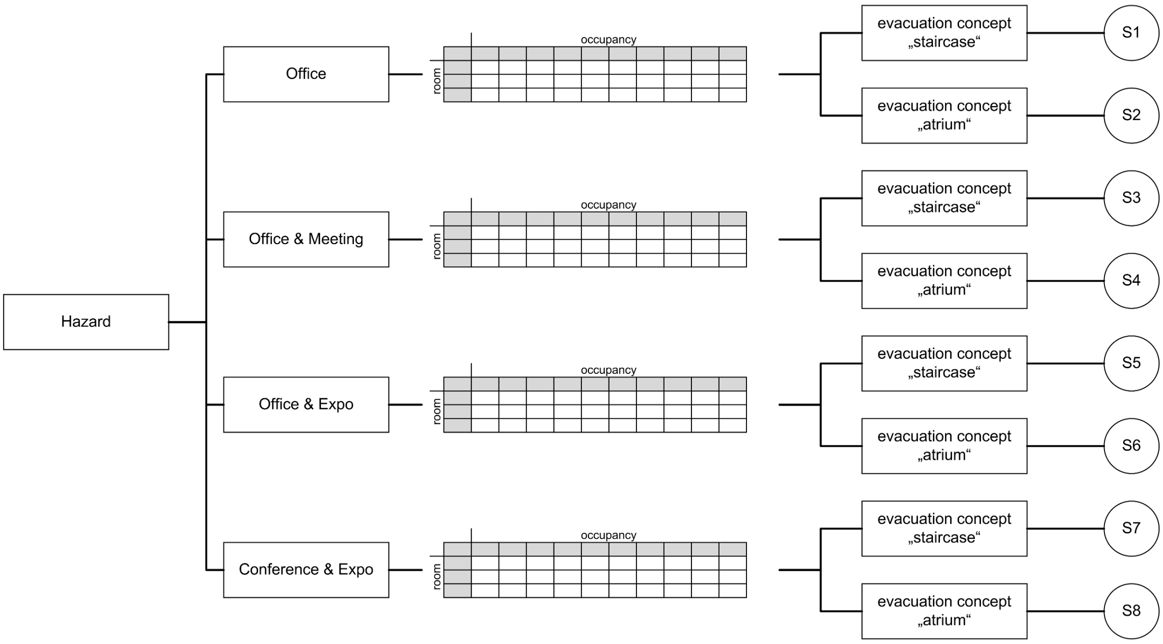


Figure 5: Excerpt of an exemplary event tree for the combinatoric of occupant scenarios

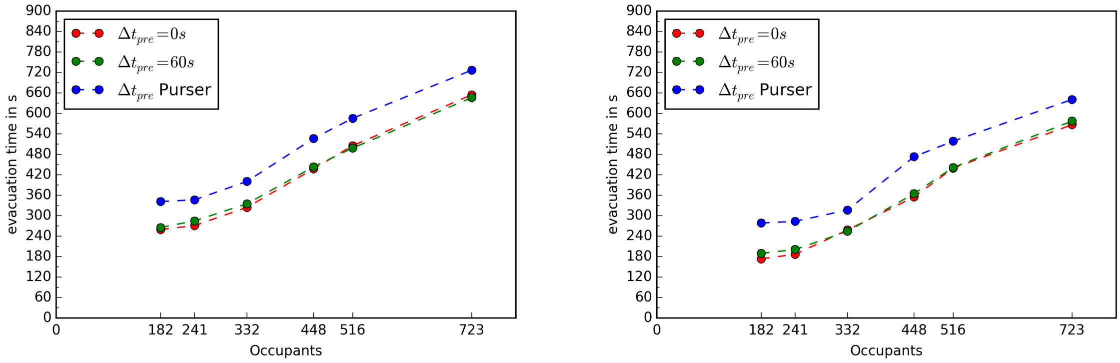
Up to now, potential probabilities and consequences of single branches are implicitly considered when omitting bagatelle and worst-case scenarios. However, the computational efforts for full-factorial sampling approaches will drastically increase the more parameters are considered. Thus, a discussion about the consideration of efficient strategies like Latin Hypercube Sampling (LHS) should be established as well. However, not only the variability originated in the scenario parametrisation but also the stochastic model-based variability of most pedestrian simulators has to be addressed as well. In order to ensure convergence of the results, 50 realisations have been computed per scenario. In this respect, the incorporation of approaches to reduce the number of realisations as proposed by Lovreglio et. al. [9] is reasonable and may be incorporated into the further work.

Determination of Significant Occupant Scenarios

Once the specified occupant scenarios have been parametrised and calculated, the produced datasets have to be analysed. Although this task appears to be straightforward, a multitude of considerations should be made in advance. In general, data analysis can be categorised in four steps: problem definition, data preparation, implementation and deployment [11]. The problem definition has already been issued while defining the objectives and related performance criteria at the beginning of this chapter. In the context of this article, this step will be focussed on the overall evacuation times and the jam times. Additional criteria may be incorporated according to the project scope. Within the data preparation, the data has to be cleaned, consolidated and transformed as necessary. In this article, this step is mostly related to prepare agent trajectories in a way that the desired information can be derived. The implementation is the core step of the analysis. Here, it can be divided into the summary of data and the identification of relationships. The latter will be addressed in the section "Selection of Design Occupant Scenarios". In terms of summarising data, a very appropriate approach is the visualisation in graphs e.g. correlation plots as shown for the analyses of the total evacuation times and jam times.

Analysis of Total Evacuation Times

The analysis of the total evacuation time is the most frequently used result in life safety assessment. The presentation may contain the minimum, maximum and the significant total evacuation time. The 95th percentile is mostly recommended as the significant value [14]. The two plots in Figure 6 illustrate the 95th percentile of the 50 computed realisations per scenario. The total evacuation times raise in correlation with increasing occupant numbers.

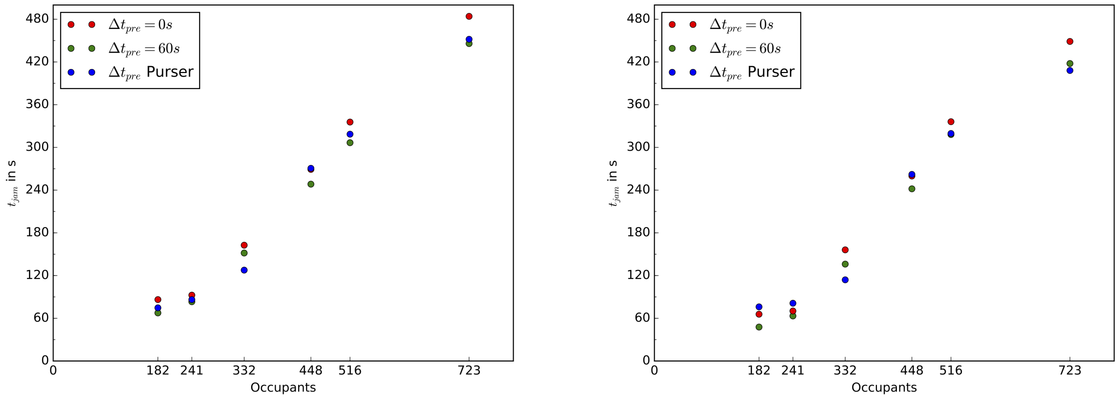


(a) rescue plan Atrium (b) rescue plan Stairs

Figure 6: Correlation plot opposing the 95th total evacuation time percentiles with the number of occupants

Analysis of Jam Times

Beside the classical analysis based on the overall evacuation times, the observed jam times are considered as well. The intention of this approach is to identify occupant scenarios that result in significant jam situations. The definition and evaluation of jam is a vital scientific discussion in the pedestrian dynamics community and has been issued in a couple of publications [10, 15]. In this work, walking speeds less than 0.25 meters per second are assumed as indication for the occurrence of jam. Further on, the jam times are measured agent-based and cumulatively for each realisation of the ensemble. Therefore, the 95th percentile of the jam times will be used for further analyses. The two plots in Figure 7 illustrate the scatter of the jam times for the two presented evacuation concepts.



(a) rescue plan Atrium

(b) rescue plan Stairs

Figure 7: Correlation plot opposing the 95th jam time percentiles with the number of occupants

In analogy to the total evacuation times, the jam times raise in corellation with increasing occupant numbers. Furthermore, it becomes evident that the influence of the uniformly distributed pre-evacuation times is only moderate. This conclusion is likely to be different considering additional variations of the pre-evacuation characteristics according to Purser [13]. However, scenarios with more scattered pre-evacuation times appear to be less jam-prone.

Selection of Design Occupant Scenarios

In this section, we address the division of the set of significant occupant scenarios into one or more clusters that are represented by design occupant scenarios (See Figure 1). In terms of data analysis, this incorporates the identification of relationships within the data such as clustering and grouping, which might be a promising approaches for that purpose [11]. However, it might be hard to establish these techniques in the day-to-day business of FSE. Hence, a discussion how to cope with this task in conjunction with engineering and expert judgement is necessary. Regarding this question, no normative commitments have been made so far.

Thus, we employ a very simplistic approach to derive the design occupant scenarios out of the significant scenarios. In the first instance, we rely on the scenarios that yielded the maximum results for the evacuation concepts and performance criteria presented above. The results of this workaround are summarised in Table 2.

Table 2: Design Occupant Scenarios – First Iteration Step

Scenario ID	21	24	19	22
Pre-evacuation times				
t_{pre_1}	$60\ s$	$60\ s$	$0\ s$	$0\ s$
$p_{pre_{99}}$	$240\ s$	$240\ s$	$60\ s$	$60\ s$
Building use	C+E	C+E	C+E	C+E
No. occupants	723	723	723	723
E00	89	89	89	89
E01	500	500	500	500
E02	134	134	134	134
Evacuation concept	2 Staircases	Atrium	2 Staircases	Atrium
Performance criterion	t_{evac}	t_{evac}	t_{jam}	t_{jam}
Result	**641 s**	**726 s**	**448 s**	**484 s**

The results allow a first classification of the scenarios. Assuming a notional threshold value for the intervention time of the fire brigade (e. g. 8.5 minutes), the number of possible scenarios can be reduced. The compliance of these identified scenarios with other criteria has to be proved in subsequent iteration steps. The results of the final iteration step are summarised in Table 3.

Table 3: Design Occupant Scenarios – Final Iteration Step

Scenario ID	9	12	7, 8, 9	10, 11, 12
Pre-evacuation times				
t_{pre_1}	$60\ s$	$60\ s$	$0, 60, 60\ s$	$0, 60, 60\ s$
$p_{pre_{99}}$	$240\ s$	$240\ s$	$60, 180, 240\ s$	$60, 180, 240\ s$
Building use	Office	Office	Office	Office
No. occupants	332	332	332	332
E00	64	64	64	64
E01	134	134	134	134
E02	134	134	134	134
Evacuation concept	2 Staircases	Atrium	2 Staircases	Atrium
Performance criterion	t_{evac}	t_{evac}	t_{jam}	t_{jam}
Result	**317 s**	**401 s**	**156**, $136, 113\ s$	**162**, $151, 127\ s$

Here, we evaluate the jam times for all calculated variations related to the evacuation concept and occupant's pre-evacuation times. Regarding the latter, it becomes evident that wider distributions result in less individual jam time. Additionally, the evacuation via the atrium is slightly more jam-prone. One can conclude that the scenarios 9 and 12 do not represent design occupant scenarios in terms of jamming. Consequently, the scenarios 7 and 10 have to be included into the set of design occupant scenarios as well. The jams of the latter should be examined in more detail in terms of their locations, sizes and densities.

Once the design occupant scenarios have been identified and selected, the robustness of the belonging results has to be proven. This can be achieved by slightly modifying the input parameters and checking the influence on the previously evaluated performance criteria.

CONCLUSIONS AND OUTLOOK

This article presents the current standardisation activities related to evacuation and life safety assessment in Germany. Firstly, a brief overview about the history and actual situation of performance-based fire safety design is given. Within the presented DIN 18009 framework, the basic ideas and demands for the evacuation and life safety assessment are presented. Furthermore, the current methodology is applied to a rather straightforward application example. It is intended to support more concrete discussions in both the international community and the standard committee, which is responsible for DIN 18009 Part 2.

Although there are a couple of criteria published which can be utilised to evaluate jamming, it is not always clear how these measures shall be determined and processed. The question if it is more reasonable to refine and analyse the magnitudes for each single jam phase or not has not been answered yet. In addition, we mostly talk about distribution of magnitudes. Which percentile appears to be appropriate to evaluate a certain quantity? This also applies to the evacuation times. As an example the RiMEA guideline [14] proposed the 95th percentile as the significant value for the evacuation time. However, the recent version no longer defines such a general measure so that it has to be agreed upon with the authorities. In comparison to that, the characteritic values of fire load densities in the safety concept for constructive fire protection required the 90th percentile [4].

The determination of ASET and its coupling to the evacuation analysis will imply additional complexity to the overall assessment. Subsequently, the interdependence of the various categories for the description of occupant scenarios and fire scenarios should be examined. For this purpose, the cooperation with the working group DIN 18009 Part 3 is required and already planned. In this collaboration, it can be possible to determine the main parameters and their interfaces for the ASET/RSET concept as discussed in [12, 13].

Without doubt, the above-mentioned insights, results and issues will be valuable for the further work.

CLOSING REMARKS

The contents of this article reflect the opinion of the authors and may not be misinterpreted as a direct excerpt of the future standard DIN 18009-2. It may not be understood as the documentation of a complete assessment process. It is rather supposed to record the methodological, technical and regulative considerations made in the past months. In the framework of a more or less straightforward application example, the further work shall be supported with concrete numbers. Furthermore we aim at international exchange and discussion, which is warmly welcome. The presented approaches, assumptions and conclusions may not be misinterpreted in any context of the prescriptive regulations in Germany. This research is partly founded by the German Ministry for Education and Research (BMBF) contract No. 13N13266 (project ORPHEUS).

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