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Evaluating 900 Potentially Harming Fires in Germany: Is the Prescriptive Building Code Effective? German Fire Departments Assessed Fire Safety Measures in Buildings Through On-Site Inspections

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Abstract. Fire statistics mirror the outcome of fire prevention. Most fire statistics in Germany deal with the loss of life, value, and fire department actions (number of interventions, nozzles used, or alarm category like a false alarm). However, these results also represent the safety level the legislator has set through the prescriptive building regulations. The current statistics cannot evaluate the level of fire safety and the fulfillment or necessity of fire safety precautions. Today, expert judgment from firefighters is necessary to fill this gap. Here, we show the first evaluation of fire prevention and hazard protection measures by evaluating 900 potentially harming fires throughout Germany. In contrast to minor fires, these fires have advanced to the extent that they could potentially violate the protection objectives outlined in building regulations. The fire department association developed a questionnaire to evaluate the fire safety level and possibly reduce unnecessary fire safety regulations. One hundred twenty-three fire departments carried out the questionnaire, which are responsible for 25% of the German population. Fire prevention officers of the fire departments went to the scene after the fire was extinguished, and the fire safety concept of the building could be evaluated. We found a high rate of injuries, smoke

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spread, need for rescue by firefighters, and higher than expected firefighter response times after arrival at the scene. Surprisingly, smoke spread rates correlated with building height and not with building age. It was even possible to assess the risk of multiple casualties. Overall, the questionnaire results give insight into the current level of fire safety in existing buildings. Ways and rates for smoke and fire spread prove the importance of second escape routes and the influence of human misconduct. According to these results, current building code regulations are sufficient to prevent fire spread. On the other hand, smoke spreading is a severe threat to people's safety. For example, the data shown can be applied in Bayes nets or other risk calculations to optimize individual building designs or even governmental building codes concerning fire safety engineering. Based on our observations, science, and building codes, authorities could in the future establish a performance-based building code instead of the current prescriptive code. This paper presents the first approach in Germany to quantify the expert judgment of fire departments and use it as a source of knowledge for fire prevention.

Keywords: Fire statistics, Fire safety level, Fire safety objectives, Smoke spreading, Residential fire safety, Building regulation**PACS:** 89.65.Lm

1. Introduction

Fire safety engineers and their counterparts, building authorities, discuss the level of fire safety regarding the given code (e.g., German model building code [5]). Authorities, control/proof engineers, or authorized fire brigades carry out the four-eyes principle. Currently, the proof engineer or the building code authority only checks whether minimum building regulations have been complied with. In Germany, politicians intensely discuss the level of safety needed and the cost of fire prevention in apartment buildings [10], which has led to fundamental changes in the model building code in Germany. Grenfell Tower, London 2017, showed that knowledge about real fires is crucial for plausibility checks [40] to assess the effectiveness of preventive fire protection measures.

Key aspects are:

1. Fire building code: effectiveness unclear in case of a fire

In particular, fire safety engineers and risk engineers need reliable data to build on [41]. Most fire safety engineering relies on reverse engineering [13, 18, 32] based on prescriptive building rules [5]. To what extent these prescriptively designed buildings meet acceptance criteria by law remains unclear [12, 14].

In committee work for developing and evaluating building regulations, the elected officials of fire departments regularly face questions of doubt concerning their opinions and their belief in the necessaty of changes. This doubt stems from the lack of data on the outcome after firefighting. The experience of firefighters cannot be proven. The Association of Fire Prevention Experts of the German Fire Departments therefore developed the questionnaire presented in this paper [3]. The core idea was not to improve fire safety, but to start a discussion about what works and what does not. Unnecessary fire safety measures required by law or standards (such as DIN, CEN, ISO or IEC) could then be evaluated.

2. Data: potentially harming fires impact on buildings

When fighting a fire, fire departments have to deal with questions about the quality of building constructions, prevention of fire spread, or whether the fire code was followed in all other terms concerning firefighters and people's safety. Their knowledge is crucial in developing and improving building codes. For this reason, German fire departments are part of the expert groups in the Conference of Building Ministers in Germany, dedicated to ensuring fire safety [22]. The level of expertise within expert groups used to depend on the individual fire chief involved or the accumulated experience of the fire departments discussing these topics. Objective data are therefore rare. Expert judgment based on the experience of individual officers or fire departments remains an important contribution to firefighting knowledge. However, this is regularly challenged by fire safety engineers in Germany.

3. Core finding: enhance preventing smoke propagation

From the fire department's point of view, people's safety is about smoke prevention and management [2]. Smoke, especially carbon monoxide, is the leading cause of fire deaths [1, 28]. As a prescriptive building code has measures to prevent the spread of smoke with walls or self-closing doors, risk engineers tend to believe that a self-closing door and the model building code prevent the spread of smoke sufficiently. This assumption of adequate security has not yet been verified or quantified in Germany.

Hammann [29] recently presented an overview of methods and evaluated data sources. Expert discussions on building rules and even on individual fire safety design are found in these statistics.

The main aspects of fire statistics are:

- Fire death rate [8, 15, 24, 36]
- Fire injuries [8, 15, 36]
- Cause of fire [31, 33, 36]
- Number of fires [6, 8]
- Number of fire-fighters [6, 8]
- Number of engines, ladders, equipment [6, 8]
- Technical fire protection [25, 26]

A general probabilistic approach is now added to the general influencing factors. Sander [39] has recently shown that a purely probabilistic approach is also possible. In general, the relationship between building codes and fire deaths is not well documented internationally [8].

None of these statistics provide combined data about the impact of fires, size, and age of buildings or smoke/fire spreading. Fire departments in Germany are now trying to fill this knowledge gap with fire site inspections.

The process and timing of the data collection is basically based on the chosen methodology and the course of the project by the German fire brigades. In the case of quantifying the expert judgment of the German Fire Departments, the data presented were collected from August 20, 2016 to July 22, 2022. The project is ongoing. Clear, written instructions have been formulated for the individual data collection. The data are summarized, counted, calculated, interpreted, presented and discussed transparently, depending on the chosen methodology. All statistical methods used in this paper are state of the art, including standard operating procedures with algorithms, and the software tool *R* [38] is used for evaluation and presentation [27]. Traditional statistical methods were used to show frequencies and distributions (Figures 3 to 7). A logistic regression analysis describes the distributions as a function of direct variables (see Figures 9 and 10). Only the F-N curve of Fig. 13 was described using probabilistic a priori methods [7].

2. Methodology

2.1. Data: Fire site inspections

Most fire statistics focus on lost lives, cause of fire, or effectiveness of technical fire protection measures. To supplement this narrow focus, the expert group for fire prevention within the association of professional fire chiefs[1] and voluntary fire departments[2] in Germany designed a questionnaire on fire site inspections. The form contains 105 characteristics [3]. Fig. 1 shows two pages of the form. An English translation is added in the online version of this article (refer Supplementary material).

The expert group did a lot of outreach to collect data. Many fire departments were initially intimidated by the idea that their work in the field was being studied. This fear was allayed by explaining the questionnaire and making it clear that the focus was on buildings. Intervention methods or tactics were not evaluated. The primary motivation for the fire service association to develope and advertise this questionnaire was not only to obtain data on effectiveness, but also to potentially reduce unnecessary requirements.

2.2. Participating fire departments and potentially harming fires

The number of participating fire departments has increased significantly in the last two years. Data sets have increased the more departments participated: 284 data sets as of 31 Dec. 2019, 500 as of 28 Feb. 2021, and 900 now examined as of August 2022.

The participating fire departments represent their local area of responsibility, 24.7% of the German population (cf. Table 1). This percentage allows us to assume that these results would be similar to other fire departments in urban areas throughout Germany.

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[1] “Arbeitsgemeinschaft der Leiter der Berufsfeuerwehren in Deutschland im Deutschen Städtetag” https://www.agbf.de

[2] “Deutscher Feuerwehrverband e. V.” https://www.feuerwehrverband.de

DEUTSCHER
FEUERWEHR
VERBAND

AGBF bund
im Deutschen Städtetag

Recommendations of the Association of Professional Fire Departments Chiefs
and
the association of voluntary fire departments in Germany

Questionnaire for the evaluation of preventive fire and hazard protection measures (on-scene inspections)

2017-05

Translation: April 2023

Expert committee for fire and
hazard protection of German fire departments
(FA VB/G)

c/o Branddirektion München
An der Hauptfeuerwache 8
80331 München

Ltd. BD Dipl.-Ing. (FH) Peter Bachmeier
Phone: 089 2353-40000
Telefax: 089 2353-40099
E-Mail: bfm.vb@muenchen.de

Questionnaire for the evaluation of preventive fire and hazard protection measures (on-scene inspections)

General information
(In the statistical analysis, it is not possible to allocate to general data).

Fire object (Address)

If nec. Object specification a./o. exact location of the event (e.g. residential building, 4th floor, middle unit)

Room of fire origin (e.g. Kitchen, living room, boiler room)

No. of Assignment | **Date** / Time | **Keyword**

(or attach alarm transcript!)

Short description of incident

Type of first alerting (e.g. smoke detection system, resident, police, pedestrian)

Cause of fire:
☐ Unknown

☐ Human failure
☐ Electrical fault
☐ Environmental hazard
☐ Other

Description:

Fire department / station involved

Further units (e.g. Volunteer fire department, chief officer,...)

If nec. No. of Operational plan

Contact person (name, rank, function)

1 von 16

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Figure 1. Officers for fire prevention within the Association of German Fire Departments developed a questionnaire for on-scene inspections. The figure shows pages 1 and 3 of the form.

Fires to be investigated were named as having to be “potentially harming”: potentially violate fire safety objectives by German (model) building code *Musterbauordnung* (cf. § 14 in [5][3]). This harm is potentially in violation of the protection objectives of building codes and other regulations (spread of fire and smoke, rescue of people and animals, safety of rescue teams, effective firefighting, environmental protection, protection of cultural heritage, and protection of property). Scenarios and severity can vary widely within the same building types. From the perspective of preventive fire protection, these fires can be potentially harmful:

- Loss of life
- Injured persons
- Fire or smoke spread outside compartment/unit/building
- Problems during fire fighting
- Escape of persons potentially in danger
- Environmental pollution
- Loss of high values

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[3] “FIRE PROTECTION–Structural facilities are to be arranged, erected, modified, and maintained in such a way that the outbreak of a fire and the spread of fire and smoke (fire propagation) is prevented and, in the event of a fire, people and animals can be rescued, and effective fire fighting operation is possible.”

Table 1
Participating Fire Departments, Contributed On-Site Fire Inspection Data Sets of Potentially Harming Fires (as of July 22, 2022) and Inhabitants (31-12-2021)

City	Data sets	Inhabitants
Munich	481	1,562,128
Berlin	77	3,677,472
Dortmund	19	588,375
Essen	18	588,375
Detmold	14	73,969
Mülheim (Ruhr)	14	172,776
Dresden	13	561,002
Bochum	12	370,146
Bonn	12	330,578
Bottrop	9	117,311
Mönchengladbach	8	261,001
Düsseldorf	7	619,477
Bad Salzuflen	7	54,074
Düren	7	93,660
$\geq$3 data sets: 28 fire departments	106	5,388,088
$<$ 3 data sets: 81 fire departments	96	6,115,751
Total	900	20,574,183

- Cultural heritage loss
- Fully developed fires *without* objective violation

From a fire safety engineer’s point of view, the observed fires are at least partly developed, left the primary place of origin, and could potentially harm fire-safety objectives. As it is almost impossible for the data-collecting fire departments to refer to standardized values (heat release rate, smoke release rate, financial loss), a common comparison had to be introduced as a cut-off threshold for potentially harming fires. E. g., small fires in a kitchen, where the fire has just started (like burnt food: especially burning oil), are quickly extinguished and associated with only a small loss, were excluded. These small fires regularly do not challenge fire safety objectives set for a building (fire resistance, limiting smoke spread). A scenario in which early firefighting of comparatively small fires reduces the thread emanating from them is declared irrelevant in the questionnaire [3] as irrelevant. In addition, the questionnaire was not developed by scientists but by the fire department association. Their expert judgment view focused on what they called “potentially harming fire”. These developing kitchen fires “as a common cause for fire department interventions” are not interesting for the investigation (as here and explicitly explained in the questionnaire [3]).

Fire fighting officers, educated and experienced in fire prevention and building code, conduct these on-scene fire inspections (Fig. 2). They usually collect this data the day after, and the consent of the investigating police and the building owner is required to go to the scene. Then the questionnaire is being sent to the

Figure 2. Site inspections are usually carried out after the fire has been fought. In rare cases, data is collected during the operation. Photo: K. Steinbauer, FD Munich.

Munich Fire Department to analyze the data on behalf of all German fire departments. The Technical University of Munich (TUM) supports the Munich Fire Department in on-scene investigations (Master's theses). The students examine potentially harming fires in and around Munich in collaboration with experienced officers to collect data. They also participate in fire prevention and firefighting tactics at the department. With the support of TUM, the Munich Fire Department can contribute most of the data.

2.3. *Questionnaire: Protection targets*

The following survey aspects are discussed below:

- Limitation of smokespread during the fire
- Limitation of firespread
- Observed paths of smoke and fire spread
- Usage of affected building
- Building age
- Injured or fire fatalities
- Self-rescue completed before arrival of the fire department
- Fire extinguishing attempts before arrival of fire department
- Intervention time

The descriptive information on propagation in the free input field of the questionnaire was then categorized. No categorization was given. For example, "stairwell smoky due to fire fighting through the door" led to the category "rescue process".

The ondata of fires collected on scene was evaluated using *R* [38]. The data set was scaled mainly using dichotomous, categorical, and continuous features. In the first step, a descriptive approach was chosen (cf. Figures 4 and 5), where initial tendencies and descriptive connections were/can be identified and compared to determine the actual connections between individual characteristics by comparison. The descriptive approach primarily focuses on analyzing the spread of smoke and fire from the originating unit. Correlation coefficients show the strength of association. For this purpose, the variables with the most substantial connection to the characteristic "limiting the spread of smoke" were preselected. This allows for the probability of smoke propagation to be determined for a specific feature constellation using logistic regression. The regression analysis was based on the dichotomy of the target variable "smoke spread limited" [29]. The results of this regression model are shown in Fig. 8.

2.4. Data set

Table 2 and Fig. 3 provide an overview of the data set on building classes in Germany (from single-family homes to multi-story buildings) and their respective use. Most buildings are residential, so the collected data set constitutes most observed fires there. Another focus of observation: The data set can clearly be described as urban. Most potentially harming fires have been recorded in class 4 (floor level more than 7 m above ground; units smaller than 400 m^2) and class 5 multi-story buildings (highest floor more than 13 m above ground). The distribution of building types is similar to another major German statistic from the German Fire Protection Association (GFPA; vfdb in German) [26]. Only infrastructure buildings are at a higher level in the GFPA dataset, as 44% of the questionnaires submitted were from plant fire departments.

The large proportion of urban buildings (classes 4 and 5) in the data set results from the large participation of metropolitan fire services in the survey (cf. Table 1). Almost all departments are responsible for cities with more than 50,000 inhabitants (e.g., Munich (GER) contributed 42 percent of the records). In the future, more fire departments in rural areas will be addressed directly to participate in the study to widen the view. Due to the large number and diversity of fire departments, the associations of voluntary fire departments will be addressed intensively[4].

3. Results

As the first step, a descriptive approach was chosen for evaluating the data (fatality rate, smoke, and fire spread, building type, and age). Based on this, the extent of the relationships between the variables was determined using the correlation

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[4] 22,167 voluntary fire departments (1,003,594 firemen/-women), 110 professional fire departments (34,854 firemen/-women) as of 31-12-2019. https://www.feuerwehrverband.de/presse/statistik)

Table 2
Categorized by Building Class (bc) acc. to German Law [4]: bc 1—Stand-Alone House, Class 2—Townhouse, Class 3 to 7 m Max. Upper Edge of Finished Floor, Class 4 to 13 m Maximum Upper Edge of Finished Floor and All Units $< 400\ m^2$, Class 5—Other Buildings Including Underground

	bc 1	bc 2	bc 3	bc 4	bc 5	∑
Construction site	-	-	2	-	3	5
Accommodation	1	2	10	10	16	39
Educational institution	2	0	4	3	11	20
Assembly hall/Stadium	0	0	5	2	9	16
Car park	0	0	2	7	8	17
Restaurant	0	0	2	1	1	4
Health facility	0	0	3	7	20	30
Industrial, Repair shop	3	1	40	7	23	74
Buildings of Infrastructure	0	0	0	0	2	2
Combined: Living and Profession	1	3	13	42	53	112
Other	5	1	6	5	5	22
Public service	0	0	0	0	3	3
Office and Administration	0	0	1	3	16	20
Residential	38	42	103	172	182	537

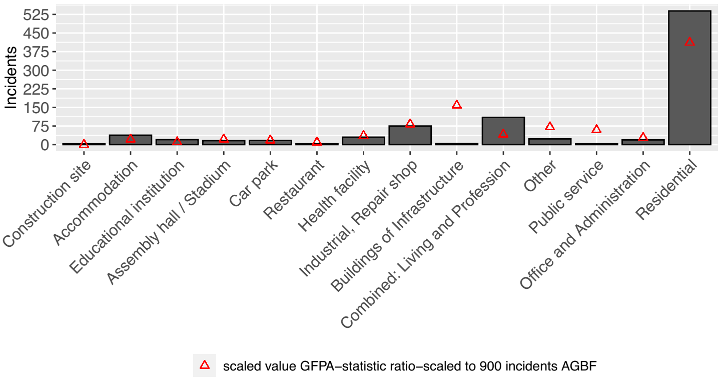

Figure 3. Potentially harming fires categorized by type of use ($n = 900$).

coefficient Cramer's V and the point biserial correlation. Here, the parameter *limiting the spread of smoke to the originating unit* was considered in correlation to the other parameters. Based on this mathematical evaluation, a logistic regression model was developed for the propagation of smoke in a pre-defined set of features (Fig. 9). Correlations with fire propagation were not evaluated, as the fire spreading rate was comparatively low (cf. Fig. 5). Fig. 4 shows the evaluation of fire fatalities, injured persons, and self-rescue rate in the data set.

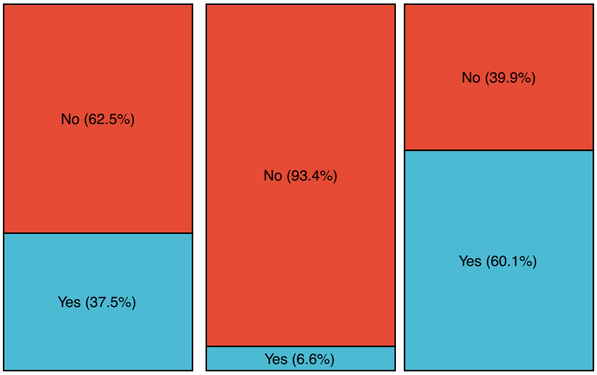

Figure 4. Injured people (left, n = 807), fire fatalities (middle, n = 854), and completed self-rescue before the arrival of the fire department (right, n = 898).

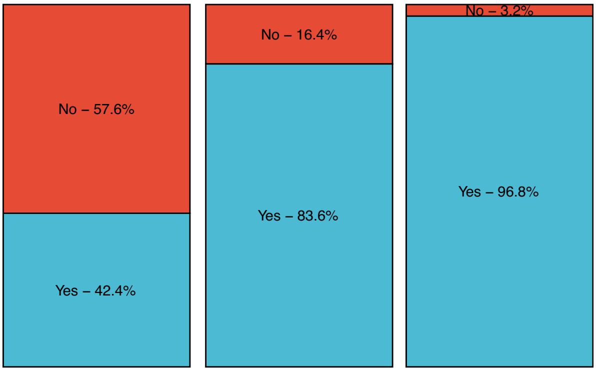

Figure 5. Propagation of fire and smoke (n = 900): limitation of smoke spread to a unit (left), limitation of fire spread to a unit (middle), limitation of fire spread to a building (right).

3.1. *Smoke and fire spreading*

Figure 5 reflects the overall experience of fire departments and fire safety engineering judgment: smoke spreads highly dynamic in a building and spreads in many more cases than fire spreads through a building. Building law states to *limit the spread of smoke* **and***fire* ([5, § 14]). However, the low rate of fire propagation out of the originating unit (n = 416) or even a building was surprising. Preventing the spread of fire has been an essential aspect of fire safety since the Middle Ages and is deeply embedded in building regulations (e.g., firewalls or hard roofing as in §§ 22 ff. in [5]). The low numbers of fire spreading (spread to other buildings n = 32) show how well the building code in Germany regulates this aspect. Compared to smoke spreading, fire spreading outside the compartmental unit is at a low rate of 15.7% (n = 141).

As explained and shown in Fig. 5, smoke spreading is an often-observed threat and is the leading cause of death in the case of fire [1, 15, 28]. Rescue paths through stairwells are essential for a safe escape. But apartment doors to stairwells were observed to be the main route of smoke spread, endangering a safe escape. The outer (windows n = 100) and inner spreading relates to established fire fighting tactics by German fire department regulations: check the first escape route (stairwell n = 31) for victims and then for smoke spread to the level above (regularly through open or broken windows), check the top floors. This tactical approach is essential for a rapid firefighters response. In a detailed examination, smoke did not just spread to the next level / floor via windows or shafts. Mainly, smoke spreads to the top floors of the building through (ventilation) shafts. One explanation may be that smoke does not normally travel outdoors through air vents as quickly as it travels through a building's ductwork and into the attic apartments, especially in older buildings with ventilation systems dating from the 1960s and 1970s. This observation aligns with the experience of firefighters, who regularly see internal smoke spreading to upper floors.

Smoke spread affects about half of the observed potentially harming fires and can be grouped into main categories: apartment doors to the stairwell inside, open or cracked windows on the outside, and shafts (cf. Fig. 6). Opened doors or self-closing doors that are kept open (fire/smoke resistant doors, rescue process) and leakage of walls, floors, and ceiling ("building substance") follow in a narrow percentage rate. The leakage rate of smoke control or fire doors, the stairwell, and horizontal penetration were rarely observed as a cause (categorization following the fire department's answers). The heterogeneous classification follows the experience of firefighters and their phenomenological observations. Without a rating, results are presented to show primary smoke propagation paths - as observed. The phrase "apartment door" includes doors from other units to the stairway, too. The phrase was used as the commonly used one between fire-officers and not as precisely used in the building law. Doors inside a unit (apartment, office, hotel suite) or inside a single-family house are not part of the questionnaire as building law has no regulations within a unit or stand-alone house/townhouse. All propagation pathways described in Figure 6 and 7 were previously treated by transforming free-text field entries into categorical data and then summarizing the observed pathways.

The propagation of fire is a rare-observed event (15.7%; see Fig. 5), and no focal point of the propagation paths outside the units (apartments) could be pointed out (Fig. 7). When fire spreads, it takes every possible route from the phenomenological point of view of the fire departments. Fires that spread by crossing firewalls between buildings are almost negligible (3.6%; compare Fig. 5) and only occurred in class 2 townhouses where the ridge purlin or foot purlin crossed firewalls, which is against the building code.

Smoke primarily spreads through the stairwell via apartment doors, obstructing the primary escape route in over 29% of cases. This led to 38% of recorded fire victims being unable to complete self-rescue. In Germany, the redundant escape route in standard buildings is regularly secured by fire department ladders (portable or fire ladder truck; the fire department must rescue these persons).

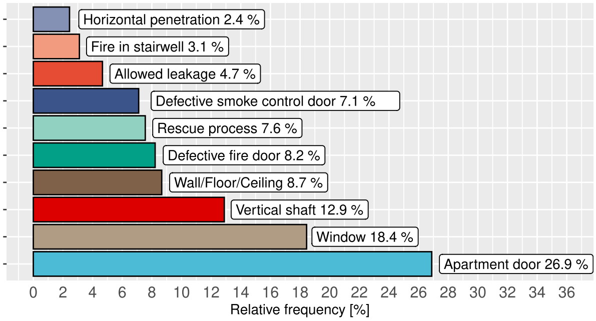

Figure 6. **Categorized ways of smoke spread (n = 546).**

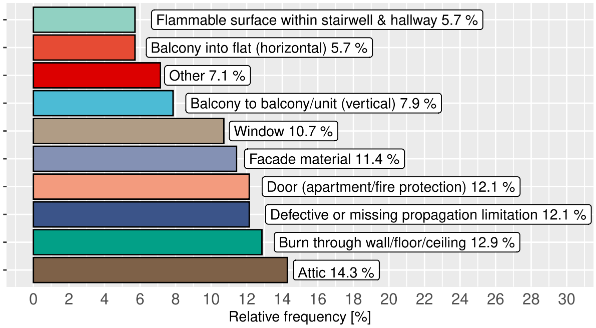

Figure 7. **Categorized ways of fire spread (n = 177).**

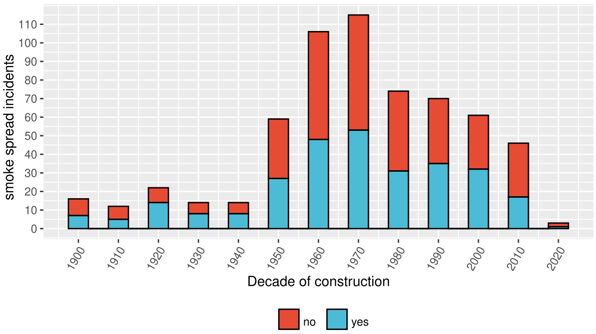

Figure 8. **Distribution of smoke spread by age (n = 612).**

3.2. *Influencing factors for smoke spread*

As a hypothesis, we estimated the building age to be essential for fire safety. However, a smoke-spreading correlation analysis with point-biserial and logistic regression showed no correlation to age (correlation coefficient $\ll 0.1$). The distribution throughout the decades in Fig. 8 represents the average building age in

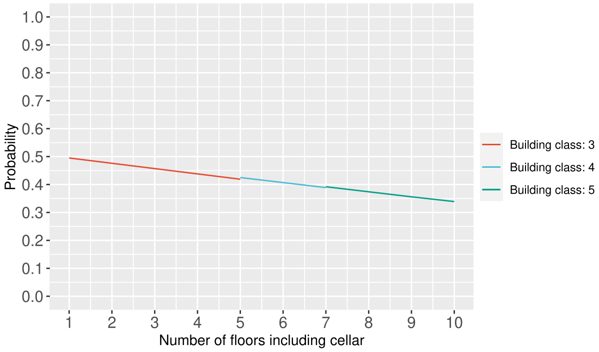

Figure 9. Logistic regression provided evidence of a relationship between building height and smoke containment probability.

German cities (the building rush after World War II and the decline during the 1970s oil crisis) and no enhanced risk for smoke spreading connected to a decade.

Variation of point-biserial analysis components showed a hint for the height of a building to be of significance for smoke spreading. This correlation was used to give an impression of how the data can be used in further statistical analyses. Fig. 9 shows the estimated probability of the successful limitation of the spread of smoke to the originating unit. It should be noted that this logistic regression model was chosen because of the dichotomous nature of the target variable “smoke spread confined to the unit”. In Fig. 9, the number of stories proved dependent on the probability of the limitation of smoke spreading. As described, building class 3 is buildings up to a maximum of 7 m floor level above ground, resulting in regularly three levels above ground. The regression analysis counted the overall number of levels within the building, including cellar levels below ground. This number must be added to understand the building class 3 regression, reaching up to five stories.

Figure 9 shows a tendency for a higher probability of smoke spreading in higher buildings regardless of the floor where the fire occurred. This higher rate of smoke spread in higher buildings was intensely discussed with fire departments. From their point of view, it was estimated to be caused by two major factors: building maintenance and fire department intervention time. In their professional experience, fires occur more often in larger buildings with poorer residents (e.g., having older electrical devices compared to wealthier population groups and living in smaller apartments, resulting in a higher population density per building). This hypothesis could not be tested by the given data set. Nevertheless, intervention time was part of the questionnaire and examined.

Fire safety may not be federal law by the constitution and is regulated at state level. Figure 10 is a regional analysis of the data set. In the 1990s, the state of Bavaria (GER) changed its building code from solid wooden doors between apartments and stairwells (38 mm thick) without self-closing mechanism to now self-closing and solid doors according to today’s model building code [5]. Legislators expected to improve safety in stairwells. This is a well-known and most common

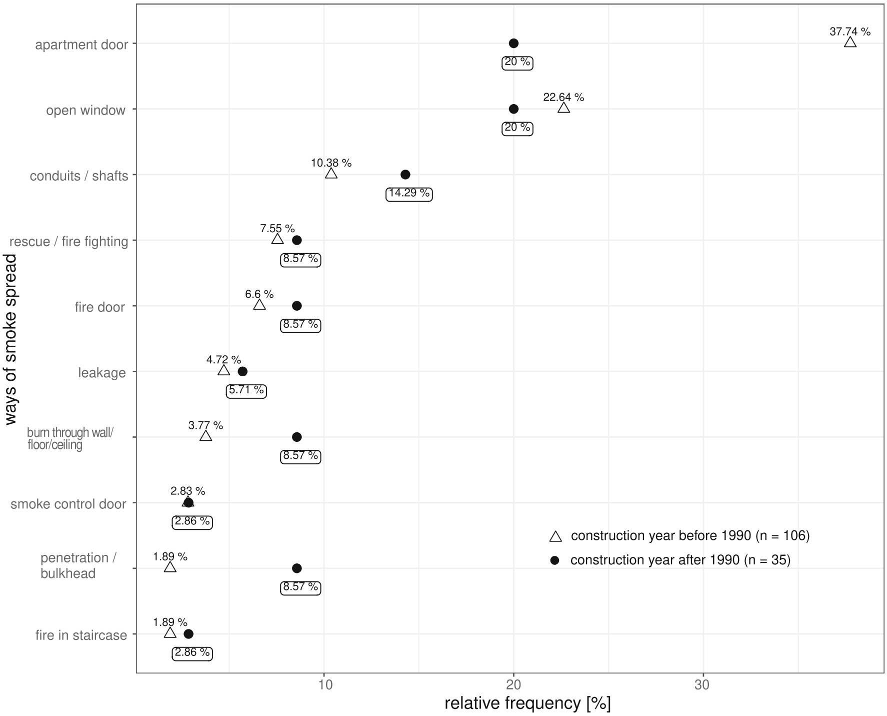

Figure 10. In the 1990s, Bavarian buildng law (GER) changed to self-closing doors towards the stairwell. Smoke spreading rates changed. Residential buildings, class 3 to 5 (n = 142).

way for smoke to spread (cf. Fig. 6). After this change in the law, it was obvious to evaluate the data for residential buildings with stairwells (building classes 4 and 5; cf. [5, § 35]) and year of construction. The smoke spread observed has now made it possible to investigate the change in legislation, as the proportion of smoke spread through the apartment door to the stairwell has decreased from 37% to 20% in newer buildings. This still is the main route, but to a much smaller extend. Thus, other shifts are within statistical fluctuations due to the low numbers within this data subset.

We have chosen Bavarian state law, because not all federal states have adopted the amendment to the model building code for self-closing doors. For example, North-Rhine Westphalia rated accessibility for disabled people above self-closing doors for fire safety. Since most of the data besides Munich come from federal states without this change or from a later decade, the Bavarian data shows identical regulations in the model building code in Germany today. All of the cities listed in the table 1, with the exception of Munich, do not have self-closing doors in their respective state laws.

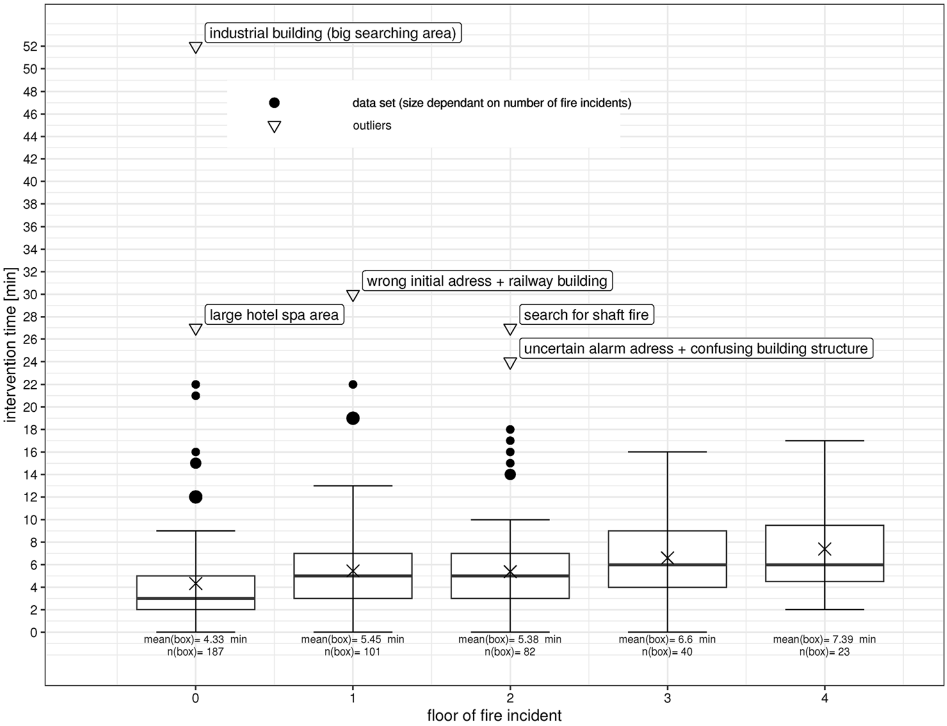

Figure 11. Box-plot of the intervention time for different floors. The size of the data points shows the number of fire incidents (n = 479, 2017-2022).

3.3. Risk factors

Intervention time was defined as the time between the arrival of the first fire truck on scene and the start of extinguishing work. Results can be found in Fig. 11 and Table 3. The taller the building, the greater the length of time required for firefighters to ascend. This is the first time that this has been proven in Germany.

Prolonging the mean value up to the 22 m border to high-rise buildings in Germany (compare [5, § 2]; eighth floor) firefighters need approx. 9.3 min after arrival on scene to start extinguishing. Data from floors 5 and 6 were excluded due to small numbers (less than 20 data points) and the use of dry risers in some interventions (cf. Table 3). This extrapolation was published by the German fire departments in order to be able to justify different response times, particularly in urban peripheral areas [4]. In these areas, there are usually only small terraced houses. The fire departments therefore argue that it takes just as long to initiate firefighting there as it does in tall houses in more densely built-up areas near the fire stations.

Table 3
Intervention Time Between Arrival and the Beginning of Extinguishing, Categorized by the Floor (2017–2022)

Floor of fire incident	25-%-quantile	75-%-quantile	Mean	Median	n
ground floor	2.0	5.0	3.83	3	219
1st floor	3.0	7.0	4.78	5	122
2nd floor	3.0	7.0	4.85	5	94
3rd floor	4.0	9.0	6.48	6	52
4th floor	4.5	9.5	6.55	5	29

Box-whisker plots in Fig. 11 visualize the distribution and identify outliers; quantile values are used to determine the intervention time; In the run-up to the data evaluation, an extensive investigation was carried out concerning the data points marked as outliers. Texts of the evaluation forms or from the post-deployment (transcribed radio messages, deployment reports) showed conclusive explanations for the prolonged time span and were therefore excluded from quantile and median values.

Also, the outlier limit derived from the upper whisker of the box-whisker plot shows that the upper limit of the exploration and development time increases with increasing incendiary floor. A calculation of the correlation coefficient (Pearson's product-moment correlation) gives a correlation coefficient of $+0.24$ at a significance level from $p = 10^{-5}$, well below a 0.05 rejection limit. Correspondingly, there is a significant connection between the fire floor and the exploration and development time, as a positive correlation exists.

Another aspect of the questionnaire is first-aid firefighting with fire extinguishers. German federal law mandates that every place of work must be equipped with extinguishers. Therefore, we examined the risk of injuries while trying to fight the fire before the arrival of a fire department. Fire extinguishers must be in place according to the fire load, often resulting in several extinguishers in one place. German firefighters predicted that the provision of multiple extinguishers would increase the risk of injury, as experience has shown that fires are often too large for non-professionals to handle without proper training and equipment. Figure 12 shows a tendency of an increasing number of injuries depending on the extinguishing attempt made by an untrained person. Although the data set does not include all fires because it excludes small fires, the higher injury rate still can be observed. It indicates that training must include the information to stop firefighting before it is life-threatening. A complete set of statistics must be considered in order to correctly classify the figures on the probability of injury from the use of fire extinguishers. German regulations do not require fire extinguishers in homes but do require them in workplaces. [23]. So training in the workplace could focus on the need for retreat.

Nowadays, fire safety engineers reverse-engineer the level of safety by comparing building codes to simulation results. Until today, it is difficult to define a level

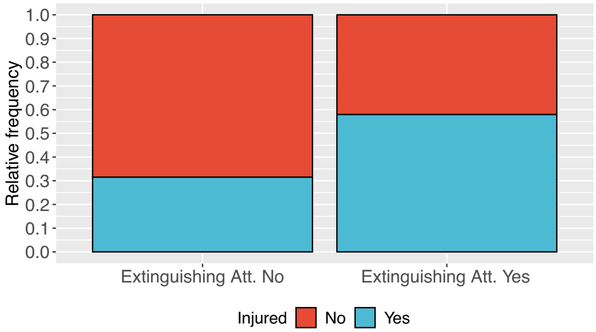

Figure 12. Frequency of injury when attempting to extinguish a fire with fire extinguishers before the arrival of the fire department, compared to when not attempting to extinguish.

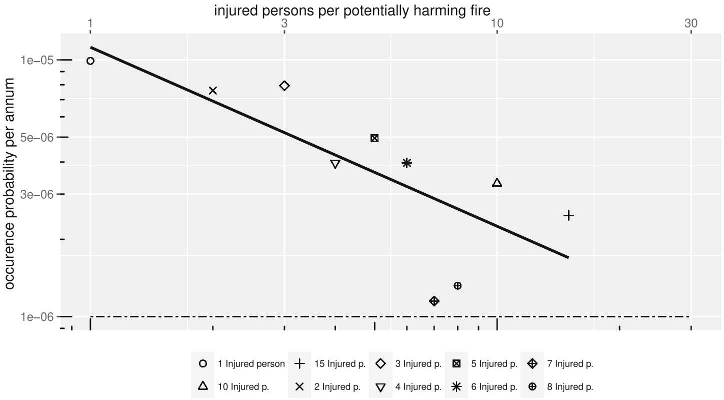

Figure 13. Probability to be injured in case of a potentially harming fire within the City of Munich (2018–2021). Dashed line: probability level to die due to a fire as of 10^{-06} [34, 35].

of safety in numbers [14, 29, 34]. As explained above, the city of Munich provided most of the data within a scientific cooperation with the Technical University Munich (cf. Table 1). Due to the possibility of a complete coverage over 3 years of the potentially harmful fires described in the study, and as the population of Munich is known, a probability of injury could be specifically determined here. For comparison of magnitude, Leksin [34] suggested a single value for acceptance, as low as 10^{-06} to be killed by a fire per year. Leksin did not differ between a single loss of life or multiple losses at once. His mentioned risk level was established without recognizing the different societal acceptance of multiple fatalities at once [13]. We identified a distinct inverse correlation between the annual risk of fire-related injuries and the occurrence of simultaneous injuries (compare Fig. 13). It is unlikely for fire departments to encounter multiple injured persons simultaneously - far less than the expectation based on the simplistic equation of "risk equals the probability of exposure times the extent of damage". However, the rate of negative slope is lower than the F-N curve for fire fatalities proposed by the German Firefighters Association [35].

4. Discussion

Fire safety engineers as well as fire department officers questioned the quality of data collected by this questionnaire in conferences and talks when first presented. In their view, the quality of the statistics is questionable because of the vague definition of potentially harming fires and the fact that scientists did not collect the data. Since fire-fighters in Germany receive mandatory training in preventive fire protection, starting at the basic command level (group leader for a single fire engine), the authors believe that the data are accurate and filled with expert knowledge, even though they were not collected in a scientific setting.

It is necessary to evaluate the representativeness of our fire dataset for Germany. The complex nature of the firefighting responsibility in Germany's communities and cities, which number approximately 10,000, creates a complicated dataset with a high number of departments (see section 3). Recently, Maiworm [35] detailed the intricate federal structure in Germany. Although statistics exist for all fire department interventions in Germany (approximately 220,000 [16]), only the total number is reported. Furthermore, data on fire department work is inconsistent across cities within the federal states. However, this questionnaire accounts for all fires, but excluding small fires that do not harm fire safety objectives by law. This dataset constitutes the initial scientific analysis of potentially harmful fires in Germany.

The distribution of building types and numbers of fires within (Fig. 3) overlap with the statistics by the German Fire Protection Association (GFPA) [26] in recent years. As GFPA data contains more incidents and other participating fire departments, this also indicates a representative data set and distribution presented here. Though, the statistic only represents potentially harming fires. As the data set from Munich corresponds to provided data from other cities within a small percentage, fire departments seem capable of gaining appropriate data on a scientific level about these potentially harming fires.

The dataset represents a substantial portion of potentially hazardous fires in Germany, as the participating cities account for almost a quarter of the country's population. However, the dataset is limited because the fire services participated voluntarily, the duration of participation varies between the departments, and data from smaller towns and villages are scarce. Thus, it can be hypothesized that our evaluation aligns with the safety standards prescribed by the model building code, given that the majority of fire safety regulations apply to buildings in class 4 and 5. These building categories are typically concentrated in urban areas and are included in the evaluation process.

Presented statistics only contain potentially harming fires in which the protection goals/objectives of the building regulations in Germany were either endangered or not complied with. The focus is on limiting smoke spread to other units (hallway, stairwell, neighboring apartment). Although the building code explicitly describes the prevention of smoke in other units, this was not the case in almost 50% of the cases. So there is a comparatively high difference between the given fire protection objective (smoke spread is to be prevented) and the then-found realization.

The hypothesis that building age was a risk factor for smoke spread was rejected. Spread of smoke was equally distributed over all building ages—the statistical accumulation of buildings from 1950 traces back to World War II and the reconstruction of cities in Germany. In any case, it must be reviewed whether the data can also be transferred to other countries since most of the buildings have been built in the last seven decades.

In building class 3, for example, fire resistance must have (R)EI 30, and in class 5 it is (R) EI 90. Therefore, we expected less (smoke) to spread in these buildings. Smoke resistance is part of German building regulations in addition to the EI-criteria[5]. However, as shown in Fig.5, building law seems to prevent fire spreading regularly and lacks in smoke spreading prevention. This and Fig. 7 could be an indication that the regulations of the building code stop the fire equally well on all routes and all safety requirements. The numbers in Figures 6 and 7 could add information to the recent discussions in Germany about facade fires and objectives [21].

A change in legislation for self-closing apartment doors altered the risk of smoke spreading, as shown in Fig. 10. Since the smoke propagation paths were extracted from free text fields and the values for the resulting categories are given in relative numbers, the relative rate of, for example, shafts or bulkheads in newer buildings increased unexpectedly. Since these are very low numbers (from all other paths), the value uncertainty could also be part of the shift. It can be assumed that relative changes in values do not follow a change in risk. It is noticeable that the observed smoke spreading for self-closing "ordinary" apartment doors did not drop to the level of fire doors or smoke control doors and kept up to 20%.

The regression analysis allows conclusions to be drawn about the relationship between the number of floors and the spread of smoke (see Fig. 9). However, it is essential to investigate whether a chimney effect or another factor is contributing to the smoke's dissemination. The available data can solely establish a correlation and cannot determine causality.

Shown probability of injury for the City of Munich shows two clear findings (1.58 Million inhabitants): on the one hand, the risk of an inner-city fire for the simultaneity of injuries decreases, and on the other hand, the value is above the assumptions of 10^{-06} [34] per year for the probability of death but clearly below the proposed risk-curve of the British standard PD 7974-7 for fire fatalities [9, Fig.7]. The curve presented serves as an additional factor to consider when evalu-

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[5] MVV TB 2021/1: A 2.1.3.3.1 General "Parts of building structures are fire-resistant when they permanently prevent the spread of fire for at least a certain period of time specified below, the room closure is not impaired even in the area of connections and joints to adjacent parts of building structures, and when there is no significant smoke development and no significant falling or dripping of components on the side facing away from the fire." [17].

ating the level of safety in a performance-based code for fire safety engineering [35].

A higher risk for first responders to be injured could be shown. It can be explained by two factors: 1) First responders go towards the fire and tend to wait too long before fleeing. This risk could be reduced by training. 2) Second, federal law requires multiple fire extinguishers in a location depending on the fire load. It was observed in the on-scene inspections and described by first responders that when multiple fire extinguishers were used, the necessary retreat from the developed fire was even more disregarded.

Figure 13 describes the relationship between the incidence (injured per potentially harming fire) and the probability of occurrence per year. The presented F-N-curve [11] is notably lower than the suggestion for fire fatalities in the British standard (cf. Figure 7 "F-N diagram" in PD 7974-7:2019 + A1:2021 from BSI [9]). This relationship can also be applied to deaths as an incidence per potentially harming fire here examined and is supported by data from the fire brigade in London [30].

As smoke spreading rates increased by building size/height, it was interesting to examine the intervention time of the fire department after arrival on the scene before extinguishing started. An explanation for the prolonged time can be found in the technical equipment: According to standard operating rules [37], the standard fire extinguishing operation in Germany is accomplished by an "attack troop" (two fire-fighters carrying one hose transport cage by three hoses type C [20], 15 meters each [19]) and backed up by the "safety troop" resp. "water troop" (two firefighters each). Since one hose is used by the "attack troop" to reach the floor of the fire incident through the staircase, the remaining two hoses are used in the compartment/unit to search and extinguish fire. A fire incident that occurs above the third/fourth floor requires another troop of firefighters to maintain the supply of hose material (the length of a standard hose is 15 m). As the mean intervention time is approximately rising for one minute every two floors to reach (see Fig. 11, floors 0 to 4), the data leads to the presumption that above the 4th floor, the intervention time is further increasing due to the additional time for hose material supply. While the number of fire incidents observed above the 4th floor is too small to calculate mean or quantile values, the upward tendency can at least be stated as a rough estimation. This additional time after arrival on the scene can be an influence factor on fire safety, considering the high level of observed smoke spread and injured persons.

Figure 10 proves that low-cost measures can greatly impact fire safety. In the 1990s, Bavarian building law was changed to self-closing doors towards stairwells, and this led to a measurable decrease in smoke spreading rates and higher safety for the main escape route.

5. Conclusion

German fire departments examined more than 900 potentially harming fires. This first-time evaluation of the outcome of fire safety design in buildings by building code in combination with fire fighting measures gives an inside view of its effectiveness. Smoke propagation has been found to be a critical issue. In more than half the fires, smoke spread led to 37% of persons injured and 6% fire fatalities, violating legal regulations. Smoke spread primarily through stairwells or windows, resulting in 38% of fire victims needing to be rescued by firefighters. Therefore, knowledge about the smoke spread and smoke management on the scene is crucial to fire safety in existing buildings. Details of fire-spreading routes and discussions about fire resistance do not meet the core of a risk assessment. Cheap measures like self-closing doors can reduce smoke spread by about 50% but still do not reduce risk to the level of fire or smoke doors.

The urban data set also showed that the time difference between arrival on the scene and starting to fight a fire rises in higher buildings—showing that it takes on average nine minutes for German firefighters to begin fighting at the edge height of high-rise buildings (i.e., those that top out at around 22 m above ground) once they have arrived on-scene. This new information could lead to a novel approach to fire-safety-assessment. The authors believe that the higher risk of smoke spreading in higher buildings might result in a later attack time. Therefore, we emphasize higher fire safety measures in higher buildings to ensure equal safety for inhabitants.

In GER, a permanently installed dry riser for fire fighting is partially installed in taller class 5 buildings. However, the requirement for the presence of a dry riser is linked to a higher number of floors. This explains the lack of expected increase in times above the 4th floor. Background information: In Germany, the AGBF VB/G (group for fire prevention within the association of professional fire chiefs) has already taken this into account and made a recommendation to supplement requirements plans for fire departments [4].

Data is also currently being examined on how financial aspects influence the outcome of fires in buildings. A main hypothesis is that poorer areas are more likely to be damaged by fires, and more vulnerable in the process. This cooperation with social science is still ongoing and cannot be proven solely on the basis of the presented data. One following idea is to educate, better inform residents and emphasize the responsibility of the landlords. This could include higher control densities by authorities based on social data.

Also, the regularly observed low level of fire protection, as well as human misconduct (open fire doors, combustible materials in stairwells or hallways, poor state of buildings) in urban areas characterized by high building structures as well as a variety of social classes, could be the cause for elevated smoke-spreading rates. In many cases of social housing, landlords tend to invest only as little as the law requires. The observation of social aspects of fire-injuries will be evaluated by combining the presented data with social data aspects. The authors hope that this new knowledge of risk will evolve in fire-protection education customized for the social groups within the district, consultations with landlords, and low-cost high-effective refurbishing efforts in terms of fire safety (self-closing doors). As a result of the data set and the knowledge gained, the approach of dynamic fire inspection deadlines was elaborated in Munich. Inspection periods will be defined by risk and not by categorization. Instead of focusing on the number of hotel beds, for example, smaller hotels with poor escape routes are inspected more frequently. Following this idea of risk approach for inspection periods, Bayes nets on fire safety can now be based rather on data than assumption or simulation of fire dynamics [42].

To address the ongoing discussions in Germany regarding fire safety, cost reduction, and necessity, we must emphasize the importance of redundant escape routes. The presence of such routes and effective, rapid response from fire departments is essential in minimizing the number of fatalities in the event of a fire.

A general statistic about fire safety in Germany would be valuable for fire safety engineering. It must combine several views on the topic: public safety, rescue teams' safety, financial aspects, and a societal view on acceptable loss to give just a few aspects. Today, these views can be found separately in the described different statistics. Only at a governmental level and politically pushed, a general statistic seems reachable. In a federal republic such as Germany, it will be impossible by law, as not mandated by the constitution, to have a general statistic after all. Research cannot fill the void the government left.

Firefighting is a responsibility at city or even village level in Germany. This expert knowledge about fires and their outcome in real life has now been quantified for the first time. In future discussions regarding state or federal (model) building regulations, the fire department's previous subjective viewpoint can now be incorporated with scientific validation.

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SUPPLEMENTARY INFORMATION

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