

Article

Defect Trends in Fire Alarm Systems: A Basis for Risk-Based Inspection (RBI) Approaches

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Abstract: This article presents a comprehensive statistical evaluation of defect frequency in fire alarm systems under real operating conditions, focusing on risk-based factors. The aim is not to introduce a complete RBI approach but rather to assess defect trends that can inform future RBI-based inspection strategies. The study categorizes and evaluates defects by frequency, particularly examining components such as cable and wire systems, acoustic signal devices, and the impact of detector contamination. These findings establish a foundation for developing tailored risk-based inspection and predictive maintenance strategies. A three-stage explanatory research design was employed, analyzing 4629 inspection reports with findings verified through expert surveys and cross-sample analysis. Results indicate that certain components, including acoustic devices and detectors, exhibit a significant increase in defects after 10 years, especially under challenging environmental conditions. Additionally, while ring bus technology supports less frequent functional testing, cable and wire systems require heightened attention in the early operational years. The study also identifies statistically significant trends and their potential for application to a broader system population, supporting enhanced RBI-based maintenance practices. These insights contribute to refining current maintenance approaches and offer practical recommendations for optimizing inspection routines based on risk factors. The article does not propose a system overhaul but lays essential groundwork for further research and improvement in fire alarm system reliability through targeted, risk-informed practices.

Keywords: testing; maintenance; fire alarm system; defects; trends; inspection; risk



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1. Introduction

Fire detection and alarm systems make significant contributions to the safety of both people and livestock in complex or publicly used buildings [1,2]. In terms of the requirements of building regulations, these systems fulfill the tasks of detecting fires in the incipient phase, localizing the hazardous event, alerting emergency services (e.g., fire brigade, police, rescue service), warning persons in the danger area and controlling other parts of the technical building equipment relevant to fire protection.

To achieve these protection goals, these systems must meet comprehensive availability requirements. For this reason, numerous national and European specifications have defined the operation, maintenance, servicing, and regular testing of these systems with regard to their proper condition [3].

The current regulatory requirements for the maintenance and testing of fire alarm systems have been defined independently of risk factors. According to the standards current maintenance routines are purely preventive systems [4]. This approach can avoid unplanned system failures in many cases; however, the high requirements also produce high costs, lead to high personnel expenditures, especially for highly qualified specialists, and contribute to increased material use. As a result, the operation of fire alarm systems entails high consequential costs for building operators.

Similar challenges have been recognized in the operation of plants in the process industry as well as in the operation of power plants for several decades. For reasons related to environmental and personal safety as well as sustainably high availability of production, maintaining the technically flawless condition of these plants has traditionally played an important role. At the same time, the costs for preventive maintenance approaches according to the classic model—maintenance of all plant components at the same intervals within the same amount of time—are disproportionately high and lead to economic losses. For this reason, the methodology of “risk-based-inspection (RBI)” was introduced in the American region in the 1990s. The underlying logic of this concept is that the majority of high-risk components are concentrated in a limited area of an investment. It is, therefore, necessary to prioritize the inspection and maintenance of these installations and to allocate additional resources. These additional costs can be offset by lower maintenance costs of other, lower-risk equipment [5]. In order to be able to implement such a concept—regardless of the system to which it is applied—the system components with a higher and lower risk of defects must be well known.

The aim of this study is to analyze and evaluate the frequency and underlying causes of technical defects in fire alarm systems, based on real-world operational data. By categorizing and assessing defect occurrences and identifying key risk factors influencing these failures, the research seeks to provide a comprehensive understanding of defect trends. Specifically, the study investigates how the influencing factors of system age, system size, and operational environmental conditions affect the risk of defects. By examining these factors, the study aims to uncover patterns that contribute to higher defect frequencies, offering valuable insights into how different conditions impact system reliability. The findings are intended to serve as a foundation for the future development of risk-based inspection strategies and predictive maintenance measures for fire alarm systems, contributing to enhanced system reliability and safety in practical applications.

This study is novel in its approach, as it examines risk factors not merely through mathematical analysis of individual systems, but from a comprehensive, operational perspective across diverse, real-world fire alarm systems. For the first time, risk factors related to fire alarm systems are evaluated in terms of defect trends, providing insights that can be directly applied to develop a risk-based inspection (RBI) approach for enhanced maintenance strategies in practical applications.

2. Literature Review/Background

To determine the current state of research regarding existing availability and system failure investigations, risks, and risk-based inspection methodology associated with the occurrence of defects in fire alarm systems, a keyword analysis of the literature relevant to the subject area was first performed. The results of the literature review analyzing the current state of research on the aforementioned topics relating to fire alarm systems can be divided into the following three thematic focal points:

1. Fire alarm systems and related components
2. Data processing with IoT, cloud, and AIoT according to fire alarm systems
3. Risk analyses and case studies according to maintenance and inspection.

The literature review was carried out via Web of Science, Scopus, and Google Scholar. Only those works that have an impact on the research topic with a link to the area of fire alarm systems are analyzed. From an examination of the current state of research regarding the individual topics, it can be stated that relevant studies have not yet been reported regarding the frequency of occurrence of technical defects in fire alarm systems from the point of view of practical plants in operation. This applies in particular to studies that attempt to cluster the defects in this context according to risk factors and system assemblies. For this conclusion, it is important to distinguish that the study presented here is concerned with the frequency of the occurrence of faults in fire alarm systems in real operation. The annual statistical evaluations of the TÜV Verband in Germany on the general occurrence of defects in safety-related systems in buildings provide the results that

are closest to the planned investigations—irrespective of the topics covered in the literature review. The statistics are published in the ‘Baurechtsreport’ and show how many of the systems inspected had no defects, minor defects, or significant defects [6]. Figure 1 shows a separate compilation of the results of the reports from 2013–2023, each of which contains the key figures for the previous year. In contrast to the investigations carried out here, it does not analyze which defects are involved and under which influencing factors they occur more frequently/less frequently.

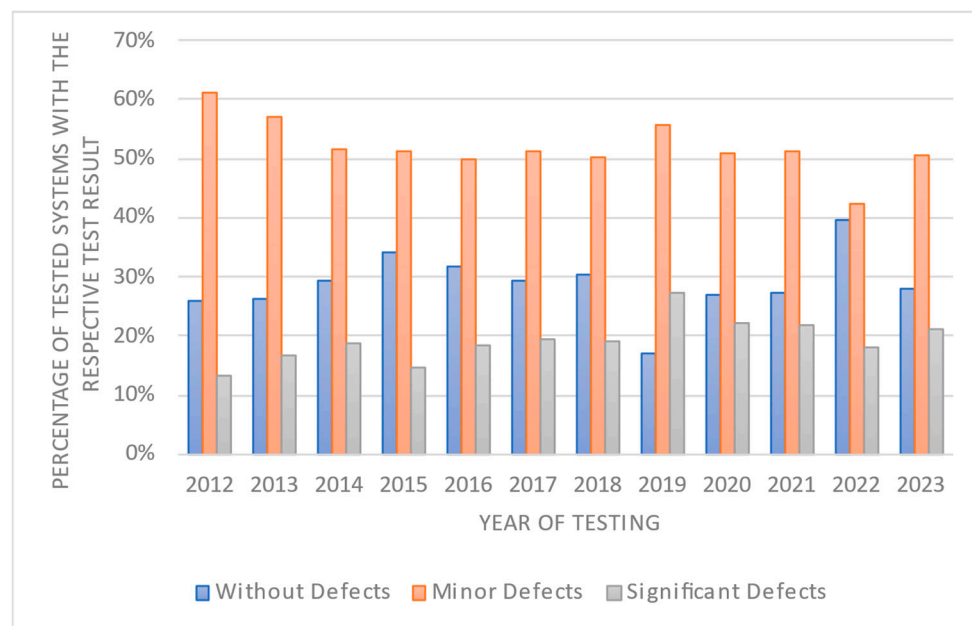


Figure 1. Graphical representation of the results of existing TÜV Verband statistics on the proportion of faulty fire alarm systems in the total number of systems tested in Germany.

This gap in statistical data is confirmed by a detailed examination of the current state of research. Regarding the first thematic focus on fire alarm systems and their associated components, a wide range of research work has been performed regarding the technical development of fire detection technology, in particular with regard to the sensor technology used, the fire parameters examined, and the algorithms used to evaluate them [7–9]. In addition, previous studies have addressed the availability of the systems and their power supplies [10,11]. In particular, numerous studies have examined the availability of systems based on the probability of failure of individual assemblies, either theoretically or using the example of individual systems [11–16]. While previous research has primarily focused on analyzing individual systems with respect to the failure probabilities of specific components, a comprehensive examination of the detailed failure probabilities of these components within real, operational systems has not been thoroughly explored. This study aims to address this gap by providing an in-depth analysis of the failure probabilities at the component level, specifically within systems that are currently in operation, thereby extending the existing body of knowledge.

A broad investigation of the defects that occur in practice in real systems is not available in current research. Studies with a comparable data basis do not relate to the occurrence of defects but consider, for example, the occurrence of false alarms and their causes. Data on this are available from various European countries in [17–19]. In the field of maintenance and servicing of fire alarm systems, current research has focused on remote services [20]. This trend is strongly connected to digitalization, which has an influence on the second thematic focus, as numerous studies have continued to promote new development of fire alarm systems with regard to IoT and AIoT technology [7,9]. In this case also, however, no content has suggested the frequency of technical defects

occurring under risk-related influencing factors in real systems. Adujora's research focuses on the further development of predictive maintenance methods under the influence of IoT technology in fire alarm systems. The focus here differs from the studies shown, as this research is about process improvement and not about analyzing the system components that are potentially subject to more defects [21].

In the area of risk analyses and case studies, research approaches have been undertaken in the field of fire protection systems. First of all, various research approaches have investigated the possibilities of using risk-based methods (such as RBI) in fields of application other than the petrochemical industry [22]. With regard to security systems and equipment in buildings, Sobral and Ferreira have focused on the application of RBI to automatic fire extinguishing systems [23]. Their research has indicated the importance of testing, inspection, and maintenance procedures related to sprinkler systems, and they have proposed a methodology, based on international standards and supported by test and inspection reports, to adjust the frequency of these actions according to the degree of deterioration of the components and consideration of safety aspects. Research has shown that the maintenance of this type of equipment is of particular importance; that is, these systems usually operate in a dormant state, and their operability in an emergency is, therefore, not known. Comparable studies in the context of maintenance strategies are presented in [24].

Much of the research has focused on the general investigation of risks to people in buildings when hazardous situations occur. In addition to studies on the assessment of the level of life safety of people by Van Weyenberge and Deckers et al. [23,25]. Similar work deals with the risk of failure of buildings—including the failure of safety systems such as fire alarm systems [26–28]. Detailed event trees supported by statistical data and analyses are used to calculate the corresponding probabilities [25–28].

The literature review has shown that there are currently numerous research approaches for analyzing the availability of fire alarm systems and the probability of the failure of individual system components of individual fire alarm systems. The big difference is that these studies relate to a specific system from one manufacturer and do not take into account the influencing factors of real systems from different manufacturers, years of manufacture, and environmental conditions that are in operation. Furthermore, there is already comparable work on determining failure and damage risks in other technical areas of application in the field of risk-orientated maintenance. All approaches from other areas share a common understanding of when and how often technical defects are likely to occur, as well as the relevant influencing factors that lead to an increased incidence of such defects. However, this knowledge is currently still lacking for fire alarm systems. There is a lack of data from practical operations independent of the theoretical consideration of failure probabilities.

The work presented here narrows this research gap. It shows which trends the occurrence of defects in real fire alarm systems follows when risk factors occur. These risk factors—namely system age, system size, and operational environmental conditions—were selected based on existing research that highlights their significance in determining system reliability and defect frequency. Previous studies have demonstrated that system age has a direct impact on the likelihood of technical failures, with older systems showing higher defect rates due to aging and wear [15,29]. Furthermore, research indicates that system size correlates with defect frequency, as larger systems, with their increased complexity and number of components, tend to experience more frequent failures [13,26]. Additionally, environmental conditions, such as dust, moisture, and temperature fluctuations, have been shown to increase the risk of defects in fire protection systems, particularly in challenging operational environments [10,23]. By examining these specific risk factors, this study aims to provide a comprehensive understanding of how they influence defect trends in fire alarm systems, thereby establishing a basis for risk-based inspection and maintenance approaches tailored to practical conditions. The work substantiates existing TÜV Verband statistics, which only contain general data on defective systems—but not on the defects themselves.

3. Methods

The methodology applied in this study follows a systematic, three-stage explanatory research design aimed at identifying trends in the frequency of defects in fire alarm systems under specific risk factors. The approach includes the collection and analysis of primary data, followed by sample verification, ensuring the reliability and applicability of the results to real-world scenarios. This section outlines the materials used for the research and the processes involved in verifying the samples. The general structure is shown graphically in Figure 2.

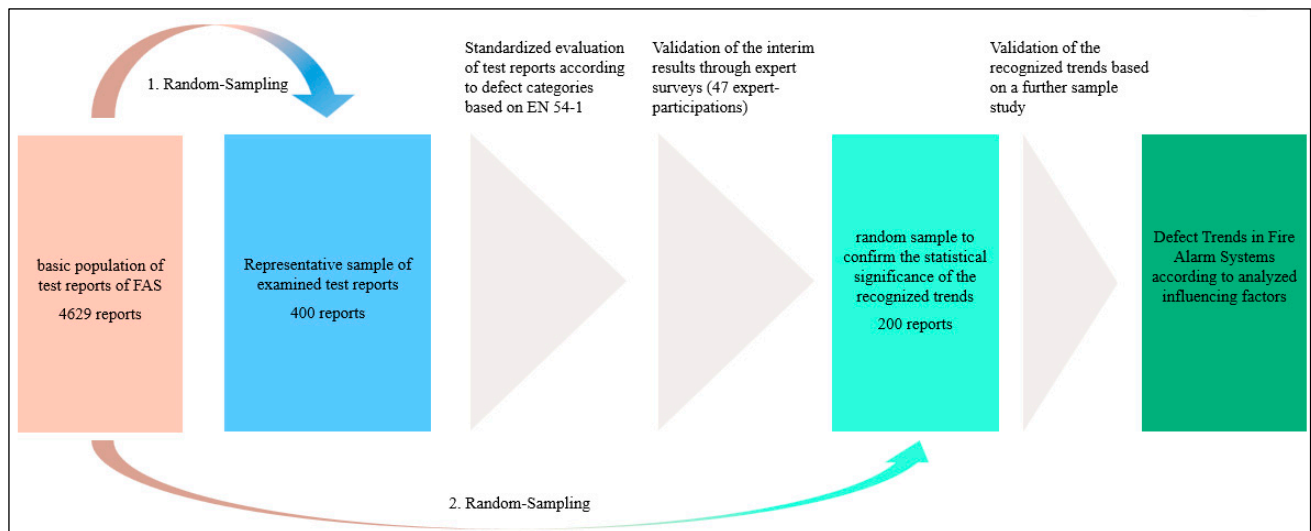


Figure 2. Three-step explanatory research design as a methodological basis.

3.1. Materials

The extensive primary data used as the basis for the analyses originates from original test reports of the periodic inspections of fire alarm systems carried out by the experts of TÜV SÜD Industrie Service GmbH in Germany. These are complete test reports of the periodic inspections of the systems in accordance with German building law, which contain information on all defects found in the systems in addition to the technical system data used to categorize the systems. The defects are formulated in the reports in free text and not clustered, which is conducted in the course of analyzing the data in this research work.

The investigated period was limited to 2020–2022. The reason for choosing this three-year cycle is that fire alarm systems in Germany must be tested every three years. The choice of this data source effectively prevents duplicate data from being included in the sample. The available data included a total of 4629 test reports. Due to the power of the population of available data, a sample analysis was performed based on a random sample.

In the first step, the minimum required size of the sample is determined from the finite (known) population. The determination is carried out with the following formula Minimum number of samples required for a finite population [30]:

$$n \geq \frac{N}{1 + \frac{(N-1) \cdot \epsilon^2}{z^2 \cdot P \cdot Q}} \quad (1)$$

n = minimum required sample size for a finite population.

N = number of items in the population.

ϵ = chosen tolerated error.

z = value calculated from the central probability of the standard normal distribution.

P = actual mean of the population or percentage of the population.

$Q = 1 - P$.

Based on the methodology of the research carried out here (mixed-methods approach with subsequent verification of the data by expert interviews), the value 0.05 (95% safety probability) was chosen as the chosen tolerated error. The 5% tolerated error, which corresponds to a 95% confidence level, was chosen based on established statistical conventions for studies that aim to generalize findings to a larger population. In this case, given that our study focuses on recognizing and presenting trends in defect occurrences in fire alarm systems, the 5% error margin was considered appropriate to ensure a balance between statistical power and practicality.

Furthermore, this selection was informed by the operational characteristics of fire alarm systems, particularly the three-year inspection cycle mandated in Germany. The data used in this study spans a complete inspection period, which ensures that no duplicate data from previous cycles is included, allowing for a clean and representative sample of system performance across this interval. Given the relatively stable nature of fire alarm system operations during this period, and the need to detect subtle trends in defect occurrences, we determined that a 5% error margin would provide sufficient sensitivity to capture these trends while maintaining a high level of statistical confidence. Given the selected tolerated error, special emphasis was placed on the verification of the results to ensure their robustness and practical relevance. Therefore, this approach ensures the results are both statistically significant and relevant for broader generalization to fire alarm systems in practical operation.

Since the value for P is not known in advance of the research, P and Q are chosen so that the product of P with Q takes the maximum possible value to calculate a sufficiently large sample size n even in the worst-case scenario.

For $P = 0.5$, the product $P \cdot Q = 0.25$. Since $Q = 1 - P$ depends directly on P , $Q = 0.5$ must be chosen.

The factor z is determined from the distribution function of the standard normal distribution. Corresponding tables are available for this purpose [29,30]. For the selected safety probability of 95%, the distribution function of the standard normal distribution results in a value of $z = 1.96$. Based on the calculations, the minimum size of the sample is $n > 355$, considering the above-mentioned framework conditions and the thickness of the population. Thus, a sample of at least 355 reports is drawn from the 4629 available test reports.

The selection of the sample elements is software-supported by Microsoft Office Excel (Version 2410, Build 18129.20116) using the so-called lottery procedure. For further evaluation, randomly determined 400 test reports (as elements of the population) were used. The number of test reports analyzed is thus higher than the minimum sample required, resulting in a representative data set. This described sample is referred to as the 'main group' in the remainder of the document. The reason for this is to distinguish it from the second sample examined, which is referred to as the 'comparison group' and is only examined in a subsequent step.

3.2. Sample Verification

The test reports analyzed in the samples were first categorized in terms of risk categories, such as the size of the fire alarm system under consideration (number of detector groups), the age of the system tested, and the conditions of the operational environment. The presentation of the results contains a more detailed explanation of the choice of risk categories and the corresponding categorization for coding. The deficiencies listed in the test reports were recorded and assigned based on assemblies of fire alarm systems coded according to the European product standard for fire alarm systems. The aim of this procedure was to quantitatively evaluate the data in a structured manner to determine whether a particularly frequent or rare occurrence of defects in the system assemblies could be determined from the risk categories assigned.

The data obtained from the quantitative content analysis of the test reports were enhanced and verified in the first step using an open survey of experts in fire alarm systems.

As part of the survey, the results of the quantitative analysis (diagrams and tables) were presented to the experts. A total of 47 experts took part in the survey, which was conducted separately in two sessions on 15 March 2023 in Eichstätt (GER) and on 27 April 2023 in Mannheim (GER). In total, 39 of the participants were recognized as experts under building law by the relevant building supervisory authority with regard to their professional qualifications. Eight participants were active as experts without recognition under building law.

The experts have the following professional experience in the field of fire alarm technology:

0 years: 1 participant (2%)
1–3 years: 5 participants (11%)
3–5 years: 3 participants (4%)
5–10 years: 18 participants (38%)
>10 years: 21 participants (45%)

This distribution ensures comprehensive expertise in the field of fire alarm technology. The experts were asked up to 42 questions as part of the survey. The surveys were structured in two stages for each diagram/table. On the one hand, a closed question was formulated as to whether the results or the recognized trends of the curves were confirmed or rejected from the experts' point of view. The results of these questions were analyzed quantitatively. As a supplement and to improve quality, open questions were also formulated for each area of investigation, the answers to which were analyzed according to Mayring. The answers were clustered according to a coding guideline and analyzed quantitatively. The coding guideline was created inductively for each question and subject area based on the analysis of the answers. The results serve to verify the recognized trends from the statistical work with the test reports from practice.

An important quality criterion of the work is the ability to generalize the findings from the analysis of the sample in the form of trends to a significantly larger amount of data. To further sharpen this quality criterion and effectively demonstrate the applicability of the results to larger data volumes outside the samples, the trends are tested in a second verification step by analyzing a further sample (comparison group) of test reports. The aim here is to investigate whether this second sample—which is drawn from the same population with a quantity of 200 examined reports—shows the same influencing behavior of the examined risk factors as is the case for the first sample with the verification by the expert surveys. The random sample was generated using the same method as in the first research step. The lower number of reports was chosen here because it is no longer a question of determining a more precise percentage distribution—but rather of verifying trends.

It is assumed that this combination of a three-stage explanatory research design consisting of quantitative and qualitative analyses can highlight relevant trends in the occurrence of defects among the influencing factors investigated. The aim here is not to present exact percentage values and frequency distributions, but to develop trends in order to recognize under which influencing factors defects occur more or less frequently in certain system assemblies of fire alarm systems.

4. Results

4.1. Analysis of the Frequency of Deficiencies Regardless of Risk Factors

An evaluation was first performed to determine which defects were generally detected—regardless of risk factors—during tests of fire alarm systems and at what frequencies. In accordance with the planned methodology, defects were first classified into 16 defect categories (DCs). The frequencies of occurrence and the corresponding presentations are indicated in Table 1. Of the 400 fire alarm systems considered in the random sample of the main group, 84 systems (21%) were found to have no defects; all other systems were defective. The distribution of these deficiencies among the individual categories was examined. The comparison of the number of non-defective systems with the figures of the

overall statistics of the TÜV Verband from Figure 1 shows that the examined/selected sample represents a realistic picture of the total number of defects in fire alarm systems. This verifies the chosen methodology for selecting the sample.

Table 1. Evaluation of the percentage frequency of the occurrence of faults as a function of the total number of faulty fire alarm systems separately for the evaluated samples of the main group and the comparison group in accordance with the methodology used in Section 3 (in the following order: main group/comparison group).

DC	Category—Explanation	Number of Checked Systems with Faults	Percentage Frequency of Defects of Named Category
DC.1	Add. defects with influence on fire fighting	167/97	53/59%
DC.2	Information defects	124/68	39/41%
DC.3	Other deviations from technical regulations	21/50	7/30%
DC.4	Defects in cable system and fire protection of system parts	90/40	28/24%
DC.5	Technical defects of automatic fire detectors	15/7	5/4%
DC.6	Deficiencies in the arrangement of automatic detectors	152/77	48/47%
DC.7	Technical defects of manual fire detectors	2/0	1/0%
DC.8	Deficiencies in the arrangement of manual detectors	69/34	22/21%
DC.9	Defects in the power supply	66/37	21/23%
DC.10	Defects in the FACU operating and display equipment	30/19	9/12%
DC.11	Alarm deficiencies	126/58	40/35%
DC.12	Deficiencies in the control of linked systems	70/39	22/24%
DC.13	Deficiencies in the reaction of linked systems	76/43	24/26%
DC.14	Deficiencies in the handling of fault messages	25/11	8/7%
DC.15	Deficiencies in the transmission of alarm messages	8/2	3/1%
DC.16	Deficiencies in additional management functions	5/0	2/0%

The individual categories of defects can be described as follows. Defect category DC.1 describes defects that relate exclusively to the operational tactics of the fire brigade in the event of a fire, but not to the technical condition of the system itself. Typical examples of deficiencies in this category are faulty fire brigade route maps or changed floor plans or routes.

Defect category DC.2 refers to defects related to technical documentation. This includes missing or inadequate documentation as well as correspondingly contradictory or unclear information. Defect category DC.3 describes other deviations from the anchored rules of technology, such as formally unapproved deviations from technical building regulations.

Whereas the aforementioned categories of defects describe exclusively nontechnical defects, defect category DC.4 represents the first class of defects in which technical defects are present in the system. This category describes deficiencies in the piping system that are mainly caused by deficiencies in functional integrity in the event of a fire. This category also includes all other defects of the piping system, for example, defective fasteners.

Defect category DC.5 describes technical defects in automatic detectors—as detectors that are no longer suitable for triggering fire alarms due to technical defects in the detectors themselves. DC.6, on the other hand, also refers to automatic point detectors but includes all environmental conditions. Thus, deficiencies related to the arrangement or scope of monitoring are also recorded. Defect categories DC.7 and DC.8 are equivalent to DC.5 and DC.6 but concern manual detectors (manual call points). In particular, DC.8 includes defects related to incorrectly arranged or missing detectors.

Defect category DC.9 considers faults in the power supply, ranging from an exceeded maintenance interval to faulty bridging times of the accumulators or defects in the general power supply. DC.10 includes errors in the evaluation and display functions of the fire alarm and control unit (FACU).

An important category of deficiencies is DC.11, which includes deficiencies in the alerting device. The most common defects in this category are defective sounders, missing signalers, faulty alarm signals, or insufficient alarm sound levels. Defect categories DC.12 and DC.13 refer to the proper functioning of fire alarm systems. DC.12 includes deficiencies that can be traced back to faulty programming by the BMZ. DC.13, on the other hand, includes deficiencies occurring in the reaction of the controlled system, such as an incorrect reaction of a controlled ventilation system. The final three categories DC.14, DC.15, and DC.16 consider the scope of the transmission of alarm and fault messages or messages to other management systems.

Overall, the result of the analysis of the overall distribution is that the analyzed defect categories can be divided into three groups with regard to the distribution of defect frequency. Firstly, the group of the most frequent defects, which occur in more than 30% of the defective systems, is formed by the defect categories DC.1 and DC.2 which on the one hand represent the additional defects that only affect the fire brigade's operational tactics or missing documents/information defects. Furthermore, the categories DC.6 and DC.11 can be counted as technical deficiencies, which describe deficiencies in the arrangement of automatic detectors and deficiencies in the area of alerting.

The second significant grouping of the frequency of occurrence of defects in fire alarm systems is described by the very rarely occurring defects with a frequency of less than 15% in relation to the defective systems. This includes the defects in categories DC.5 and DC.7, which describe technical defects in detectors. Furthermore, the categories DC.14–DC.16 can be found here, which describe the handling of fault messages, alarm messages, and other management functions. The last category in this group, DC.10, represents Cfaults in the FACU display. All other faults are assigned to the middle group, which occurs with a frequency of 20–30% in relation to the faulty fire alarm systems.

The following aspects are noteworthy with regard to the percentage distribution of deficiencies:

- Technical defects in automatic and nonautomatic detectors occurred very rarely. In particular, in the area of manual detectors, only two deficiencies could be identified. This situation was perhaps unexpected because, in accordance with the testing principles, special attention had been paid to the functional testing of detectors and manual detectors. The trend towards a very low probability of occurrence of technical defects in detectors was confirmed by the technical experts surveyed. Due to the technical characteristics of fire alarm systems, the probability of finding these defects is very high, and they are usually detected and corrected independently by the system.
- Deficiencies that had no influence on the effectiveness and operational safety of a system but would only influence the operational tactics of a fire brigade, as well as deficiencies in the technical documentation of the systems, constituted the majority of the findings.
- Among the technical deficiencies detected, the most common system components with defects were alarming devices like sounders. In addition, major deficiencies were noted in the cable and line system as well as in the power supply system.

The above findings were verified during the expert interviews. The experts were asked whether they could confirm the distribution of defects across the individual defect categories and the findings presented from practical experience. The results were confirmed by 77% of the experts surveyed. A further 17% of the survey participants did not provide any information due to a lack of assessment options. Only 6% of the 47 survey participants disagreed with the identified distribution of deficiencies. However, the disagreements of this group relate exclusively to individual values in the graph, so that the basic population of the findings is not called into question here either. The results could also be confirmed based on the second verification step by comparing them with the second evaluated sample (comparison group). Only in the defect category DC.3 was a larger deviation in the percentage distribution found. However, as no trend is derived for this area, this deviation is not relevant to the results of the study.

Overall, the results of the statistical evaluation can thus be confirmed and show a realistic picture of the defect-occurrence while the operational practice of fire alarm systems. With the knowledge of this overall distribution, analyses of the influencing factors on the defect distribution were undertaken.

4.2. Analysis of the Frequency of Deficiencies According to the Risk Factor “Age”

The next step in the research process was to investigate whether certain categories of defects had occurred more frequently depending on the age of the fire alarm systems examined or whether their frequencies may have even partially decreased. For this purpose, risk categories were designated in an initial research step. These risk-of-age (RA) categories are found in Table 2.

Table 2. Classification of fire alarm systems into age-risk categories separately for the evaluated samples of the main group and the comparison group in accordance with the methodology used in Section 3 (in the following order: main group/comparison group).

Category	Age of Systems	Periodic Inspection Cycle	Number of Systems in the Samples (Main Group/Comparison Group)
Total	All	–	400/200
RA.1	<1 year	0	28/5
RA.2	<4 years	1	65/44
RA.3	<7 years	2	84/35
RA.4	<10 years	3	58/34
RA.5	<13 years	4	37/30
RA.6	<16 years	5	28/11
RA.7	<19 years	6	11/17
RA.8	≥19 years	7 and more	35/17
N.D.	Not specified	Not specified	54/7

The risk categories for the risk of age were formed based on the audit obligations underlying the audit reports that form the primary data analyzed. A test cycle of 3 years applies to the tested fire alarm systems. For this reason, the respective test cycles were selected as risk categories, each with a delay of 1 year—to compensate for corresponding delays in the first periodic test after commissioning. This optimizes the test basis in terms of a possible later application of the data as part of a risk-based inspection.

Considering the distribution of defects as well as the age of the plant, a distribution according to Table 3 could be found. This table indicates the percentage of the audited investments in the respective risk categories of age (RA) with deficiencies in respective defect categories at the time of testing. Information on the distribution of defects from the comparison group is only included in relation to the overall distribution and the defect categories separately with a ‘/’, for which relevant trends could be identified in the main group and which should be verified in more detail according to the methodology described.

Regarding the percentage distribution of deficiencies according to the age of the audited system, the following aspects are striking:

- A conspicuous distribution of deficiencies according to the risk category of age arose in the case of cable and line systems (DC.4). It is noticeable that defects in the cable and wiring system occurred mainly with new or modified systems in the first test cycle (RA.1). In the following cycles or considered risk periods (RA.2–RA.8), the percentage distribution of deficiencies was then almost constant, considering random statistical fluctuations. This trend is also confirmed by the comparative sample examined. Even if the individual percentage values differ here, the overall behavior can be derived from the studies as statistically significant in the sense of a trend curve.
- According to 81% of the experts surveyed, the reason for the higher frequency of defects in the cable system at the time of commissioning or in the first years of operation is due to construction and design errors. In total, 70% of the experts agree

that the decreasing frequency of defects in the first years of operation is due to the partial elimination of defects found during the pre-commissioning inspection or the first periodic inspections. The constant frequency thereafter, according to the expert group, results from the fact that many defects in the cable system can no longer be economically repaired after commissioning due to difficult environmental conditions for the necessary repairs. Examples of difficult conditions include the possible need to remove false ceilings, open shafts and cable ducts, and fire barriers. In these cases, repairs are carried out only at the beginning, shortly after the plant has been built.

- In addition, 11% of the experts surveyed agreed with the percentage distribution but attributed the results to the content of the test. According to the experts, more defects are found during the tests at the beginning of the operating period because the cabling system is more visible to the test personnel. According to these colleagues, fewer defects are found during later inspections because the cabling system is not accessible. None of the respondents fundamentally disagreed with the findings or found them implausible. Figure 3 presents the described effect graphically.
- Another conspicuous feature was the increasing percentage of systems with deficiencies in alerting; this effect was particularly noticeable in the age-risk categories RA.7 and RA.8 and was confirmed by 77% of the experts as well as out of the investigations according to the comparison group through the second verification step. According to 64% of the experts surveyed, this trend can be attributed to the “wear-out” of the components. In contrast to automatic fire detectors, alarm devices—especially sirens and sounders—are not subject to a replacement cycle, leading to age-related failures and performance weaknesses. In addition, according to the answers of 13% of the surveyed experts, defects in alarm systems often occur even after remedial measures. According to the experts surveyed, doors and room-enclosing components are frequently replaced during renovation measures. New components have improved sound insulation properties, such that originally sufficient alarm systems are no longer sufficient. Corresponding renovation measures often occur in the affected age sections RA.7 or RA.8. Figure 3 shows this effect graphically.
- No further abnormalities related to a change in the frequency of defects in the individual categories according to system age could be detected.

Table 3. Frequency of occurrence of defects in relation to the total number of defective fire alarm systems by system age separately for the evaluated samples of the main group and the comparison group in accordance with the methodology used in Section 3 (in the following order: main group/comparison group).

Cat.	Total	RA.1	RA.2	RA.3	RA.4	RA.5	RA.6	RA.7	RA.8
NO DEF.	21/18% (84/36)	25% (7)	32% (21)	17% (14)	24% (14)	8% (3)	18% (5)	36% (4)	11% (4)
DC.1	42/50% (167/100)	50% (14)	42% (27)	45% (38)	48% (28)	43% (16)	39% (11)	36% (4)	34% (12)
DC.2	31/37% (124/74)	32% (9)	18% (12)	35% (29)	28% (16)	38% (14)	21% (6)	18% (2)	40% (14)
DC.3	5/25% (21/50)	11% (3)	5% (3)	4% (3)	5% (3)	8% (3)	11% (3)	9% (1)	3% (1)
DC.4	23/20% (90/40)	32/60% (9/3)	17/18% (11/8)	25/26% (21/9)	19/9% (11/3)	27/23% (10/7)	21/27% (6/3)	18/12% (2/2)	23/24% (8/4)

Table 3. Cont.

Cat.	Total	RA.1	RA.2	RA.3	RA.4	RA.5	RA.6	RA.7	RA.8
DC.5	4/4% (15/7)	4% (1)	6% (4)	5% (4)	2% (1)	3% (1)	4% (1)	0% (0)	3% (1)
DC.6	38/39% (152/77)	43% (12)	34% (22)	32% (27)	38% (22)	49% (18)	36% (10)	55% (6)	49% (17)
DC.7	1/0% (2/0)	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)	3% (1)
DC.8	17/17% (69/34)	18% (5)	17% (11)	17% (14)	16% (9)	16% (6)	14% (4)	27% (3)	17% (6)
DC.9	17/19% (66/37)	29% (8)	5% (3)	18% (15)	17% (10)	14% (5)	11% (3)	9% (1)	34% (12)
DC.10	8/10% (30/19)	11% (3)	5% (3)	11% (9)	3% (2)	11% (4)	4% (1)	9% (1)	14% (5)
DC.11	32/29% (126/58)	29/40% (8/2)	34/23% (22/10)	33/23% (28/8)	24/18% (14/6)	32/23% (12/7)	21/55% (6/6)	36/53% (4/9)	51/59% (18/10)
DC.12	18/20% (70/39)	21% (6)	18% (12)	17% (14)	21% (12)	14% (5)	18% (5)	18% (2)	23% (8)
DC.13	19/19% (76/38)	14% (4)	20% (13)	19% (16)	22% (13)	19% (7)	29% (8)	18% (2)	23% (8)
DC.14	6/6% (25/12)	14% (4)	5% (3)	4% (3)	7% (4)	14% (5)	7% (2)	9% (1)	3% (1)
DC.15	2/1% (8/2)	4% (1)	0% (0)	4% (3)	0% (0)	0% (0)	0% (0)	9% (1)	3% (1)
DC.16	1/0% (5/0)	0% (0)	0% (0)	2% (2)	2% (1)	0% (0)	0% (0)	0% (0)	0% (0)

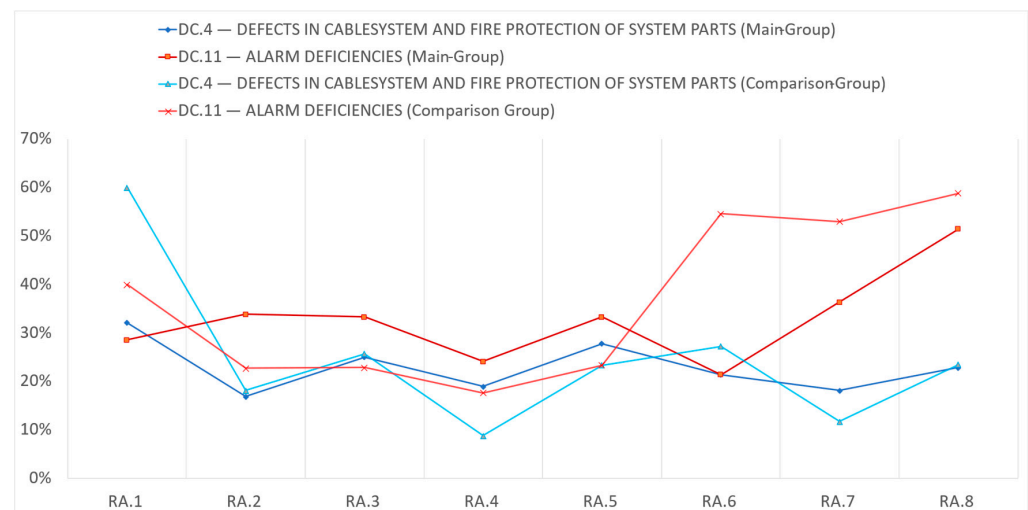


Figure 3. Conspicuous defect distribution curves by system age separately from the investigation of the main and comparison group with conspicuous features with regard to the frequency of occurrence of defects in the cable system (DC.4) in the age risk category RA.1 and strongly increasing defects in older systems RA.6–RA.8 on the alarm systems (DC.11).

4.3. Analysis of the Frequency of Deficiencies According to the Risk Factor “System Size”

The next research step investigated the frequency of occurrence of defects according to the sizes of the individual fire alarm systems. For this purpose, as before, risk-of-size (RS) categories were designated according to Table 4.

Table 4. Classification of fire alarm systems into system-size risk categories separately for the evaluated samples of the main group and the comparison group in accordance with the methodology described in Section 3 (in the following order: main group/comparison group).

Category	Number of Detector Groups	Number of Systems in the Sample (Main Group/Comparison Group)
TOTAL	Alle	400/200
RS.1	≤30	136/63
RS.2	≤100	145/74
RS.3	≤200	47/28
RS.4	≤500	36/27
RS.5	>500	10/4
N.D.	Not specified	26/4

The classification into risk categories according to system size was carried out inductively using the available system data. The most important limits were defined as systems with fewer than 30 detector zones as “micro systems” and systems with more than 500 detector zones, which must meet defined redundancy and thus increased availability requirements in accordance with the normative requirements. In between, limits were defined inductively for a target-oriented, practical evaluation of the occurrence of corresponding defects.

From examining the distribution of the deficiencies and considering the respective system sizes, a distribution according to Table 5 could be found. This table indicates the percentage of the audited investments in the respective risk categories of system size (RS) with deficiencies in the various defect categories at the time of testing. Information on the distribution of defects from the comparison group is only included in relation to the overall distribution and the defect categories separately with a ‘/’, for which relevant trends could be identified in the main group and which should be verified in more detail according to the methodology described.

Table 5. Frequency of occurrence of defects in relation to the total number of defective fire alarm systems by system size separately for the evaluated samples of the main group and the comparison group in accordance with the methodology used in Section 3 (in the following order: main group/comparison group).

Defect Category	Total	RS.1	RS.2	RS.3	RS.4	RS.5
NO DEFECTS	21/18% (84/36)	29/30% (40/19)	18/15% (26/11)	23/7% (11/2)	8/7% (3/2)	0/0% (0/0)
DC.1	42/50% (167/100)	25% (34)	46% (66)	53% (25)	67% (24)	70% (7)
DC.2	31/37% (124/74)	35/35% (48/22)	31/34% (45/25)	28/36% (13/10)	19/33% (7/9)	10/0% (1/0)
DC.3	5/25% (21/50)	2% (3)	5% (7)	11% (5)	3% (1)	0% (0)
DC.4	23/20% (90/40)	18% (25)	21% (30)	32% (15)	22% (8)	30% (3)
DC.5	4/4% (15/7)	3% (4)	3% (5)	4% (2)	6% (2)	0% (0)
DC.6	38/39% (152/77)	26% (35)	41% (59)	40% (19)	47% (17)	90% (9)
DC.7	1/0% (2/0)	0% (0)	1% (1)	0% (0)	0% (0)	0% (0)

Table 5. Cont.

Defect Category	Total	RS.1	RS.2	RS.3	RS.4	RS.5
DC.8	17/17% (69/34)	14% (19)	20% (29)	15% (7)	14% (5)	30% (3)
DC.9	17/19% (66/37)	18% (24)	13% (19)	15% (7)	22% (8)	30% (3)
DC.10	8/10% (30/19)	2% (3)	6% (9)	13% (6)	14% (5)	30% (3)
DC.11	32/29% (126/58)	30% (41)	27% (39)	36% (17)	47% (17)	40% (4)
DC.12	18/20% (70/39)	9% (12)	19% (27)	26% (12)	22% (8)	50% (5)
DC.13	19/19% (76/38)	8% (11)	21% (30)	32% (15)	22% (8)	60% (6)
DC.14	6/6% (25/12)	5/6% (7/4)	6/4% (8/3)	17/11% (8/3)	0/7% (0/2)	0/0% (0/0)
DC.15	2/1% (8/2)	2/2% (3/1)	3/0% (4/0)	0/0% (0/0)	0/4% (0/1)	0/0% (0/0)
DC.16	1/0% (5/0)	1/0% (1/0)	2/0% (3/0)	2/0% (1/0)	0/0% (0/0)	0/0% (0/0)

With regard to the percentage distribution of deficiencies in terms of system size, the following aspects are striking:

- First, it can be noted that for most defects, the frequency of occurrence increased with increasing system size. According to the experts, the reason for this effect is that the probability of defects increases with an increasing number of system components. The corresponding distribution is shown in Figure 4. In the cases of the most-categorized fire alarm systems, with more than 500 detector groups, there were no test reports without noted defects. This distribution is almost congruent between the two samples examined and can, therefore, be well verified.
- The practical relevance of this result was also validated by the expert surveys. During the survey, 47 experts were asked whether they agreed with the following statement: “As the system size increases, the number of fire alarm systems without defects decreases, or as the system size increases, the percentage of systems with defects increases?”—The questionnaire asked for agreement from 1 (no agreement) to 5 (full agreement). The experts overwhelmingly agreed with this, with an average rating of 4.17.
- Contrary to this trend, there were defect categories whose probabilities of occurrence decreased to a greater or lesser extent with increasing system size. The corresponding trends are shown graphically in Figure 5. These specifically affected deficiencies were related to the technical documentation of the systems (DC.2), and others concerned the handling of fault messages (DC.14), the transmission of alarms (DC.15), and supplementary management functions (DC.16). According to the opinions of the experts, potential reasons for these effects are regarding the operating behavior of these systems. Fire alarm systems in the category RS.5 usually have professional operators or professional maintenance partners who provide additional technical care in the affected points—especially in the area of documentation. This effect can also be interpreted clearly from the figures. In total, 67% of the experts surveyed agreed with the mentioned trends and explanations while only 7% disagreed or could not confirm the trends out of their practical experience.

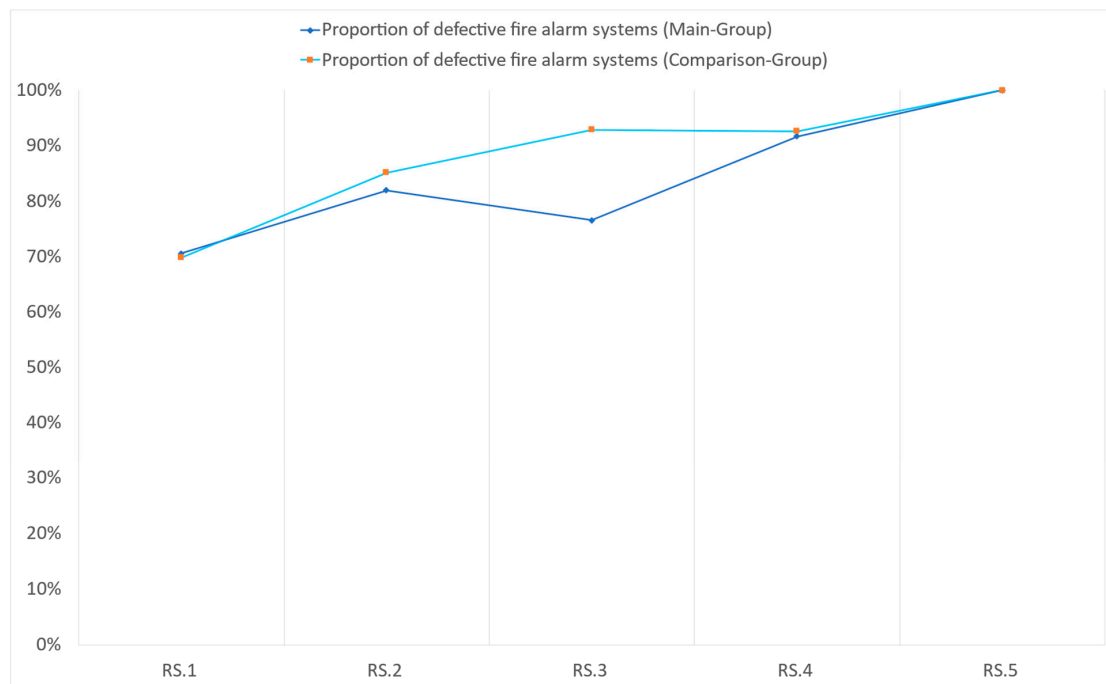


Figure 4. Comparison of the course of the percentage distribution of fire alarm systems without defects depending on the size of the system, evaluated separately for the main group and comparison group with good agreement and thus verification of the trend course.

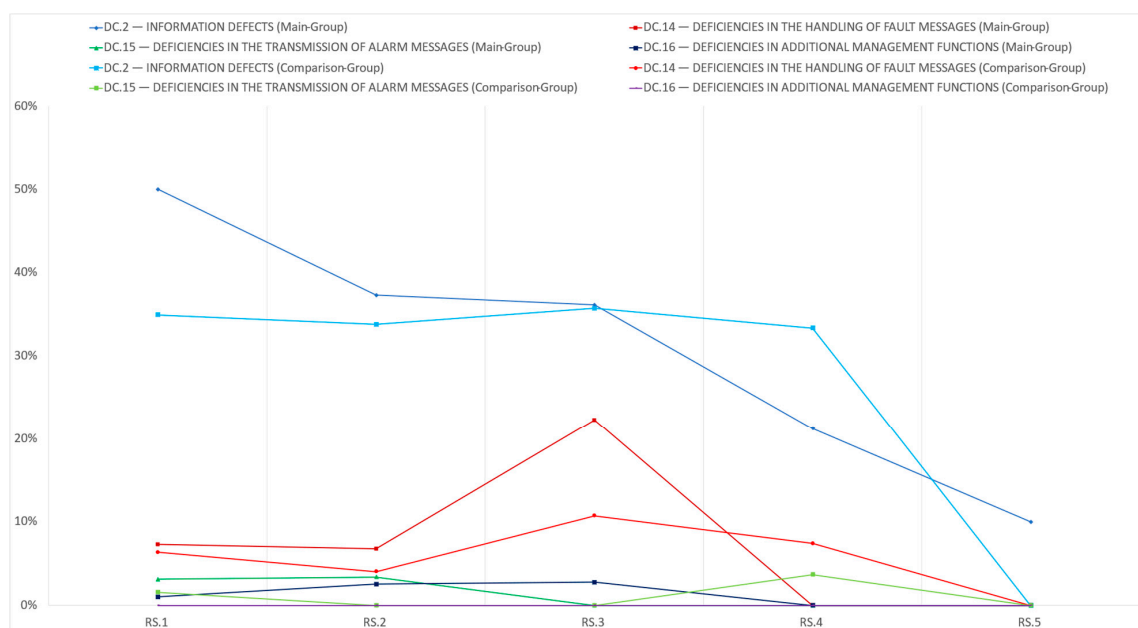


Figure 5. Percentage course of the frequency of occurrence of defects in the individual defect categories with a decreasing trend with increasing system size, separated into the evaluated main and comparison group, which provides a reliable verification of these trends.

4.4. Analysis of the Frequency of Deficiencies According to the Risk Factor “Environmental Conditions”

The final step of the statistical investigations considered how the frequency of occurrence of defects related to the operational environmental conditions of the individual fire alarm systems. For this purpose, three risk categories (risk of environment, RE) were assigned according to Table 6. The risk categories were formed qualitatively in relation to

the respective overall system. Due to the primary data available, it is not possible to define precise physical parameters as limits for the existing environmental conditions for each system. However, in terms of the research objective, this is not necessary, and a qualitative definition of the environmental conditions is sufficient with regard to recording trends in the frequency of occurrence of defects.

Table 6. Classification of fire alarm systems into risk categories of operational environmental conditions separately for the evaluated samples of the main group and the comparison group in accordance with the methodology described in Section 3 (in the following order: main group/comparison group).

Category	Designation/Explanation	Number of Systems in the Sample (Main Group/Comparison Group)
Total	All	400/200
RE.1	Low pollution/stress <i>This category describes environmental conditions that place only low loads on the technical components of the fire alarm systems, e.g., rooms and areas with relatively constant temperature curves, dry ambient conditions without condensing moisture, and very low levels of dust. Examples of such areas are clean rooms, hospitals, laboratories, etc.</i>	78/14
RE.2	Environmental conditions with normal pollution/average stress <i>This category describes normal environmental conditions that place normal loads on the technical components of the fire alarm systems. For example, such areas include offices, non-manufacturing businesses (retirement homes, care facilities), schools, etc.</i>	306/167
RE.3	Environmental conditions with increased pollution/raised stress <i>This category describes challenging environmental conditions that place high/higher loads on the technical components of the fire alarm systems, e.g., rooms and areas with strongly fluctuating temperatures, humid environmental conditions possibly with condensing moisture, and the presence of large quantities of dust and dirt. Examples of such areas are manufacturing businesses (carpentry, joinery, etc.) or industrial operations as well as commercial kitchens.</i>	16/19
N.D.	Systems without assignment	0/0

Again, from examining the distribution of the defects and considering the respective operational environmental conditions, a distribution according to Table 7 could be found. The table indicates the percentage of the tested installations in the risk categories related to environmental conditions (RE) with deficiencies in the various defect categories at the time of the test. Information on the distribution of defects from the comparison group is only included in relation to the overall distribution and the defect categories separately with a ‘/’, for which relevant trends could be identified in the main group and which should be verified in more detail according to the methodology described.

Regarding the percentage distribution of deficiencies according to operational environmental conditions, the following aspects are striking:

- Viewing this trend regarding the fault categories DC.5, DC.9, and DC.13, a significant increase in the frequency of faulty systems under increasingly demanding environmental conditions could be seen. This effect was particularly noticeable in the energy supply of the plants and the control of networked plants.
- In total, 55% of the experts surveyed confirmed this from their practical experience. According to the experts, this is due to the higher load on the components. In the area of automatic detectors, for example, this is due to contamination.
- According to experts, technical defects in the power supply are mainly caused by higher ambient temperatures and the associated failure of batteries in demanding ambient conditions. The increasing number in fire control is due to the fact that in

plants with more demanding environmental conditions—mostly industrial plants—there are also more subsequent controls, which also form a higher defect potential due to the higher number. The rising trends are shown in Figure 6. Although only a small majority of the experts confirmed the trends, they can still be similarly derived from the comparison sample which can be also seen in Figure 6 and thus verified as significant.

- Contrary to the previous findings, there were also areas in which the frequency of occurrence of defects decreased with more demanding environmental conditions. This observation applies to nontechnical deficiencies that influenced the operational tactics of the fire brigade (DC.1). The trend was also observed for defects in the cable system (DC.4) as part of the evaluation of the first random sample.
- This circumstance can, in turn, be explained by the installation regulations for fire alarm systems, in which, depending on the environmental conditions, higher requirements are placed on the laying of cables and wires. For example, higher-quality installation systems and types of cables, which are better protected against damage, are often used in such cases. The decreasing trends are shown in Figure 7. The diagram also shows that the evaluation of the comparative sample revealed that the trend for the defects in the cable system (DC.4) could not be verified. This is, therefore, more of a statistical fluctuation and not a relevant trend.
- As part of the survey to validate these results, 51% of the respondents were able to confirm that as environmental conditions become more demanding, the number of technically related defects in tests by experts increases, while the frequency of occurrence of non-technically related defects in the test reports examined decreases in roughly proportion to this.
- With regard to the increasing number of technical defects, the majority of the experts surveyed agree that this is due to the consumption of the wear reserve of the individual components or the higher stress on the components caused by the ambient conditions.
- The reasons for the declining frequency of non-technical defects in fire alarm systems operated under more demanding environmental conditions cannot be conclusively explained. This is also the reason why many (38% of the respondents) did not give an assessment of the practical relevance of the findings. One of the experts interviewed stated that the reason may also be the behavior of the experts when preparing the report. According to his estimation, the reason for the described trend is that insignificant, incidental defects are not included in the test reports due to the identified technical defects. The experts' mixed assessment here coincides with the weak confirmability of the trends in the second verification step.

Table 7. Frequencies of occurrence of defects in relation to the total number of defective fire alarm systems according to risk factors based on operational environmental conditions separately for the evaluated samples of the main group and the comparison group in accordance with the methodology described in Section 3 (in the following order: main group/comparison group).

Defect Category	Total	RE.1	RE.2	RE.3
NO DEFECTS	21/18% (84/36)	22% (17)	21% (63)	25% (4)
DC.1	42/50% (167/100)	52/71% (41/5)	40/48% (122/84)	25/42% (4/8)
DC.2	31/37% (124/74)	19% (15)	34% (104)	19% (3)
DC.3	5/25% (21/50)	5% (4)	5% (16)	0% (0)
DC.4	23/20% (90/40)	26/14% (20/1)	22/20% (68/34)	13/26% (2/5)

Table 7. Cont.

Defect Category	Total	RE.1	RE.2	RE.3
DC.5	4/4% (15/7)	4/0% (3/0)	4/2% (11/4)	6/16% (1/3)
DC.6	38/39% (152/77)	36% (28)	39% (120)	25% (4)
DC.7	1/0% (2/0)	3% (2)	0% (0)	0% (0)
DC.8	17/17% (69/34)	18% (14)	17% (53)	13% (2)
DC.9	17/19% (66/37)	10/14% (8/2)	18/18% (54/30)	25/26% (4/5)
DC.10	8/10% (30/19)	4% (3)	8% (26)	6% (1)
DC.11	32/29% (126/58)	33% (26)	31% (95)	31% (5)
DC.12	18/20% (70/39)	15% (12)	18% (54)	25% (4)
DC.13	19/19% (76/38)	15/14% (12/2)	19/21% (59/35)	31/32% (5/6)
DC.14	6/6% (25/12)	4% (3)	7% (22)	0% (0)
DC.15	2/1% (8/2)	1% (1)	2% (7)	0% (0)
DC.16	1/0% (5/0)	0% (0)	2% (5)	0% (0)

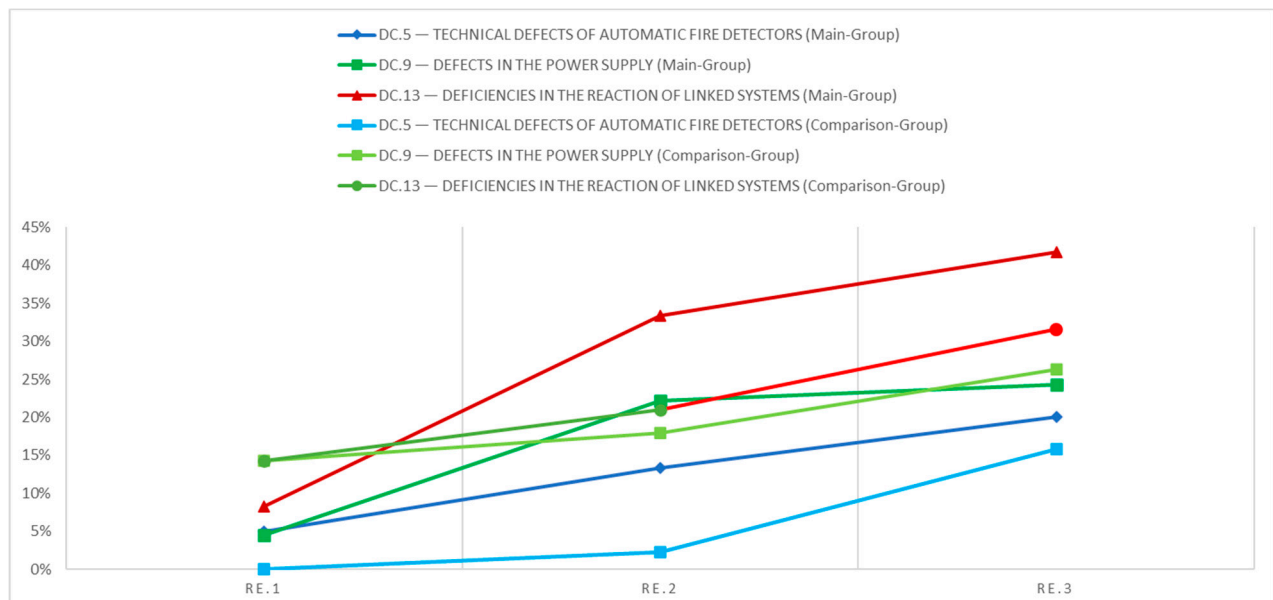


Figure 6. Trends of the error categories DC.5, DC.9, and DC.13 with increasing probability of occurrence under increasingly demanding environmental conditions shown separately in the evaluation of the main and comparison groups to verify the results.

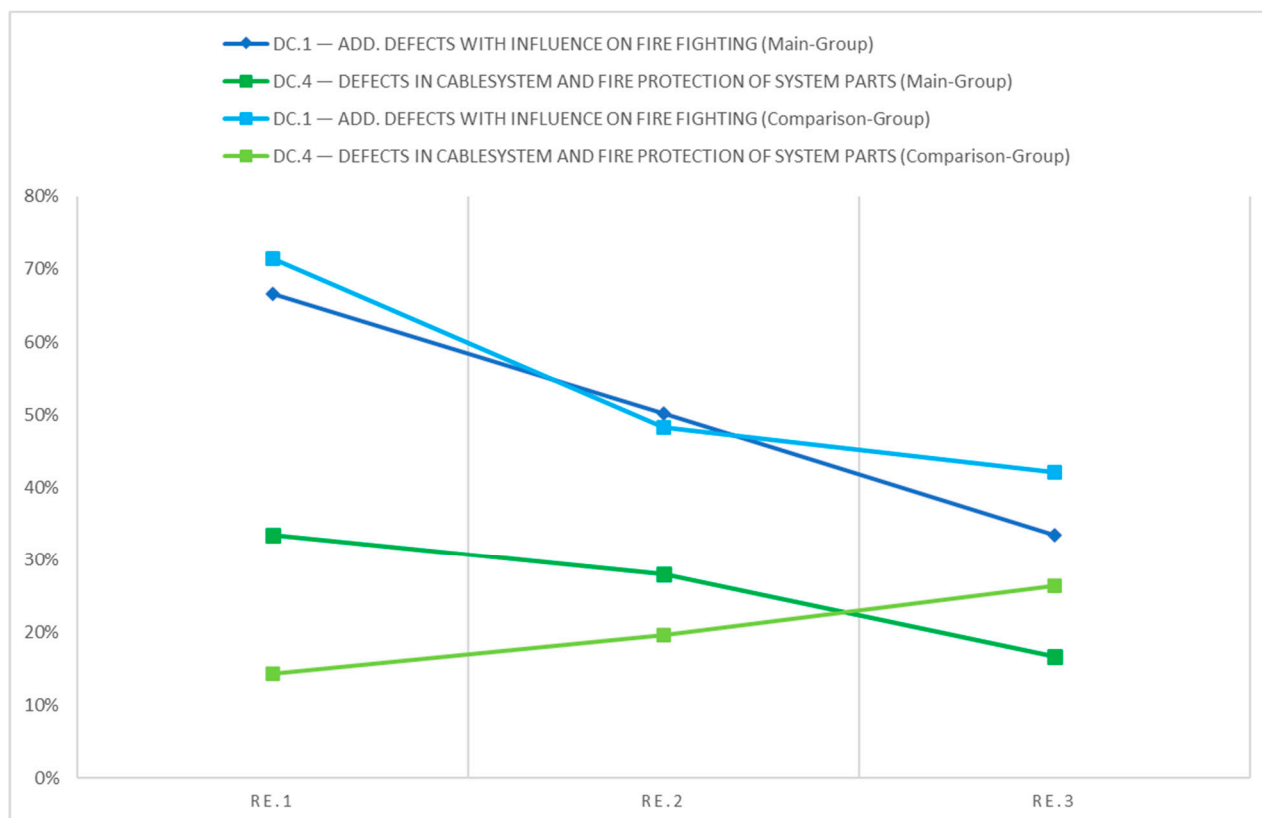


Figure 7. Trend of error categories DC.1 and DC.4 with decreasing probability of occurrence under increasingly demanding environmental conditions shown separately for the evaluation of the main and comparison group with significant deviations in error group DC.4.

5. Discussion

The presented results analyze and highlight trends in the occurrence of defects in fire alarm systems under risk-based influencing factors. In order to be able to assess the results in terms of their relevance to the subject area, three aspects must be discussed. Firstly, the statistical significance of the results—particularly with regard to whether the knowledge gained from the methodology used on the trend behavior of the frequency of defects can be applied to a larger number of systems or generalized. The second point that needs to be discussed is the influence of the results on the inspection and maintenance of fire alarm systems. Finally, it must be assessed whether the data can form a basis for the further development of risk-based maintenance and servicing approaches. In the following, the results are discussed in accordance with the research questions posed at the beginning of this article as a possible basis and with regard to their relevance for the further investigation of risk-based maintenance and repair approaches.

1. The first point of discussion is the statistical significance of the data obtained. In the authors' view, the three-stage exploratory research design ensures high data quality, including the applicability of the trends in the occurrence of defects confirmed by both review steps according to the influencing factors investigated. In detail, the following assessments arise regarding the relevance of the respective results:
 - a. The comparison of the general occurrence of deficiencies between the evaluated main and comparison groups showed a very good match both in the overall distribution of deficient systems (79% in the main group, 82% in the comparison group) and in relation to the distribution of deficiencies to the respective deficiency categories indicated in Section 4. This shows that the distribution of the deficiencies across the individual categories identified in the course of the

work—also confirmed by the evaluation of the expert surveys—is statistically significant and can also be applied to larger samples.

- b. Trends in the frequency of defects were identified in all evaluated risk categories with regard to age, system size, and environmental conditions. With the exception of the trends in Figure 7 (defect category DC.4 under the influence of environmental conditions), these could be verified in each case by the expert surveys and the second verification step carried out in the evaluation of the second sample. This confirmation means that the trends can be assumed to be statistically significant and, therefore, applicable to a larger sample.
 - c. The evaluation of the individual results has shown that the presence of a small number of systems in the individual risk categories quickly leads to larger percentage deviations with regard to the absolute values of the defect occurrence frequency. However, the trend curve shows that the trends can be mapped correctly and significantly even with a small number of systems. It can be seen from this that, as a result of the study, it is primarily the recognized trends that can be used as a statistically significant result. The figures for the individual percentage distributions may well differ in other samples but do not indicate any of the main results of this study.
2. The second section of the required discussion of the results is the influence of the results on the risk-oriented maintenance of fire alarm systems presented in the introduction to this document. While this study does not propose a complete risk-based inspection methodology, the knowledge gained has provided the following insights for the future predictive maintenance and testing of fire alarm systems:
 - a. Detectors and functional testing: For state-of-the-art fire alarm systems equipped with ring bus technology and modern detectors, functional testing of detectors plays a secondary role, as the study shows a consistently low occurrence of technical defects in both automatic and manual detectors. This suggests that the current test cycle for functional testing of detectors can be extended, and the depth of random sample inspections significantly reduced. This finding does not aim to suggest a comprehensive overhaul of the system but highlights where resources can be optimized based on the identified trends. This finding is supported by the deficiency distribution data presented in Table 2, showing minimal defects in this area.
 - b. Cable and wire systems: The study reveals that defects in the cable and wire systems are most prevalent during the early years of system operation, particularly in the first inspection cycle (within 3 years of installation). Therefore, the depth of testing during initial inspections should be increased to address these early defects effectively. Trends identified in Figure 3, verified by expert interviews, highlight the importance of focusing maintenance efforts on the cable and wire systems during this critical early phase to prevent long-term operational issues. A practical recommendation is to allocate more attention to this during the early operational stages.
 - c. Alarm devices: As systems age, particularly after 10 years of operation, the study shows a significant rise in defects in alarm devices, particularly acoustic signals. Therefore, inspection intensity for these components must increase with system age, with comprehensive inspections recommended no later than 10 years into the system's operational life. This pattern is evident in Figure 3 and was confirmed by experts, indicating that prioritizing alarm device inspections in older systems can prevent critical failures. This is a direct proposal for optimizing inspections in older systems based on the study results.
 - d. Environmental conditions and detector contamination: In environments with high levels of dust, humidity, or other stress factors, the study highlights an increased risk of detector contamination, particularly affecting automatic detectors. This trend, illustrated in Figure 6, suggests that in such demanding

environments, more frequent and thorough functional tests of detectors are essential. The need for more frequent inspections under these conditions is not only supported by the data but also by expert feedback. Detectors in such environments face higher stress, justifying more rigorous maintenance practices to ensure system reliability. Specific environments need tailored inspection strategies as outlined here.

- e. Control functions and networked systems: Systems with networked or network-controlled components exhibited a consistently high rate of deficiencies, particularly in environments with harsh conditions. Given the complexity and criticality of these systems, maintenance strategies should incorporate more frequent cross-system functional tests. Additionally, maintenance plans must include provisions for cross-system components to address the high rate of deficiencies noted. The results of this study, as shown in Table 2, suggest that these faults are often difficult to detect and diagnose during routine maintenance, further underscoring the need for enhanced inspection protocols in networked systems. Similar patterns have been observed in other technical fields, highlighting the complexity of such systems [31,32]. This is another key takeaway for system optimization rather than a complete system redesign.

The findings of this statistical study demonstrate that risk factors can be identified to guide maintenance measures and testing of fire alarm systems in a risk-oriented manner, aligned with an RBI approach and dependent on specific system parameters. These results provide a robust data foundation for further research in this area. Moreover, the study emphasizes that while it establishes important groundwork, further investigations into external risk factors influencing fire alarm systems are necessary to fully develop and optimize a comprehensive risk-based maintenance strategy.

6. Conclusions

This paper has presented a statistical evaluation of the deficiencies occurring during the practical operation of fire alarm systems. The analysis largely focused on the frequency with which defects in various categories—formed by system assemblies—were detected during inspections by technical experts.

The study focused on identifying statistically relevant trends from the examined sample and verifying these trends using suitable methods for potential application in a significantly larger sample. The chosen three-stage exploratory research design, combined with verification through standardized expert surveys and a second, smaller sample, made this possible.

Based on the findings, three main conclusions can be drawn in relation to the risk-factors system age, size, and environmental conditions:

System age: One significant outcome is that technical faults in both automatic and manual detectors occur very rarely across all systems. However, when considering system age as a risk factor, defects in alarm devices—particularly acoustic signals—become increasingly significant in older systems. Defects in the cable system, on the other hand, are more common in newly installed systems. These findings highlight the need for more frequent inspections of older systems, especially after 10 years of operation, to prevent increased failures in alarm devices.

System size: As expected, the general frequency of defects increases with system size. However, larger systems tend to have fewer deficiencies related to system documentation and fault messaging, suggesting better operational control in such systems. This indicates that while larger systems may experience more frequent defects overall, their operational robustness mitigates some issues, particularly related to communication and documentation.

Environmental conditions: The influence of environmental conditions was also significant. Systems operating in more demanding environments, such as those with high levels of contamination or humidity, showed an increased frequency of defects in power supplies,

automatic detectors, and networked fire control systems. These findings underscore the need for targeted maintenance strategies that take environmental conditions into account, with particular attention to functional tests for detectors in challenging environments.

Overall, this study establishes a data-driven foundation for improving inspection and maintenance strategies for fire alarm systems by identifying key trends in defect occurrence under critical risk factors such as system age, size, and environmental conditions. Supported by a rigorous methodology, including a three-stage exploratory research design and expert surveys, the findings offer practical insights for refining existing practices. These include the need for more frequent inspections of older systems and those operating in demanding environments. While the study suggests adjustments to current maintenance strategies, it primarily provides a basis for future research to develop a more comprehensive, risk-oriented maintenance approach.

The insights gained from this study emphasize system age, system size, and environmental conditions as the most influential risk factors impacting defect trends. Specifically, the results highlight the value of increasing inspection frequencies for older systems and those in harsh environments, alongside targeted assessments of larger, complex systems. These findings lay a solid foundation for implementing a risk-based inspection (RBI) approach by helping prioritize inspection efforts and optimize maintenance resources. By integrating these risk factors into RBI strategies, the study contributes to more reliable and cost-effective fire alarm system management and provides a pathway for developing data-informed maintenance protocols that meet the unique demands of practical applications.

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