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Analysis of safety systems:
Methodology and data for risk quantification in organizational, technical and structural systems with focus on fire protection

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Problems can never be solved
with the same way
of thinking that created them

Albert Einstein

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Abstract

How effective is fire protection? To be able to answer this question regardless of location, this thesis aims to define methodologies to determine the best ratio between the financial resources used and the increase in safety for the overall system.

Preventive fire protection consists of three parts: Organizational, technical and structural systems, each of which provides protection for building occupants and property, as well as, effective extinguishing measures.

In organizational fire protection, preventive complex trains of thought are described, which must be called upon in a targeted manner in the event of a fire. The most common displays of those trains of thought are in text, algorithm or image format. In this thesis, these formats are examined for their reliability via experiments with test persons in the environment of a flight simulator. The goal is to identify and therefore reduce the number of errors which can occur in the transmission of information between two or more people. This enables the definition of evidence-based action instructions in fire protection and moreover increase their efficiency. Additionally, applications of this information, especially arise in rare situations with regard to defensive and organizational fire protection, so that processes are implemented and actions are able to be carried out effectively in the event of an emergency as well.

Technical fire protection combines technical measures for fire detection and fire fighting. Fault tree analysis (FTA) offers the possibility to display the reliability of a system comprehensibly and is able to evaluate influencing factors. In this thesis, algorithms for the quality of the results and the corresponding calculation methods are developed. The informative value regarding the implementation of improvement measures for an FTA is increased by factors such as multiple redundancies, maximum technical feasibility of redundancies and costs for redundancies. In addition, a dynamic FTA is developed to include component aging as well. This is based on characteristic values for the reliability of individual components, which are also presented in a collection of the 150 most important failure probabilities in fire protection.

In order to evaluate the effectiveness of measures taken in structural fire protection and also in fire protection concepts, real fires, fire inspections and the structure of defensive fire protection must be analyzed. In this thesis, a pattern recognition of correlations by means of artificial intelligence is applied to the example of the protection goal “the safety of occupants”. For this purpose, an algorithm for the classification of the EU fire protection law for fire inspections is developed. In addition, the influencing factors on real fires are now able to be examined and standardized. Furthermore, the work describes all currently identified influencing factors in order to be able to perform pattern recognition through the methodology of AI.

As a result, this work contributes significantly to quantify the effectiveness of preventive and defensive fire protection independent of location.

Zusammenfassung

Wie effektiv ist der Brandschutz? Um diese Frage ortsunabhängig zu beantworten, definiert die vorliegende Arbeit Methodiken, die das beste Verhältnis zwischen den eingesetzten finanziellen Mitteln und dem Zuwachs an Sicherheit für das Gesamtsystem bestimmen (Best-Performance-Ratio). Der vorbeugende Brandschutz besteht aus drei Teilen: Organisatorische- anlagentechnische- und bauliche Maßnahmen, welche jeweils den Schutz der Gebäudenutzer, der Einsatzkräfte und Sachwerte sowie wirksame Löschmaßnahmen ermöglichen.

Im organisatorischen Brandschutz werden präventive komplexe Gedankengänge beschrieben, welche im Brandfall zielgerichtet abgerufen werden müssen. Die häufigsten Darstellungsformen der Gedankengänge sind in Text-, Algorithmus- oder Bildform. Diese werden durch Experimente in der Umgebung eines Flugsimulators mit Probanden auf ihre Zuverlässigkeit untersucht. Ziel ist die Reduzierung von Fehlern in der Übertragung von Gedankengängen zwischen Personen. Das ermöglicht die Definition von evidenzbasierten Handlungsanweisungen im Brandschutz. Anwendungen ergeben sich speziell im abwehrenden und organisatorischen Brandschutz bei seltenen Einsatzlagen, um auch hier effektiv handeln zu können.

Der anlagentechnische Brandschutz vereinigt technische Maßnahmen zur Branddetektion und Brandbekämpfung. Die Fehlerbaumanalyse bietet die Möglichkeit, die Zuverlässigkeit des Systems nachvollziehbar darzustellen und Einflussfaktoren zu bewerten. In dieser Arbeit werden Algorithmen für die Qualität der Ergebnisse und die dazugehörigen Berechnungsmethoden erarbeitet. Die Aussagekraft bezüglich der Umsetzung von Verbesserungsmaßnahmen der Fehlerbaumanalyse wird durch Faktoren wie Mehrfachredundanzen, maximal technische Umsetzbarkeit der Redundanzen und Kosten für Redundanzen erhöht. Darüber hinaus wird eine dynamische Fehlerbaumanalyse entwickelt, um die Alterung von Komponenten ebenfalls miteinzubeziehen. Die Grundlage bilden Kennwerte zur Zuverlässigkeit einzelner Komponenten, die ebenfalls als Sammlung der 150 wichtigsten Versagenswahrscheinlichkeiten im Brandschutz darstellen.

Um im baulichen Brandschutz die Wirksamkeit ergriffener Maßnahmen beurteilen zu können, müssen Brandschutzkonzepte, reale Brände, Feuerbeschauen und die Struktur des abwehrenden Brandschutzes miteinbezogen werden. Es wird in dieser Arbeit eine Mustererkennung von Zusammenhängen mittels Künstlicher Intelligenz am Beispiel des Schutzziels der Sicherheit der Gebäudenutzer angewendet. Hierzu ist speziell für diesen Zweck ein Algorithmus zur Gliederung des EU-Brandschutzrechtes für die Feuerbeschau entwickelt worden. Zudem können nun Einflussfaktoren realer Brände standardisiert werden. Ebenfalls beschreibt die Arbeit alle Einflussfaktoren, um durch die Methodik der KI eine Mustererkennung durchführen zu können.

Im Ergebnis trägt diese Arbeit maßgeblich dazu bei, die Effektivität des vorbeugenden und abwehrenden Brandschutzes ortsunabhängig zu quantifizieren.

List of Abbrevations

AGL	Above Ground Level
AI	Artificial Intelligence
ALARA	As low as reasonably achievable
ALARP	As low as reasonably practicable
APR	Approach Button
DBC	Descriptive Based Code
DFT	Dynamic Fault Tree
DFTA	Dynamic Fault Tree Analysis
DIN	Deutsches Institut für Normung (Eng. German Institute for Standardization)
DL	Deep Learning
EP	Esary-Proschan
EU	European Union
FSD	Institute of Flight System Dynamics
FTA	Fault Tree Analysis
HDG	Heading
HEP	Human Error Probability
HFE	Human Factors Engineering
MC	Monte Carlo
ML	Machine Learning
MOB	Multiple Occurring Branch
MOE	Multiple Occurring Event
MTBF	Main Time Before Failure
NM	Nautical miles
PBC	Performance-Based Code
PSF	Performance Shaping Factor
PYLL	Potential Years of Life Lost
RAMS	Reliability Availability Maintainability Safety
SPD	Speed Control
TBE	Technical Building Equipment
TFTA	Temporary Fault Tree Analysis
TUM	Technical University of Munich
USA	United States of America

Variable directory

Variable	Description
$C(E)$	Cost of a redundancy in a primary event E
$c(E)$	Consequence of an event E
E_d	Load factor value for the destabilizing effect
ϕ	Arithmetic mean of complete population
H_0	Null hypotheses
H_1	Alternative hypotheses
Hz	Frequency $1Hz = 1\frac{1}{s}$
$I(c)$	The costs of the consequence
$I(o)$	The cost of the risk
η	Effect strength of ANOVA test
k	Number of independent events
kt	Knots
$M(G)d$	Possible multiple redundancies of G gates
$M(R)$	Approximate real risk of $R(E)$
μ	Mean of the result from a sample
μ_0	General population mean
μ_x	Statistical mean of the introduction form of x
N	Number of times
n	Number of repeated experiments
$p(E)$	Probability of an event E
$\bar{p}(E)$	Nonoccurrence of probability of an event E
$\mathcal{Q}$	Quartiles
R_d	Load factor value for the stabilizing effect
$R(p)$	Reliability of the probability p
$r(E)$	Risk of an event E
S_d	Safety factor for the destabilizing effect
$S(p)$	Safety of the probability p
σ	Standard deviation
σ^2	Variance
$T(E)d$	Technical redundancy of a technical element E
$t(E)$	Real true probability of an event E
θ	Threshold element
t	Time
x	Independent variable
$\bar{x}$	Arithmetic mean of x
y	Dependent variable

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Chapter 1

Introduction to basic methods and term definition

The requirements in fire protection are constantly increasing, but the deaths related to fire protection have been studied over recent years. The current approximate amount of 400 fire deaths per year in Germany are a politically acceptable residual risk. However, due to the ever increasing fire protection costs, questions have to be asked about the efficiency of the current measures. This thesis presents possibilities for the risk assessment of special buildings and gives possibilities for quantifying the risk.

Requirements for engineering are becoming more complex because machines have to take on a growing variety of tasks. At the same time, the failure probabilities must be kept as low as possible, so that the question of improvements within the system must be made in order to maintain its profitability. From these two factors (increase reliability and reduce costs) comes the question: "What do I have to change to improve the system in general?" Depending on the subject, most methods are quite dated and in other areas a standard does not exist. For example, existing global standards to calculate the failure probabilities of nuclear reactors [Fac15, Int08a] versus each state creates its own safety standards in fire protection [PMV10, Bau12].

This thesis describes a variety of options for risk quantification, new standard methods and practical application of new knowledge and outcomes. The predominant part consists of the description of new methodological approaches and the merging and combination of previous scientific methods established by other scientists. For this reason, a brief introduction to the scientific knowledge theory follows. The goal of forecasting is to predict reality as much as possible. However, a forecast is always situated in the future, the forecast is also combined with an amount of uncertainty. The associated scientific theory began in the distant past, all the way back in the 4th century BC with Aristotle's book ANALYTICA POSTERIORA [Det14]. Various other philosophers and scholars such as Descartes, Bacon, Galilei and Popper, honed and continuously improved the scientific methods. A main reason for the steady increase in developments was the advancement of scientific method. The main focus is on scientific theory with new methods of answering questions [IL74]. Empirical methods have different functions. The three most important functions are the descriptive function, the explanatory function and the forecast function. In order to fulfill the functions you need all of the prerequisites. The prerequisites must be described precisely, suitable hypotheses must be generated and the hypotheses must also be verifiable [LS05]. The interplay between ever new theories and empirical investigation is the real subject of science. There are the four steps in the classical empirical methods,which are [Wil18]:

1. *Data collection*: There are classical methods for data collection for example, to collect information via questionnaires, experiments, measurements or tests. Therefore, the two different parts are split into firstly, the test setting in laboratory investigation in an artificial environment and secondly, field investigations in a real environment. The methods to collect data vary depending on the research in different subject areas. In mathematics, computer science, nature and technical the quantitative approach is most often used, but in the humanities the qualitative approach is often followed. Behind these different methodological approaches completely different motivations exist. Questions such as: "Is human behavior quantifiable, predictable or at all predictable?" What constitutes dependent or independent data? What is the dependent or independent data? These are all questions that should have already been answered before data collection begins.

2. *Data evaluation*: In general, data is evaluated using descriptive statistical methods. The raw data obtained from the data collection is processed and standardized. Since the results are usually diverse and individual, a large data set is described in more detail using statistical parameters. Typical calculation methods are the frequency distribution, average, range, variance and so on [NP28]. The methods differ in the different scale levels, which are discussed in more detail within this thesis.

3. *Hypothesis generation*: The data evaluation is the basis for the hypothesis determination. By analyzing the data from a selected sample, conclusions can be drawn about the whole group. This is defined as induction and the deduction bases conclusions on the whole group of a specific case. This can be done by using classical statistics with a regression model, cluster analyses and similar methods. This is where probability theory comes into play. It indicates the probability with which a result can be wrong and the statement made can be made as non-transferable to the whole. The aim is to differentiate the alternative hypotheses H_1 and the null hypothesis H_0. In statistics the null hypotheses focus on the probability distribution of multiple random variables. The alternative hypotheses also provide a quantity of alternative conditions differing from the null hypothesis. To verify the hypothesis it needs to be operationalized in a correct form [Fis25].

4. *Hypothesis testing*: Scientific methods must be empirically testable. For this procedure, remove a random part of the whole sample, to check the created hypotheses. The general population mean is defined as μ_0 and the mean of the sample of results is μ. Now, there are three different types of hypotheses pairs in case of the means:

$$H_0 : \mu = \mu_0 \ vs. \ H_1 : \mu > \mu_0 \tag{1.1}$$

$$H_0 : \mu = \mu_0 \ vs. \ H_1 : \mu < \mu_0 \tag{1.2}$$

$$H_0 : \mu = \mu_0 \ vs. \ H_1 : \mu \neq \mu_0 \tag{1.3}$$

   The significance level tells you how certain you are that the hypothesis is fulfilled or rejected by the information given from the sample [Cow89]. This is the level of significance α.

To describe facts, every proposition is considered to be only true or false [BSMM15]. Here there are only two possible answers. In other logical systems like Fuzzy, there are extended outputs of true and false. In this system pattern recognition occurs for the precise detection of the imprecise [KBB+15].

1.1 Influence values for risk calculation

Theoretically, risk is defined by the probability of occurrence and the corresponding consequence. In case of fire protection, the likelihood of the origin of a fire or the probability of the failure of preventive measures and therefore the consequence is the spread of a fire or the expected damage plus the measures to prevent or stop the fire. To calculate the risk, two general values need to be input. The first one is the probability of an event $p(E)$ and the second is consequence of this event $c(E)$. The combination of the two influences are the total risk of an event $r(E)$ with:

$$r(E) = p(E) * c(E) \tag{1.4}$$

Since both input variables of the risk are described as well as possible in an mathematical way, the true risk of an event $t(E)$ is approximate to the calculated risk $r(E)$. The distinction is particularly important in technical systems, which can be extensively damaged in the event of an emergency. It is impossible to really define all the influencing factors. Thus, the mathematical approach of risk $r(E)$ is always an attempt to describe the true risk $t(R)$. Thus, it can be stated that:

$$r(E) \approx t(E) \tag{1.5}$$

A simple example in fire protection, is the calculation for the complete loss of a building. Assuming that the probability for a fire event is .02 per year and the costs for recycling, planning and construction of the new building are 50 Mio. €, then it is possible to calculate the risk per year with:

$$r(E)_{year} = p(E) * c(E) = .02 * 50\ Mio.€ = 1\ Mio.€ \tag{1.6}$$

That is a simple example, but normally it is not so easy to define the probability and the consequence of an event. The probability of an event $p(E)$ is defined with [Arn06]:

$$p(E) = \lim_{x \to \infty} \frac{N}{n} \tag{1.7}$$

Here, N is the number of times event E occurs in the n repeated experiments. The probability of occurrence of an event E is always between 0 and 1 with:

$$0 \leq p(E) \leq 1 \tag{1.8}$$

By definition, the sum of the probability of occurrence p and nonoccurrence $\bar{p}$ always 1 for an event E. Therefore:

$$p(E) + \bar{p}(E) = 1 \tag{1.9}$$

As further influencing factors on the probability p, the combination and permutation of events need to be considered. The probability of the union of k-independent events is [Dhi18]:

$$p(E_1 + E_2 + ... + E_k) = 1 - \prod_{i=1}^{k} [1 - p(E_i)] \tag{1.10}$$

With the probability of an event $p(E)$ is the probability of occurrence of an event E_i for $i = 1, 2, 3, ..., k$. The probability of the union of k mutually exclusive events is [Dhi18]:

$$p(E_1 + E_2 + ... + E_k) = \sum_{i=1}^{k} p(E_i) \tag{1.11}$$

The last important formula is the probability of an interaction of k-independent events with:

$$p(E_1 E_2 ... E_k) = p(E_1) p(E_2) ... p(E_k) \tag{1.12}$$

Since these mathematical methods are an essential basis for calculating the risk in this thesis, another short example follows. A typical application in fire protection or in nuclear power plants is the combination of probability of an Event occurring in different systems. So, there is now a subsystem $p_1(E)$ and a subsystem $p_2(E)$ each with different occurrence probabilities:

$$p_1(E) = .005 \tag{1.13}$$
$$p_2(E) = .016 \tag{1.14}$$

The aim is to calculate the failure probability of the complete system c:

$$c(p_1 + p_2) = 1 - \prod_{i=1}^{k} [1 - p(E_i)] \tag{1.15}$$
$$= p_1 + p_2 - p_1 p_2 \tag{1.16}$$
$$= .005 + .016 - (.005)(.016) \tag{1.17}$$
$$= .02092 \tag{1.18}$$

It is therefore clear that all possible outcomes of a fire protection system in their entirety always show the combination of all possible variables. These general risk rules apply to all scientific fields. In technical systems, for example fire protection engineering, the focus is on the probability of an event $p(E)$.

1.2 Three possible ways to calculate risk

The possibility of calculating the failure rate of a complex system began in the 80s at the ETH Zurich (Switzerland) [Sch91]. Although the mathematical foundations had long been available, the exact calculation required the help of computers [Key21]. Today, there are a variety of different methods to calculate the risk [Mos19]. The two most important ways are classical statistics and the Bayesian networks. Both ways are based on probability calculation, however with the term probability, both understand something different from each other. Classical statistics is used for estimating parameters and for testing hypotheses only on a sample (see subsection 1.2.1 for further information). The Bayesian network uses additional information about what is known or assumed about the problem (see subsection 1.2.2 for further information). The two different methods, thus, have different approaches, which means probability is calculated differently. The classical statistical method means a relative frequency in a random experiment, while the Bayes theory means an expression of knowledge [Tsc14]. A further important term is uncertainty. Here two different forms exist, as well. They are:

1. Aleatory
2. Epistemic

Type of Risk	Annual risk of death	Annual odds of death
Smoking a pack a day	$3.6 * 10^{-3}$	1 in 278
Himalayan mountaineering	$2.8 * 10^{-3}$	1 in 356
Cancer (all types)	$2.6 * 10^{-3}$	1 in 387
Motor vehicle accidents	$6.0 * 10^{-4}$	1 in 1,667
Killed in a military war	$2.4 * 10^{-4}$	1 in 4,167
Homicide	$1.8 * 10^{-3}$	1 in 5,556
Air travel	$7.0 * 10^{-5}$	1 in 14,286
Flood	$1.0 * 10^{-5}$	1 in 100,000
Tornadoes	$4.0 * 10^{-6}$	1 in 250,000
Hurricanes	$4.0 * 10^{-7}$	1 in 2,500,000

Table 1.1: A risk comparison divided by the type of risk, annual risk of death per year and the annual odds of death (based on data from the USA) [Mos19].

The first, describes the aleatory uncertainty, with the root "alea" derived from the Latin for rolling of dice, is the inherent or natural randomness. The second form of uncertainty is the epistemic. This form describes the uncertainty that stems from the lack of data, measurement error, improper mathematical modeling, or missing explanatory variables [Mos19]. Table 1.1 shows various typical risks in daily life to exhibit an example of this form.

A further important term to describe the input values of risk are the MTBF. This is the mean probability of failure in a life time between two single failures of an technical system [Int15]. The unit of MTBF is a time frame or period, usually expressed in hours or years. The larger the numerical value, the more reliable the system described is. The mathematical calculation used is the probability density $f(t)$ of the time to failure [Dre60]:

$$MTBF = \frac{\sum(start\ of\ downtime - start\ of\ uptime)}{number\ of\ failures} \tag{1.19}$$

$$= \int_t^\infty f(t)dt \tag{1.20}$$

An additional important term in the scientific field of risk engineering is the potential of death and years of lost life Potential Years of Life Lost (PYLL). The PYLL is an indicator of premature mortality. This number is called the total years that are not lived by an individual, for example, a person who dies before the age of 75 [GS90, BJB$^+$05].

Generally, there is a huge number of different approaches in the area of risk quantification. Depending on the area of application (chemical industries, nuclear power plants, ...), there are fixed sets of regulations. In other areas of application (i. e. fire protection), there are almost no engineering approaches that deal with risk quantification. A short overview of the most important mathematical and methodical approaches is given in table 1.2. The theoretical approach is always mentioned and it's relevant fixed regulation, if one exists.

There are a multitude of different ways to calculate risk. Standard, Bayes and machine learning tools assume that it is possible to calculate generality from a sample. Therefore, the

Theoretical approach	Regulation	Method	Describing	Literature
Bayesian network	-	1	1	[Tsc14]
Event Tree Analysis (ETA)	DIN 25419	0	1	[Deu85]
Failure mode and effects analysis	IEC 60812	0	1	[Wer12]
Fault Tree Analysis (FTA)	IEC 61025	1	1	[Int08b]
Monte Carlo simulation (MCS)	VDI 4008-6	1	0	[Gla03]
Markov chain (MC)	IEC 61165	1	1	[Yev15]
Hazard and operability study	IEC 61882	1	0	[Deu16c]
Structure flow chart	-	0	1	[Sei15]
State diagram	-	0	1	[Har87]

Table 1.2: The table shows an overview of the variety of different theoretical practices. Each rule is briefly shown, as to whether it is a pure method or a description including the corresponding regulations.

different methods are compared, statistical terms defined and then shown by an example. Descriptive statistics means that there is a data set with a multitude of single values and the whole data set is described with location parameters. Although, not all single values are examined, only a small part of them. Here, the inferential statistic is needed to form a small group that allows conclusions to be applied to the whole group. Of course, the conclusions are never exact, because it is possible that the sample is atypical of the whole. In this thesis, methods are developed, implemented and evaluated to find weaknesses in fire protection. The three methods (classical statistics, Bayes Theory and machine learning tools) for proving correlations and predictions are briefly outlined below, in order to subsequently explain the structure of the thesis in section 1.6.

In the 18th century, *Sir John Sinclair* was the first scientist who presented the first methods to statistically analyze data sets with classical statistical tools in his book "Statistical Account of Scotland". During the same period, the second variant of statistical analysis after *Thomas Bayes* was introduced into science [Bay63].

Developments in the areas of Artificial Intelligence (AI) and ML have increased significantly in the last few years. The fundament of this new scientific field was an article written by *Alan Turning* in 1950 [Tur50b]. Following this article various different forms of AI have been developed. The most important methods are the ML of the 20th century by *Arthur Samuel* [Sam59].

The classical standard statistical methodology is mostly used in human, social and economic analysis [BS10, Wei13, SL14]. Competing with this, the Bayesian methodology is very common in technology science [Bol07]. In the areas of electronic and information science, machine learning methods are often used for prediction purposes [KBB+15]. Depending on how the studies are viewed, there are also different opinions on the methodological approach. So, very different conclusions can be made on the same data set. As an example, examining the treatment outcomes of lung cancer patients with the help of radiation therapy can give different statements about healing charts by using the Bayes versus ML method [JFY+10].

On the other hand, there are equally competing opinions. As already described, there are now various possibilities to make predictions from an existing data set for the future with different methodology's (classical statistics vs. Bayes theory vs. ML tools). In science, there are always different opinions on how a statement is made with regard to the methodology used. As one of the most famous arguments about the two methods and highlighting the differences between classical methodology in comparison to Bayesian theory, is the calculation of children deaths in a clinic by *Ignaz Semmelweis* [Sem62]. In this case, the aim was to prove which influencing factor effects the overall result and whether ignorance of other influences should be considered. The following is a brief introduction to the three methods (classical statistics, Bayesian theory and machine learning tools) including the main differences. For example, how they have been used to analyze the most famous problems in statistics in past [Tsc14]:

- The *Semmelweis* studies on childbed fever from 1847 [Sem62]
- The *Millikans* physics elementary charge measurement from 1913 [Mil13]
- The *Miligram* experiment on obedience from 1974 [Mil63]
- The *Jayasurya* radio therapy calculation from 2010 [JFY+10]

1.2.1 The classical statistical method

The classical inferential statistics is only used on a sample to estimate parameters and test hypotheses on a larger group [JWHT17]. The aim is with the application of scientific tools to obtain objective conclusions for their usefulness to form hypotheses based on usability. In general, they are based on information and observations, the generality is inferred and and conclusions drawn create hypotheses. Closing statistics, like mean, variances, range, etc. are used for a clearer overview of large amounts of data and the inference statistics enable hypotheses to be stated about the population. Typical population statistics are:

$$Arithmetic\ mean = \bar{x} = \frac{1}{n}\sum\nolimits_{i=1}^{n} \tag{1.21}$$

$$Variance = \sigma^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1} \tag{1.22}$$

$$Standard\ deviation = \sigma = \sqrt{s^2} \tag{1.23}$$

These are only a few examples, but the statistics describe a few pieces of data in a brief and quantitative measure, although the statistics estimate the true population parameter with an accuracy that is dependent on the size of the sample. An additional main task in classical statistics is testing for connections between two or more data sets. It is not always possible to test for connections, therefore is it necessary to check the stochastic values independently. In general, the objects examined can always be examined on the basis of measured values [Tor58]. When assigning measurable values to a real event, the following applies: "Measurement, in the broadest sense, is defined as the assignment of numerals to the object or events according to role [Ste46]." Subsection 2.2.2 specifically details with this problem and uses an algorithm to represent the scale levels of the respective possibilities of the correlation coefficient. This is particularly important because experiments are carried out in this thesis and simply put, because different scale levels are selected, not all statistical tests can be carried out.

In general, there are several ways to check correlations between two attributes. The aim of a correlation analysis is to determine the intensity and extent of the relationship. The choice of the appropriate statistical test depends on the scale level. In the following, the two most common types of correlation are presented, which are of great importance in this thesis.

If the two attributes are at least interval-scaled, the *Bravais-Pearson* test test or product-moment correlation can be used. The result r_p describes how strong the relationship between the two attributes is [BS10]. The test procedure examines how strong the relationship between the attributes x and y is:

$$r_p = \frac{n\sum_i x_i * y_i - (\sum_i x_i) * (\sum_i y_i)}{\sqrt{[n\sum_i x_i^2 - (\sum_i x_i)^2] * [n\sum_i y_i^2 - (\sum_i y_i)^2]}} \tag{1.24}$$

The second important test is called *Spearman* r_s test or rank correlation test [BS10]. This test can be used when one attribute is ordinally scaled and the other attribute is at least ordinally scaled. Due to the ordinally scaled features, only one ranking can be defined. There is no gap between the individual features. The compliance test is carried out in four steps [Bou11]:

1. Make a thesis about the strength of the relationship between the features x and y
2. Create the ranking for the objects with regard to feature x according to the thesis. Assign ranking numbers to the objects
3. Create the ranking for the objects with regard to feature y according to the thesis. Assign ranking numbers to the objects
4. Calculate the *Bravais-Pearson* correlation coefficient for the pairs of ranked numbers

The result of step 4 is the rang correlation coefficient $p_{spearman}$ with:

$$p_{spearman} = 1 - \frac{6 * \sum D_i^2}{n^3 - n} \tag{1.25}$$

with:

$$D_i = Rg\ x_i - Rg\ y_i \tag{1.26}$$

with:

$$Rg\ x_i = Ranking\ of\ the\ object\ i\ with\ regard\ to\ the\ object\ x \tag{1.27}$$
$$Rg\ y_i = Ranking\ of\ the\ object\ i\ with\ regard\ to\ the\ object\ y \tag{1.28}$$

These are the two most important ways of correlating to identify relationships between two attributes.

1.2.2 An alternative with Bayes Theory

The Bayes Theory is not only used to estimate parameters and test hypotheses in a sample as classical statistics does, it also uses additional information to gain further knowledge about the problem [Tsc14]. Thus, Bayes's theorem is another theory that now exhibits the conditional probability. "The probability of an event B, when it is known that some event A has already occurred, is called conditional probability and it is denoted by $P(B|A)$ [BSMM15]". It is defined by:

$$P(B|A) = \frac{P(AB)}{P(A)}, P(A) \neq 0 \tag{1.29}$$

Here, it is observed that $P(A|B)$ is conditional probability of result A, under the assumption that B occurs and $P(B|A)$ is conditional probability of result B, under the assumption that A occurs. $P(A)$ is the posterior probability of the result of A and $P(B)$ is the posterior probability of the result of B.

The conditional probability is defined with two properties [BSMM15]:

1. If $P(A) \neq 0$ and $P(B) \neq 0$ holds, then

$$\frac{P(B|A)}{P(B)} = \frac{P(A|B)}{P(A)}. \tag{1.30}$$

2. If $P(A_1 A_2 ... A_n) \neq 0$ holds, then

$$P(A_1 A_2 ... A_n) = P(A_1)P(A_2|A_1)...P(A_n|A_1 A_2 ... A_{n-1}). \tag{1.31}$$

A further important property of Bayes theory is the independence of the events A and B. Independence is identified if [BSMM15]:

$$P(A|B) = P(A) \; and \; P(B|A) = P(B) \tag{1.32}$$

holds.
In this case, it is

$$P(AB) = P(A)P(B). \tag{1.33}$$

If events in a complete system of events is considered, if $A_{complete}$ is a field of events and the events $B_i \in A_{complete}$ with $P(B_i) > 0 (i = 1, 2, ...)$ form a complete system of events, then for an arbitrary event $A \in A_{complete}$ the following formulas are valid [BSMM15]:

1. Total probability theorem

$$P(A) = \sum_i P(A|B_i)P(B_i). \tag{1.34}$$

2. Bayes theorem with $P(A) > 0$

$$P(B_k|A) = \frac{P(A|B_k)P(B_k)}{\sum_i P(A|B_i)P(B_i)} \tag{1.35}$$

With this methodical theory it is possible to calculate the probability including additional information about the problem. This is particularly important in extreme value statistics, as there is always a residual uncertainty that the calculated system does not include. With this method, the aleatory uncertainty can also be included.

1.2.3 New machine learning tools

Machine learning is the third methodology to find predictions about the future. The scientific field of Computational Intelligence, the ML and Deep Learning (DL) perform statistical inference and began in 1950, the development of classical information science [Tur50a]. This methodology helps us to decide, detect, interpret and find new relationships in data sets. In general, the development of such methods simulate an intelligent system at a higher abstract level. It effectively simulates artificial thinking [RN09]. The motivation for using artificial neural networks, as a part of ML is to imitate the neurophysiological mechanisms of the human brain. A distinction is made between the natural biological neural network (a brain with a nervous system) and the artificial neural network (simplified mathematical model). The simplified mathematical model only deals with the natural network in its basic structure, although it is excellent for capturing some of its functionality. The neural network of higher life forms consists of a brain and a central nervous system, both of which unite different

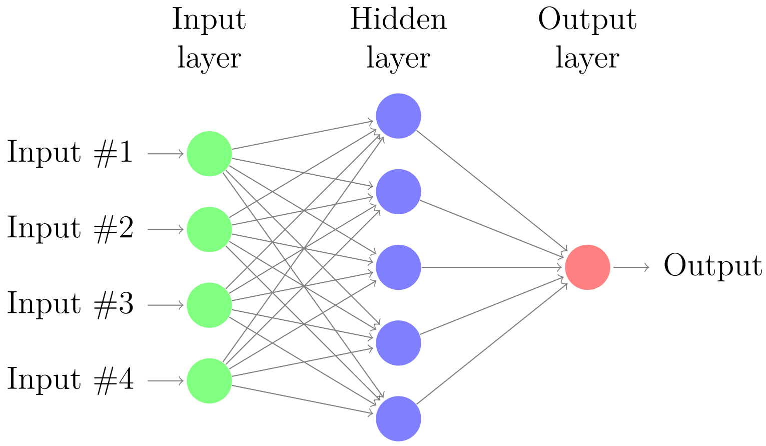


Figure 1.1: Overview of the mathematical illustration with input information layer, hidden layer to process the information and the output layer for the result.

sensory systems and control movements. The neurons are the most important nervous system components in regard to the processing of information. According to estimates, a brain has around 100 billion neurons, some of which can process information simultaneously. The neuron is a cell that collects electrical activities and transmits them according into a certain pattern. Figure 1.1 shows the basic concept by the input of information in the input layer, processing information in the hidden layer and the output of information in the output layer.

Each neuron in turn consists of a cell body with a cell nucleus, an axon and the end heads (including the dendrites). Here, the axons are the fixed paths with which the neurons are connected to each other. In an adult human, a neuron has between 1,000 and 10,000 connections to other neurons. The cell receives electrical information from other neurons through a branching system and passes electrical impulses through the axon to other cells. Whether and when the electrical impulse of a neuron is passed on is different for each cell. If the excitation of all incoming positive impulses is large enough, the signal is passed onto the other cells (the so-called threshold value). However, there are also negative impulses that inhibit the neuron through opposite electrical charges. The impulse is only passed on if the positive charges predominate. In addition, a so-called weighting factor is assigned to each incoming pulse. This means that an incoming signal from a certain neighboring neuron is weighted more than that of another. We have copied this neurophysiological principle in nature and will now use it in a generalized mathematical way to recognize patterns. In the following description four fixed steps are used to create a functional neural network in simplified manner. Further information is available in chapter 4:

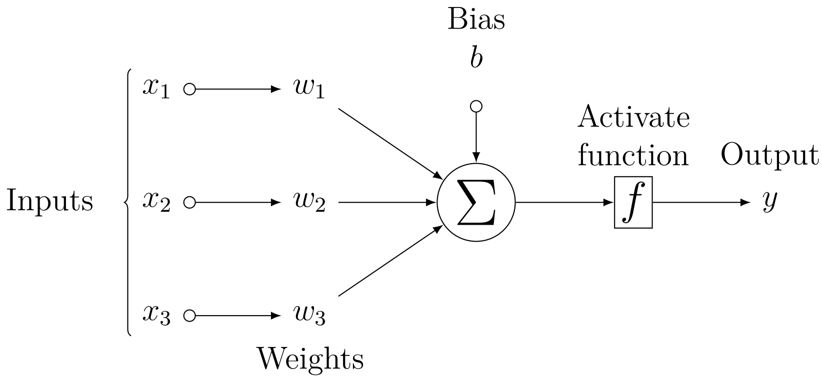


Figure 1.2: Threshold element with weighting factors with input variables in the mathematical context of an artificial neural network.

1. *Define input layer*: The first step is to create the main task to process a data set.
2. *Create the learner*: To calculate with the artificial network creation and the setting of meta-parameters is needed.
3. *Train the model*: In this step, the primary data set and the test data set are defined, as well as, the adjustment of parameters such as weighting factors.
4. *Make prediction*: In the final step, new data set can be input for prediction.

The more often a neuron is activated, the more important it becomes for the overall system. Each neuron has multiple inputs and is connected to a multitude other neurons. The individual neuron weights inputs differently, depending on the frequency, etc. of the incoming information and decides when there is an output. Now the neuron is not only subjected to an input signal once, but there is recurring information processing. The more often a certain signal arrives as an input for the neuron, the stronger the neuron weights the input, so that at some point a dominant input is created. If, at a later point in time, the input information comes again from the input branch, which is particularly well weighted, the output of the information is preferred. This leads to a dominant entry branch. This process means learning in a physiological sense and training in a computer system. This principle then enables pattern recognition in the overall system, which consists of several neurons. Figure 1.2 shows the threshold elements with the weighting factors for testing, if the sum of all inputs $\sum$ is higher than the threshold, named Bias. If the sum with all inputs x_1, x_2, x_3 including the multiplication of the weight factors w_1, w_2, w_3 is bigger than the Bias, information is then output y.

With these methods of inputting information, training the network and the corresponding output information, it is now possible to recognize new patterns in a data set. If a similar condition should arrive again as input information, the artificial neural network recognizes the pattern and enables conclusions to be drawn about it in the future. This is only a brief summary of these methods. For further detailed information, please refer to chapter 4.

1.3 State of the art technology in preventive fire protection

Engineering methods in fire protection are essentially determined by terms in the fire protection concept. There are generally three levels for fire protection concepts:

1. *Concept procedure level 1*: The proof for fire protection is created in a simple way. The direct regulations of the building code are always implemented. Here there are fixed rules such as the building laws from the federal government and/or states and any additional rules that are laid down. Examples are a maximum escape route length of 35 m, Door widths of 0.90 m or fire resistance class of 30 min for basement ceilings in class one buildings [Bay19]. This concept can be implemented very easily and effectively for small or standard buildings. The instructions are clear, the implementation is simple and the safety factors are already included in the respective requirements.

2. *Concept procedure level 2*: Another possibility to prove fire protection is by a simplified verification procedure, sometimes with small calculations. Here the regulations and laws are applied according to the given table values. Examples of this are the manual calculation methods for people escaping from a fire [PM73], a manual calculation for the required fire resistance class of building components [Deu10b] or the classical calculation for the smoke evacuation from rooms for safety in the building [EGH+11]. This method is particularly suitable if the classic requirements according to level 1 are not met. The safety factors are not taken into account here, but are generally related to a specific case.

3. *Concept procedure level 3*: The general calculation method is the special form of concept. Here there are only individual methods for detection. This level should only be carried out in agreement with the responsible authority. Proof of fire protection is very complex and requires a great deal of specialist knowledge from the engineers. It must also be ensured that the calculations are verified by an official test engineer or authority. Such methods are used in particular for special buildings such as nuclear power plants [Fac15], high-rise buildings, subways, etc. In statics these methods are state of the art [Öc20]. In preventive fire protection there are calculation methods for the removal of smoke and heat from buildings [BE19], but there are not any general methods for the safety concept as a whole. This thesis adds a new concept to these methods.

The basic thesis for the three methods is that levels 2 and 3 must be in close cooperation with a holistic fire protection concept. The lower level can always serve as a rough value to check the result.

Since there are always legal requirements in fire protection, the following gives a brief insight into the classifications and fire behavior of building materials. In 2001, the European Committee for Standardization introduced the DIN EN 13501 series of standards and thus, defined the same requirements and fire behavior of building materials and components throughout Europe [Deu19]. Since the Deutsches Institut für Normung (Eng. German Institute for Standardization) (DIN) standard is basically not legally binding, the building regulation lists of the individual countries have introduced the DIN standard as the current rule in construction, as in Germany. Through its application, now it is possible to describe the requirements for building components as a standard in all European countries. The fire behavior of building materials and building products are assessed under to DIN EN 13501 according to classes A to F [Deu19]. According to the EU regulations on the classical fire behavior of building materials, the smoke development (s1 - s3) and the burning dripping / falling (d0 - d2) that occur in a fire, all of these factors are taken into account and divided into classes and assigned to building components. Thus, the earlier national requirements of Germany and many other countries are not in direct comparison with previous building material classes according to DIN 4102 [Deu98]. The following table 1.4 on page 18 describes the standards of fire behavior of building materials and the description of the EU classes.

These general requirements for building materials according to DIN EN 13501 standard are only the testing requirements for the approval of building materials. The approval is the same in all EU countries, however the requirements of which characteristics are needed in which components are found in national regulations. For an example the fire resistance class in a classical detached house is lower than the resistance class in an underground garage or for skyscrapers. In order to strengthen comparability and also competition within Europe, the individual national requirements for components complying with the EU code are now unregulated. Table 1.3 shows the requirements with the criteria components.

The fire classification form table 1.3 describes the regulations in each country of the EU. Here, there are a lot of different systems. In approximately half of the EU countries, the technical building regulations are from the federal government or national authorities and there are no regional or local building codes. The technical building regulations from the federal states are uniform across the country. Because of special administrative units or legal traditions, in the other half of the EU countries the responsibility for determining the building regulations is distributed differently [PMV10]. In general, technical measures in buildings must be planned in conjunction with all individual measures. The essential components of fire protection in relation to the technical measures are briefly outlined below [Ver13]:

1. Preventive measures that prevent fires in the development phase:
   - Lightening protection on buildings
   - Electronic surge protection
   - Monitoring the earthing connection of electrical systems
   - Preventive fire prevention systems such as oxygen reduction systems
2. Preventive measures to detect and raise an alarm in case of fires:
   - Fire alarm system
   - Alarm systems
   - Emergency call equipment
3. Fire extinguishing systems with wet and dry risers, feed points and tapping points, sprinkler systems, fire extinguishers
4. Mechanical smoke extraction, smoke and heat exhaust systems
5. Fire dampers, smoke extraction and ventilation systems
6. Escape route marking, lighting and the associated controls
7. Fire control matrix for elevators and escalators
8. Emergency lighting system
9. Building indoor radio system for fire brigade
10. Fire and smoke protection bulkhead
11. Internal automatic building public announcement system
12. Security for power supply
13. Interfaces between building technology and building management
14. Technical connection of technical rooms and connection to electrical supply aisles
15. Installations such as raised floors and double ceilings

Abbreviations	Criterion	Area of application
R (Réistance)	Sustainability	Serves as the description of the fire resistance
E (Étanchéité)	Room containment	Serves as the description of the fire resistance
I (Isolation)	Thermal insulation under fire exposure	Serves as the description of the fire resistance
W (Radiation)	Limitation of radiation penetration	Serves as the description of the fire resistance
M (Mechanical)	Mechanical effect on wall (impact load)	Serves as the description of the fire resistance
S (Smoke)	Limitation of smoke permeability (leak, leakage rate) requirements are met at ambient temperature and at 200°	Smoke doors, with additional requirements, even in fire barriers, ventilation systems including valves
C (Closing)	Self-closing feature, possibly with the number of load cycles; including duration function	Smoke doors, fire doors, including shut-off devices for conveyors
P	Continuity of power and / or signal transduction	Electrical cable systems
K1, K2	Fire protection capacity	Wall and ceiling coverings, protective membranes
L1, L2	Different insulation criteria (under fire)	Fire barriers, including shut-off devices for conveyors
i -> o i <- o i <-> o	Direction of classification of fire resistance (in - out)	Non load-bearing exterior walls, installation shafts and ducts, ventilation systems and flaps
a <-> b	Direction of classification of fire resistance (above - below)	Suspended ceilings
ve (vertical) ho (horizontal)	Classified for vertical or horizontal installation	Ventilation ducts and dampers

Table 1.3: Classes of fire protection with their abbreviations, the criterion and the area of application by DIN EN 13501 [Deu19]. The uniform requirements apply in all EU countries.

Component requirements	Additional requirement		Classification to DIN EN 13501-1
	No smoke	No burning or dripping	Construction materials
Non-flammable	1	1	A1
	1	1	A2 - s1,d0
Flame retardant	1	1	B - s1, d0
			C - s1, d0
	0	0	A2 - s2, d0
			A2 - s3, d0
			B - s2, d0
			B - 23, d0
			C - s2, d0
			C - s3, d0
	1	0	A2 - s1, d1
			A2 - s1, d2
			B - s1, d1
			B - s1, d2
			C - s1, d1
			C -s1, d2
	0	0	A2 - d3, d2
			B - s3, d2
			C - s1, d2
Normally flammable	0	1	D - s1, d0
			D - s2, d0
			D - s3, d0
			E
	0	0	D - s1, d1
			D - s2, d1
			D - s3, d1
			D - s2, d2
			D - s2, d2
			D - s3, d2
	0	0	E - d2
Easily flammable	0	0	F

Table 1.4: This table shows the description of building material classes with the additional requirements of the EU regulations in relation to the specific national requirements. "0" means the requirements do not have to be observed and "1" it is obligatory to comply with the requirements. The abbreviations in the construction materials column are "s" for the smoke requirements and "d" for droplet requirements in the case of fire.

1.4 Existing approaches

This thesis consists of three main parts (organizational, technical and structural) to give the fundamentals of the scientific field to connect defensive and preventive fire protection systems. An overview of the structure follows in subsection 1.6. This thesis describes extended possibilities for risk quantification for fire protection measures in special buildings. Preventive fire protection engineering is classically split into three areas [MB20]:

- *Organizational system*: This area includes operational fire protection measures, which are supplemented by structural and technical equipment. This includes, for example, servicing, maintenance, use of and the correct handling of structural and technical fire protection devices, as well as, extinguishing devices, marking and keeping escape and rescue routes free of impediments, notice of fire protection regulations for fire prevention, explanation of measures in an emergency and plans for the fire brigades.
- *Technical system*: The description of technical fire protection is in its entirety all measures which, through the use of special systems and technical means, include both preventive and active fire protection for extinguishing and limiting a fire. This traditionally includes fire extinguishing systems, sprinkler systems, fire alarm systems, as well as, smoke and heat exhaust systems.
- *Structural system*: Structural fire protection describes all fire protection measures that should exist in a building. These structural measures do not only apply to all materials used in the construction of a building, but also to the construction and maintenance of escape routes and fire walls.

In order to cover the largest possible area in this scientific field, the three basic mathematical methods for quantification and prediction have been used. The methods (classical statistics, Bayesian probability theory and artificial intelligence) serve as a template. These methods were briefly explained in chapter 1.2. Now the three mathematical methods were combined with the respective division of the preventive fire protection. Generally, there are only a few different methodology principles to calculate risk. The table 1.5 shows only the most efficient combination of the methods and the splitting of preventive fire protect engineering. However, literature research has shown that the blank/white fields in the table have not yet been finally clarified. In any case, they still represent open research fields. However, in order to obtain a clear definition of the topic of this thesis, only the combinations shown are described.

1.5 Thesis objective and expected results

In the following, the three general main hypothesis are described with an explanation:

1. The assessing factors influencing fire protection, the focus is placed on unimportant areas. The effectiveness between the cost and the protected PYLL is rarely considered [Ham18].

	Classical statistics	Bayesian Theory	Artificial intelligence
Organizational system	Introduction forms		
Technical system		Fault Tree Analysis	
Structural system			Real fire inspection

Table 1.5: Overview of the different possibilities to calculate risk in the three disciplines of fire protection engineering.

Explanation: The objective and comprehensible answer to these hypotheses is, however, complex in practice. The idea for the respective decision should be formulated transparently and comprehensibly for everyone involved and in the best case also serves as a decision-making basis for future comparable applications in fire protection. When planning and implementing technical systems, regulations are often used that are driven by interests (by industry, associations, etc.). These influences represent interests that are not always useful. By developing new methods, this thesis is intended to develop a rationally comprehensible model that is only based on engineering and mathematical principles.

2. When assessing risks, human errors in an event chain are not quantified with the same care as in each of the systems' technology [Rea91, WRACB97].

   Explanation: The calculation and assessment of risks are based on mathematical operations. Application of an analysis is used for the approval or development of technical systems. Since technical systems are normally developed by engineers, and engineers are also supposed to evaluate their reliability, methods known from their own scientific field are used. However, the system is operated by people, so there is a discrepancy between the human factors and the technical system.

3. New technologies such as ML play almost no role in quantifying risks at the interface between preventive and defensive fire protection [PLY$^+$19, MIR17].

   Explanation: In order to design good fire protection, defensive and preventive measures must interlock. Preventive fire protection is highly academic and is part of the civil engineering and architect studies. Fire prevention is a highly practical activity performed by fire fighters. Relationships between theory and practice are therefore complex. Defensive fire protection is organized in a very decentralized way, so that high-quality data is difficult to generate on a large scale. This work should form the basis for strengthening defensive fire protection through scientific methods and thus close a gap.

The following thesis represents the beginning of a quantification measure in fire protection. In general, however, it can already be stated that there are large unexamined research fields in the field of fire protection. In other areas, however, the subject has been extensively examined. In the area of preventive fire protection, fire simulations are carried out to predict the physical properties of fire [Gre12]. For example, a real fire with the spread of smoke within a building can be simulated down to the second [HJRS17]. There is almost no high-quality research in the area of defensive fire protection, including the fact that there are not any peer-reviewed journals . This evident here, as in each of the eight issues from 2019 in the *Fire Safety Journal* contain a peer-reviewed publication with fire simulations, but only one in the area of defensive fire protection. So far, peer-reviewed journals do not exist in the area of fire protection. However, this also means that there is a very large, exciting and almost unexplored scientific field.

This work is also intended to help improve fire protection from a scientific point of view

1.6 Thesis structure

Table 1.6 shows an overview of the three thesis parts, for each part there is the general methodology, a preventive fire protection section and in addition practical application. There are five separate parts in this scientific thesis. The first part of this thesis is a general introduction and the main hypothesis in chapter 1 - "Introduction to basic methods and term definition" is followed by chapter 2 - "Organizational quantification with introduction forms" with the probability of human factors in complex technical systems. Human reliability refers to the ability of humans to perform a task under given conditions for a given time interval in the range of an accepted limit [Ver15]. Chapter 3 - "Technical quantification with probabilistic system" presents the quantification of the amount of risk in technical systems. Here, FTA and the probability of failure represent efficient intersections to improve overall safety. In the final chapter of methodology, chapter 4 - "Structural quantification with Machine Learning methods", contains the methodical examination of real fire events and inspections for buildings using artificial intelligence to predict and analyze weaknesses in these areas. In chapter 5 - "Review and Outlook" the focus is on the advantages and disadvantages of the topic of risk quantification and reflects on its importance in science. Figure 1.6 shows the overview of the three topics with their connection to chapters *II*, *III* and *IV*. The discussion is conducted individually for each section of this thesis.

Thesis structure in three parts

Thesis chapter	*II*	*III*	*IV*
Thesis part	Organizational system	Technical system	Structural system
Methodology	Possibility of quantification via different introduction forms with research flight simulator	Risk quantification with FTA including advanced input values	Predict structure with artificial neural network
Application	Journal publication and Introduction manual operation form for defensive fire protection in research reactor Munich II	Development and FTA package in RIAAT® Software and publication	First German high quantity questionnaire for real fire operations for ML Methods

Table 1.6: Thesis structure split into three parts. Every part examines the development of the methodologies used and the differences between them, as well as, real life applications for all system parts.

Chapter 2

Organizational quantification with introduction forms

Human error can lead to serious consequences, especially with regard to the operation of highly complex systems, such as the monitoring of nuclear power plants or the operation of aircraft. Dramatic examples can be found to substantiate this fact. Examples include the Three Mile Island accident in 1979 and the Chernobyl disaster in 1986, both caused by human error [Rea91, WRACB97]. The prevention of accidents and ensuring system safety are therefore still central issues in all of today's industries. Various studies have shown that humans play a significant role in the cause of many accidents [FP18].

Chapter 2 describes a new standard procedure for the quantification of human errors in the organizational part of an instruction manual. As already described in the introduction, this thesis scientifically examines fire protection specifically. There is a great need for action, especially in the area of organizational measures, since in engineering, the human component is generally not so heavily weighted. The following chapter is now intended to provide a further scientific perspective on this topic and has produced a peer-review published in an open access journal [HKF20b, HKF20a]. Accordingly, details are discussed on the basis of the published information and the focus is placed on the development of the methodology. The developed methodology is tested by a representative case with subjects in a flight simulator for research purposes. Organizational measures always include the human component. Today, when we consider technology, our world is becoming more and more complex, so much so that it is difficult for humans to memorize every action they have to perform when dealing with complex tasks. Therefore, it is normal for all important possible actions in complex tasks and processes to be described by a human being and written down in instructions. The main question is:" *How must this instruction be written so that as few mistakes as possible occur during its execution?*" Thus, a model is needed to provide a comparison between the different forms of behavior. The answer to this question and moreover, provide an option to standardize this process is now described. The possibility to solve a problem through communication between two people is not always available. Especially in time critical situations where action is needed immediately and the option to communicate with another person is limited or lacking [Roh10].

This chapter is subdivided into five parts. The first part focuses on the basic fundamentals for human factors engineering 2.1, the second part looks at the development of the basic model and the main hypothesis 2.2, the third part reviews the test setting for the research with a flight simulator to check the basic model 2.3, the fourth subsection presents the results of the test case 2.4 and the discussion of its application is found the last and final part 2.5.

The table 2.1 shows the overview of the argumentation and why a flight simulator was used to quantify the reliability of the best instruction form method. Today, there are increasingly more technical parts in complex systems [CC05]. A complex system represents a technical installation that is operated by a control station for example a control room of a nuclear power plant, aircraft cockpit, etc. When a complex system with high standards of safety and reliability has been built and is running, specialized and qualified staff are needed for its efficient and effective operation. If a system fails, the staff have an immense number of possible processes to get it back into operation or they are constantly running them through the processes to maintain the system. These facts have the superfluous result that it is impossible for all alternatives to be considered and to maintain dominance and control of a system at all times. The amount of potentially occurring errors is multiplied. The solution, therefore, is that the operational personnel need standard instruction forms to reduce the amount of their errors. There are a variety of different instruction forms, such as image, algorithm or text forms. To quantify the reliability of these types of instruction forms, a methodology has been developed based on the research evidence. It is necessary to check the effectiveness and efficiency of these types of forms through their use when complex systems are being operated by humans. In this case, the research is quantified with a flight simulator. The following section describes the methodology, the test setting and the results.

2.1 Theoretical principles of human factor engineering and term definitions

The field of study HEP provides an interface between the classical engineering and natural sciences, it crosses technologies in the fields of environment and climate, energy and raw materials as well as mobility and infrastructure. In 1857, at a conference, *Mr. Jastrzebowski* first mentioned the term of ergonomics [Woj57]. Almost a hundred years later in 1949, *Mr. Murrell* further defined the term of ergonomics as a study of the relationship between humans and their working environments. Today, a high quality of human factor engineering and ergonomics is achieved by a using a systems approach, through a design related perspective and by equally considering both of the design goals; performance and human well-being [DBB+12]. In the field of ergonomics various terms are used, which are now explained in the following paragraph.

Technical systems becoming increasingly complex

$\Downarrow$

Operations are becoming more complex

$\Downarrow$

It is impossible to practice all types of use

$\Downarrow$

Errors increasing

$\Downarrow$

Standard instruction forms are needed

$\Downarrow$

Methodology needs evidence based results

$\Downarrow$

Test setup must be in a very complex system

$\Downarrow$

Research in a flight simulator as an answer

Table 2.1: Overview of the argumentation schematic of the methodology and the test setup from the basic statement: "Operations are becoming more complex" to the final test setting to quantify the reliability of different instruction forms with research in a flight simulator.

As a subgroup, Human Factors Engineering (HFE) is an important field of research in ergonomics and describes the connection between humans and machines through organizational measures. First of all, a variety of fundamental terms are defined which will be used to describe a new standard of methods to quantify the organizational part of this thesis. HFE has great potential to contribute to the design of all kinds of systems involving people (work systems, product/service systems), although it faces challenges in the readiness of its market and in the supply of high quality applications. HFE has a unique combination of three fundamental characteristics: (1) it takes a systems approach (2) it is design driven and (3) it focuses on two closely related outcomes: performance and well-being. In order to contribute to future system design, HFE must demonstrate its value more successfully to the main stakeholders of system design [DBB+12]. Fundamentals are separated on the basis of definition or terms, for example work, error, performance and the compound terms like quality, risk or human error probability. Basic terms are [Ver15]:

- *Work* is the physical and/or the mental human activity that is planned and targeted to cover needs with appropriate means.
- *Task* is the request to the working persons (operators), derived from the purpose of the work, to complete an action under given working conditions and following a given working procedure with the goal of achieving a defined working goal.
- *Error* is the human action which exceeds a defined acceptance limit.
- *Performance* is the quality of work attained in a defined period of time.
- *Quality* is the extent of meeting the working task defined by the working result.

These terms are necessary for the calculation of the new methodology, however they are not sufficient and therefore they need to be combined to form new terms, which are:

- *HEP* as the likelihood of the occurrence of a human error as a parameter of human reliability is calculated as [Bub92]:

$$HEP_i = \frac{number\ of\ incorrectly\ performed\ tasks\ of\ a\ type_i}{number\ of\ all\ tasks\ performed\ of\ a\ type_i} \tag{2.1}$$

- *HRP* used for the mathematical application for the HEP [Ver15]:

$$HRP = 1 - HEP \tag{2.2}$$

This basic principle continues as the work progresses. However, only terms that are required to work on the topic are introduced. To define the number of incorrect tasks or other values there needs to be defined standard words. The VDI-Richtlinie "Human reliability" [Ver15] is a work standard in this discipline and defines a lot of terms:

- *Performance shaping factors* are all factors that influence human reliability. Figure 2.1 shows all possible variations for Performance Shaping Factor (PSF) including the external and internal factors. There are direct influences from external sources, as well as, internal and indirect influences.
- *Work task* is the request to the working persons (operators), derived from the purpose of the work, to complete an action under given working conditions and following a given working procedure with the goal of achieving a defined working result [Ver15].
- *Work error* is the human action which exceeds a defined acceptance limit [Ver15].
- *Work performance* is the quality of work attained in a defined period of time [Ver15].
- *Human reliability* is the capability of human beings to complete a task under given conditions with a defined period of time and within the acceptance limits [Ver15].

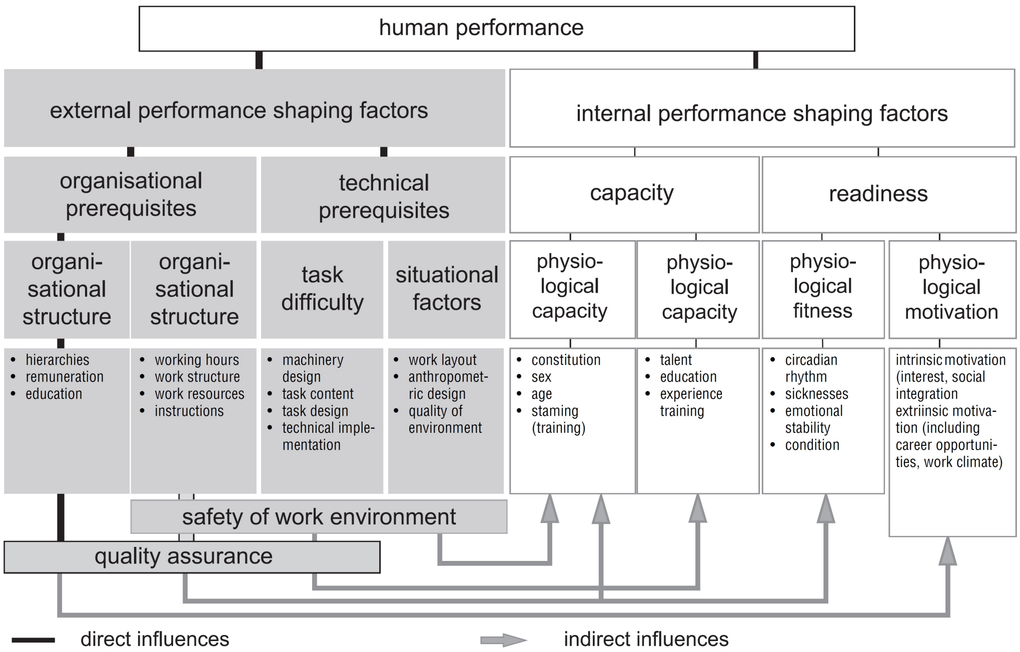


Figure 2.1: Performance shaping factors split into external and internal influences [Ver15].

In the following, a working definition will be developed for the term instruction form in order to clearly highlight the focus of this work. As mentioned in detail, the availability of effective, unambiguous instructions is fundamental for system security. For example, studies have shown that skipping instructions affects more than half of all human factors related to and disruptive for system maintenance issues. Therefore, the development and correct application of effective handling instructions are still important factors in counteracting human errors in complex systems [Dhi14, Dun14]. Therefore, some characteristics of optimally designed instructions are presented, which should, for example, enable a smooth maintenance process in complex systems. The instructions should focus primarily on the risks

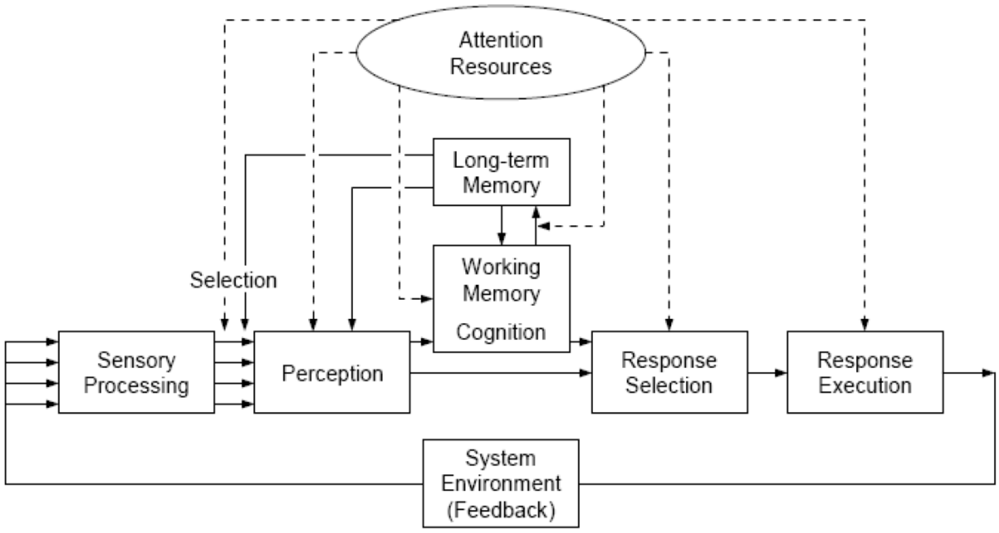


Figure 2.2: The figure describes the basic concept of the human sensory system and the response by *Wickens* [WHB12].

that prevent the execution of the task according to predetermined standards. Important aspects of the instructions must be sufficiently highlighted at relevant points. Figure 2.2 shows the basic concept of the human circle of sensory. The instructions should be designed to a reasonable extent and so conspicuously that central action steps are not omitted. They group complex and work related instructions, for example, in phases, which may consist of related work tasks. Depending on requirements, images and graphics can be used at useful steps of the instructions to clarify the work tasks. At best, they are written and tested by experts from the respective area of application in order to achieve compatibility with the users. The instructions should also be explained in a simple and consistent language and clearly written [Dhi14].

Nuclear technology instruction forms have is also been developed for the management of nuclear power plants in order to ensure their reliable operation including all of the plant equipment and subsystems involved. The control center operators are responsible for monitoring and controlling plant systems, in accordance with the prescribed operating instructions and maintenance procedures. All operator activity should be consistent with the given procedures. The initiation and execution of functional actions in normal operations, in an emergency or in an alarm state must be carried out according to the instructions given for the corresponding scenario [Int08a]. Handling instructions also represent a key element of successful safety culture in the process engineering industry, especially in the field of nuclear installations. It also requires the existence and compliance with procedural instructions or the use of procedures. Management systems require clearly written documentation that is suitable for controlling all aspects of their system security. Again, the consistency and deliberate applicability of the instructions for all staff should be emphasized. The number of procedures should be balanced, identify the most important risks, be clear and relevant to the user. To maintain a sufficient system security culture, it must be ensured that fundamental security procedures are available in a readily comprehensible form for working on critical system areas that can be used directly on-site. If the user is obliged to use procedural instructions, the use of the procedures in training should be practiced [FMD08]. In general, the principle of deep tiered security systems is considered to be an essential design feature in nuclear systems. The aim is to prevent the occurrence of safety critical events by so called barriers. Barriers are designed to reduce the level of damage through separate levels of independent security. In addition to restraint systems, such as ducts for fuel rods, security containers and electronic security measures, etc., barriers are also created in procedural forms. These should guide and support human behavior when dealing with technical systems. This happens, for example, through the development of safety instructions, or training during the education of operator personnel [BSHL12]. Processes, procedures and work instructions represent symbolic barriers which are intended to counteract or prevent malicious actions in a security relevant system. Work instructions should make actions regulated, display the system status and authorize and clearly communicate the prescribed action steps [Hol04].

In order to create a uniform consensus for the term "action instruction", the above examples are used to filter out central and eminent constituent parts. This serves to clarify the objectives and to clarify the subject matter of this work. In addition, a definition should be found which justifies the use of instructions in complex systems. In general, when we speak of the human factor of reliability we think of the human being as a partner in a complex technical system, or the human operator as integrated in the social-technical system created by themselves [DIM14].

In everyday life, we use, either at work or in private, a lot of different manuals or instruction forms. In today's society, young children apply the LEGO® manuals with simplified images with a large number of steps to build for example fairly complex cars or other vehicles. As the manufacturers of these kits want to reach a very large age range, it is clear that this is the best way to create instructions. For example, studies have shown that skipping instructions affects more than half of all human factors related to and disruptive for system maintenance issues. Therefore, the development and correct application of effective instructions are still important factors in countering human errors in complex systems [Dhi14].

So far, only the connections between humans and machines have been described, but the majority the information passes from human and human, when errors in complex systems occur. Here, classical psychology is the leading science in this area. The typical leading model for communication and the possible errors are by *Shannon-Waver* [Roe16]. The model describes that there are many chances for possible errors to occur in each single step of information transmission between the sender and the recipient. To transfer information the first step is the selection of a means of transmission through a medium or channel (normally, it is verbal communication). The information must be converted to enable reception by the recipient. In between every single transmission step there are enormous pitfalls where mistakes can be made resulting in errors. Figure 2.3 shows in a simplified way the procedure of communication by *Shannon-Waver* model.

A good example of this is a medical emergency service, where the use of instruction forms needs to be followed so that the operator achieves a successful outcome with the lowest

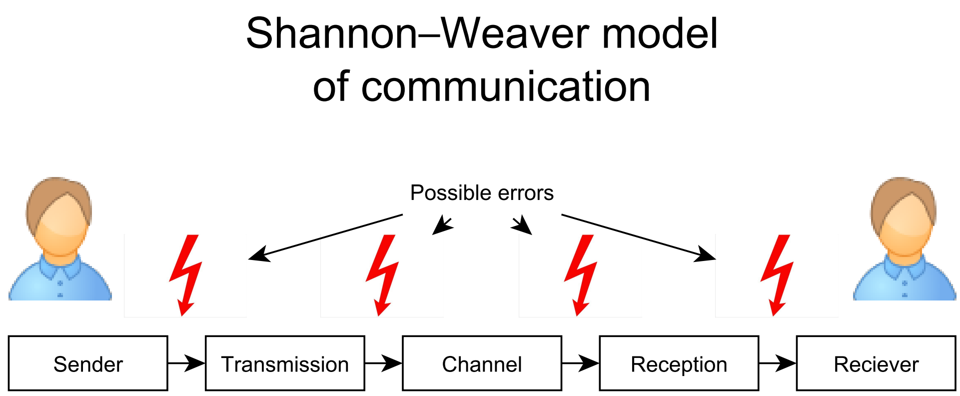


Figure 2.3: Shannon-Weaver model of communication with all separate steps from sender to recipient. In between each step there is the possibility that an error could occur.

amount of errors possible. In this case, it is a combination of positive outcome with a simple instruction to reduce large extent damage. For example, the fact is that in a case where heart palpitations are not present, the probability of the patient surviving drops by 10 % per minute if not treated [MNB+15]. Figure 2.4 now shows a concrete example for the elaboration according to an algorithm for the application of cardiopulmonary resuscitation. It becomes very clear that the only closed questions can be asked, such as "Unresponsive and not breathing normally?". Here, there are only two possible answers "Yes" or "No" [SNB+15]. The algorithm presentation is state of the art in emergency medicine.

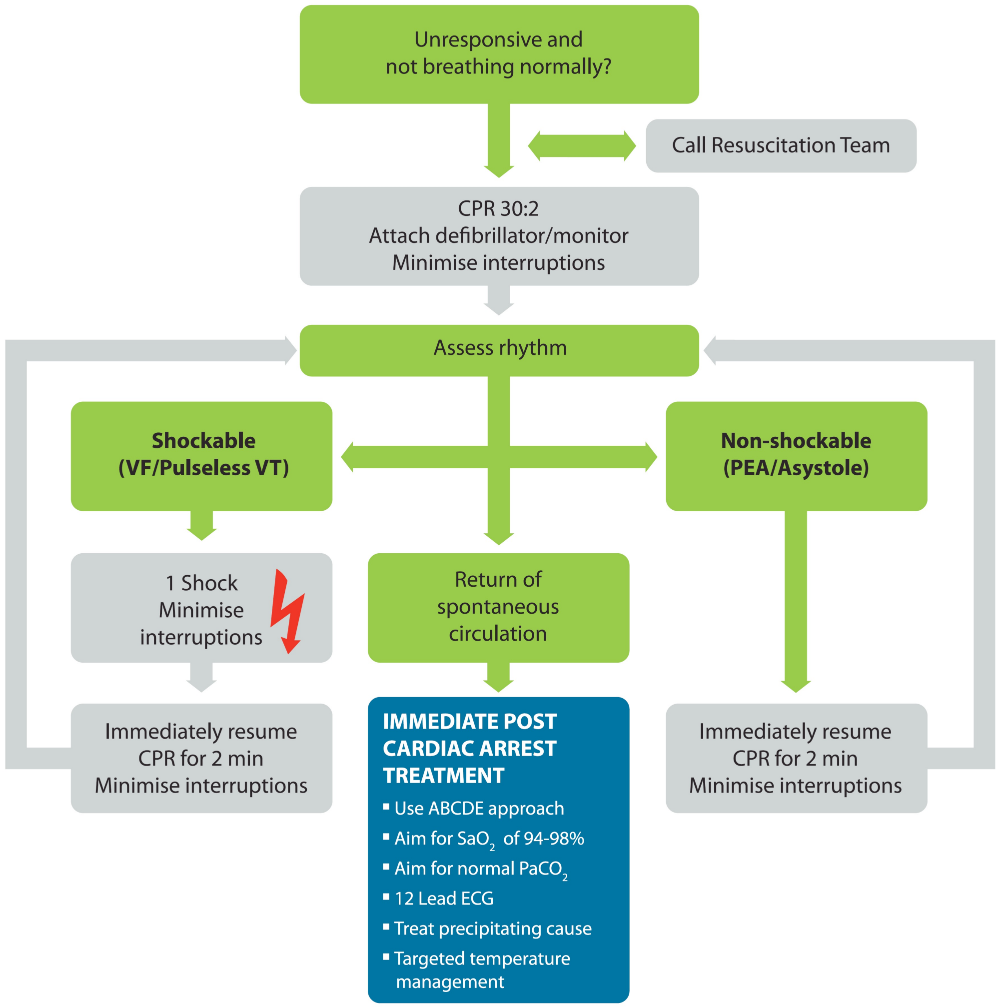


Figure 2.4: The figure shows a basic algorithm for professional paramedics [SNB+15].

2.2 Development of the basic model

In the following paragraphs, the main topic for the development of quantifying the different instruction forms is explained. The basic question in safety and reliability is: "How can we transfer thoughts from one person to the next without complex personal briefings?" There are a multitude of main principles which explain basic safety management [Pet78, Dhi18]. All principles must be fulfilled to create a new standard methodology to quantify the different instruction forms. All of the following axioms or principles start with the basic terms of safety and engineering. The text below enumerates a summary of the most important axioms of safety engineering and presents the path to the development of a new basic model to quantify different instruction forms. There are countless more axioms or principles, however, only the most relevant statements are shown. The axioms are:

- **1. Axiom: "The main function of safety is finding and defining the operational errors that can result in an accident" [Pet78]**

  In order to avoid accidents and mistakes, you have to define the influencing factors that have the greatest influence on the overall result. Chapter 3 goes into this topic in more detail in order to find the best performance ratio point between the means used and the increase in security from a FTA. The FTA is state of the art in nuclear safety and other disciplines like airplane engineering [MUBH19]. The possibility to describe the operation with an algorithm via FTA is a logical answer.

- **2. Axiom: "Most accidents are due to the unsafe acts of humans" [Hei59]**

  It is generally known that in large, inconspicuous accidents the main cause is man [Rea91, WRACB97, FP18]. Here an evidence based model is needed to reduce the amount of possible errors between sender and recipient. The information transfer from one person to another when operating in a complex system can include a variety of possible errors [Roe16]. In general, there are three main options to create an instruction manual. There are the image, text or algorithm methods to transfer information from one individual to the next without direct contact. The following test setting meets these requirements and focuses on the most important influence of accidents – “the human factor”.

- **3. Axiom: "The reasons why humans commit unsafe acts can be quite useful in selecting appropriate corrective measures" [Dhi18]**

  This axiom is very close to the second axiom "Most accidents are due to the unsafe acts of humans". The principle is specific that the reason for an accident can be negated by taking the appropriate measures. The agreed measure specifically refers to the best ratio of resources used (money, time, effort, etc.) and the increase in security in a complex system. The development of evidence based instructions for the interface between man and machine is an effective solution. Sometimes, it is even possible without any technical measures. A good program for developing algorithms is the open source Software yEd Graph Editor®. The instructions for the test setting were created through the usage of this software.

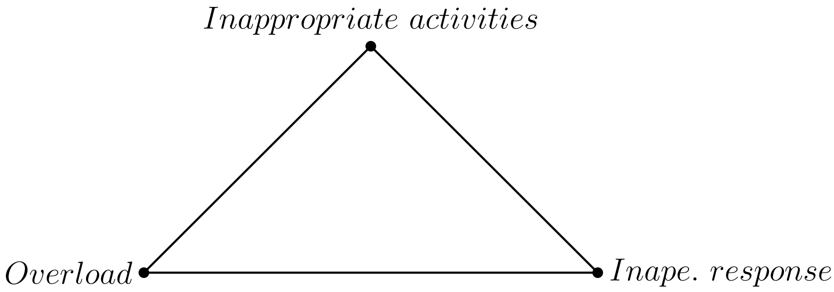


Figure 2.5: The three main factors that cause occurrences of human errors.

In all safety systems there are redundancies, so it is impossible to cause an accident through only one single human or a technical system error. Normally, the technical system controls the human system and the human system controls the technical system. So, the error is a result of an assumption of chain. In case of the organizational system, there are three main factors which influence the effectiveness of control systems (see figure 2.5). The first factor "inappropriate activity" indicates that it is a result caused by human error. A typical example for this error are individuals, who have misjudged the consequence of their actions. For example the train crash on the line between Holzkirchen and Rosenheim in Germany, which was the worst train accident in Bavaria since the 70's, because the operator was using his mobile phone. This action caused the death of 12 people and where 89 people were severely injured. This axiom must be included into the test setting to quantify the different instruction forms, while performing research on a flight simulator. The second influencing factor is "overload", which is defined by an imbalance between the capacity of an individual at any time and the load the person is carrying in a given state [Dhi18]. These definitions connect human performance with external performance shaping factors and the internal performance shaping factors [Ver15]. The third part of the main factor is the "inappropriate response", which causes other people to make further errors due to an unknown error caused by another individual involved in the event [Hei59]. This situation could not be examined in the test scenario because only one subject is being examined in the test setting. Generally, the third part is split into three separate sections [Dhi18]:

1. A person completely ignored the recommended safety associated procedures.

2. A person completely removed a safeguard from a piece of equipment or machine to improve its output.

3. A person detected a hazardous condition, but did not take any proper corrective measures.

All of these factors and axioms are considered in the test setting, where the research is conducted in a flight simulator.

2.2.1 Main hypotheses to quantify different introduction forms

The overall objective of this study is to investigate whether there are significant differences in human reliability between different forms when presenting instructions for the operation of highly complex systems. In order to refine the question, hypotheses are first put forward. After the preliminary tests, a decision is then made as to whether the hypotheses are directional or unidirectional. The hypotheses are based on the generally accepted state of the art in technology [Ver15]. To convert the hypotheses into a mathematical formulation μ_1, μ_2, μ_3 are used for the three tested instruction forms text, image and algorithm. The μ_i is the statistical mean of the tested sample and μ_j is the mean of the comparison group. The main hypotheses of the organizational system quantification are:

1. Hypotheses: Frequency of top events

   H_0 (Top event): There is no significant difference in the number of top events observed, when using the different instruction forms,

   H_1 (Top event): When using the different instruction forms, there is a significant difference in the number of top events observed.

   Definition of top event: Airplane crash landing on the ground or airplane not landing on the runway.

$$H_{0\ (Top\ event)} : \mu_1 = \mu_2 = \mu_3 \ vs \ H_{1\ (Top\ event)} : \mu_i \neq \mu_j \tag{2.3}$$

2. Hypotheses: Number of errors

   H_0 (Error): There is no significant difference in the number of errors observed, when using the different instruction forms.

   H_1 (Error): When using the different instruction forms, there is a significant difference in the number of errors observed.

   Definition of error: Any human action which exceeds acceptance limits.

   Definition of unknown error: Human action, performed for the first time.

   Definition of known error: Human action has already been performed.

$$H_{0\ (Error)} : \mu_1 = \mu_2 = \mu_3 \ vs \ H_{1\ (Error)} : \mu_i \neq \mu_j \tag{2.4}$$

3. Hypotheses: Time needed to implement the action

   H_0 (Time): There is no significant difference in the time required to implement the action, when using the different instruction forms.

   H_1 (Time): When using the different instruction forms, there is a significant difference in the time required to implement the action.

   Definition of the different instruction forms: The three test instruction forms algorithm, text and image.

$$H_{0\ (Time)} : \mu_1 = \mu_2 = \mu_3 \ vs \ H_{1\ (Time)} : \mu_i \neq \mu_j \tag{2.5}$$

4. Hypotheses: Sensitive workload

   H_0 (Workload): There is no significant difference in the workload perceived by the subjects, when using the different instruction forms, .

   H_1 (Workload): When using the different instruction forms, there is a significant difference in the workload perceived by the subjects.

   Definition of workload: Entirety of all external conditions and requirements in the working system that could influence a subject physically and /or psychologically.

$$H_{0\ (Workload)} : \mu_1 = \mu_2 = \mu_3 \ vs \ H_{1\ (Workload)} : \mu_i \neq \mu_j \tag{2.6}$$

In order to investigate the interaction of people with a complex system, a test scenario and a task adapted to the task must be found. The following criteria must be observed:

- The test stetting must make the hypotheses verifiable
- The experimental setup must enable comparability of instructions for action
- The test setting must represent a new environment for the test subjects
- The test must contain a few different options for the test subjects
- A comparison of the instructions for action must be verifiable over time
- Boundary conditions must be controllable

Furthermore, a definition of the concept of the standard is needed. Sanders [San06] defines a standard as applied procedures and principles that have been agreed upon by the persons operating within a scientific discipline. In addition, the participants should help to improve the measurable quality within a standard. Thus, standards provide a process oriented guidance for future work and therefore represent the basis for predicting outcomes of actions [Deu16a]. In order to make standardized processing of hypotheses possible, three central questions must be answered [GHN+14]:

Characteristic	Interval Scale x	Dichotomous Scale x	Ordinal Scale x
Interval Scale y	Product Moment Correlation	Point-Biserial Correlation	Rank Correlation Coefficient
Dichotomous Scale y	n. p.	ϕ-Coefficient	Rank-Biserial Correlation
Ordinal Scale y	n. p.	n. p.	Rank Correlation Coefficient

Table 2.2: Overview of the bivariate possibilities of correlation with x = dependent variable, y = independent variable and n. p. = not possible means this combination are not state of the art.

1. *Future suitability*: The developed standards must correspond to the difference of their form of science. The standards of this group must make explicit statements about the future situation. he future outcomes result in special quality requirements, which can be found especially in standards and quality criteria. For example, they address the reflection of the fundamental openness and uncertainty of the future.

2. *Scientificity*: Scientificity ensures that the meaningfulness of the result can be transferred to the general public. This means that the experiment can be repeated in the same form and the same results are expected. A certain fault tolerance is normal and differs depending on the field. Thus in laser research, results are easier to transfer, than in human trials.

3. *Effectiveness of task fulfillment*: Research by definition is characterized by knowledge acquisition, , although it always has to be checked for its effectiveness. The effectiveness is measured by the means used, the balance between effort and insight.

2.2.2 Scale level for quantification

To validate a hypothesis mathematically by means of statistical methods, need values as input. In order to check these values meaningfully, the question of the scale level must already be asked in the research methodology. The right or wrong choice of scale (nominal, ordinal, and interval) leads to a distinct choice between different methodologies. For example, not every type of scale can be meaningfully correlated with each other in the correlation. Table 2.2 shows the possible correlations for all scales.

In the following, the possible correlations from Table 2.2 are represented mathematically [BS10, PS18]. All mathematical methods are state of the art in statistical analysis, however what is most important for the main question is which scale level is used for the test setting output.

Calculation of the Product Moment Correlation:

$$r = \frac{n \sum_i x_i * y_i - (\sum_i x_i) * (\sum_i y_i)}{\sqrt{[n \sum_i x_i^2 - (\sum_i x_i)^2] * [n \sum_i y_i^2 - (\sum_i y_i)^2]}} \tag{2.7}$$

Calculation of the Point-Biserial Correlation:

$$r_{pb} = \frac{\bar{y}_1 - \bar{y}_0}{s_y} * \sqrt{\frac{n_0 * n_1}{n * (n-1)}} \tag{2.8}$$

Calculation of the Rank Correlation Coefficient:

$$r_s = 1 - \frac{6 * \sum_{i=1}^{n} d_i^2}{n * (n^2 - 1)} \tag{2.9}$$

Calculation of the ϕ Coefficient:

$$\phi = \frac{a * b - a * c}{\sqrt{(a+c)(b+d)(a+b)(c+d)}} \tag{2.10}$$

Calculation of the Rank-Biseral Correlation:

$$r_{to\ R} = \frac{2}{n} * (\bar{y}_1 - \bar{y}_2) \tag{2.11}$$

Further methods to find the right mathematical assessment with a simple main question, while taking into consideration the scale level and possible statistical theory, are through the use of an algorithm form[FMF12].

2.3 Test setting with flight research simulator

First of all, this the sub chapter "Test setting" starts with an enormous expression of appreciation and gratitude that the research and the experiment were able to be completed. The implementation of the experiment was assisted by the friendly support of the Institute of Ergonomics Technical University of Munich (TUM) (Prof. Bengler) as part of an interdisciplinary project and the Institute of Flight System Dynamics TUM (Prof. Holzapfel) for the provision of the flight simulator. Without the help of the students Sebastian Schmeiser, Simon Hurst and Karolin Wagner, the complex experiment would not have been finished and probably would have remained a theory. Their efforts are thanked most sincerely and deeply. It is a great achievement. Accordingly, the students are mentioned in the publication [HKF20b].

This chapter describes the methodology used to test the hypotheses. The prerequisites and the test environment are described, as are the metrics for data acquisition and the reasons for using the simulator. The Institute of Flight System Dynamics (FSD) at the TUM provided the flight simulator. The flight simulator was originally developed, in the year 2000, in cooperation with Fairchild-Dornier, which also designed the cockpit shell. The cockpit represents a realistic mock up of a passenger aircraft. Since the main purpose of this simulator is research, it has a generic cockpit with large screens and standard PC hardware to achieve high flexibility and modularity. It has a three channel viewing system with a viewing angle of over 180 degrees and full high definition resolution for each channel. The cockpit is equipped with an active Wittenstein side stick, which includes an electronic control charging system for force feedback as well as variable hard and soft stops. Due to the cooperation with Fairchild Dornier, the flight dynamic model is based on a high fidelity aerodynamics and engine data set and is implemented in MATLAB Simulink. In addition, an autopilot's control unit is built into the cockpit, just as it can be found in comparable aircraft. This multifaceted flight simulator environment is therefore suitable for the given task. Due to the realistic simulation of a cockpit with various buttons, switches, controllers and displays, the flight simulator represents a complex system, which is excellently suited as a test environment for subjects. The optical simulation of the aircraft environment is performed with Microsoft X-Plane, the simulation of the flight system dynamics and the entire cockpit control units is performed with MATLAB Simulink. The Simulink flight system dynamics model runs in the background enabling simple data recording during test flights in the simulator. Thus, actual states of switches, controllers, levers, buttons and displays and all inputs to them can be recorded over the entire test period. The data obtained from the Simulink model form the basis for subsequent evaluation to assess the effectiveness of the various instructions for action. The test environment is a central building block of this study. Figure 2.6 shows the flight simulator, which was used during the research. The yellow numbers show special contents of the simulator, which are described in table 2.3.

Figure 2.6: Picture of the flight simulator with a 180 degree view of the cockpit [Ins19].

It was important for the present study that the work task be as comparable and as clear as possible in terms of input and options for action. The aim was to create a scenario in which the boundary conditions can be controlled and deviations from a desired ideal solution path or action scheme can be discovered with as little effort as possible.

Number	Location	Description
1	Autopilot control unit	control panel with 4 displays, buttons and regulators to control the autopilot of the aircraft
2	Primary flight display	(mirrored for pilot and co-pilot): output unit of important flight values such as altitude, speed, distances to waypoints and spatial orientation
3	Middle information display	further output unit for aircraft data (e.g. parking brake), on the right side there is the lever for the landing gear (gear lever)
4	Navigation display	digital map view of the surroundings of the aircraft and the current movement is output here
5	Middle console	central controls of the aircraft again, including two thrust levers, the flaps lever, the lever for the spoiler, regulator for weight adjustment
6	180 degree display	high definition display for the pilot

Table 2.3: Description of flight simulator elements.

Various test fits were performed to fix an appropriate number of action steps in an appropriate time, which is defined as the test setting. The scenario has the following points:

- In the scenario, subjects start at a fixed position in the sky above Munich that is a few nautical miles away from Munich Airport.
- The aim of the scenario is to land the aircraft safely on the runway at the airport.
- To successfully conclude this task, a total of 14 individual steps are required in the simulator cockpit.
- For a successful task to be completed, it is necessary that actions be performed in the correct order and at the appropriate time.
- Some action steps have fixed preconditions.
- Control via the manual flight stick is not an integral part, since the comparability is not guaranteed by the different affinity of the subjects.

Figures 2.7 to 2.9 show the details of the cockpit with the corresponding lettering. Tables 2.4 and 2.5 show the 14 individual steps which must be carried out to successfully complete the task. An explanation of the individual steps is described at table 2.4 and 2.5.

Step	Cockpit position	Task
1	Middle console	On the rear part of the center console, between the two seats, the flaps levers is in the "off" position. The position of this lever can be changed by pulling the release. Set this lever to position "1".
2	Autopilot control unit	In the front area of the cockpit, in the middle above the large screens, there is a knob with the inscription Heading (HDG). The initial value is "0". Now search the screen in front of you for the purple display and wait until it shows "8.0 Nautical miles (NM)". Now turn the knob labeled HDG until the target setting shows "45".
3	Autopilot control unit	In the front area of the cockpit, in the middle above the large screens, there is a knob with the inscription Speed Control (SPD). The initial value is "220 kt". Now turn the knob until the target value of "180 kt" is displayed.
4	Autopilot control unit	In the front area of the cockpit, in the middle above the large screens, there is a knob with the inscription HDG. The initial value is "45". Now search the screen in front of you for the purple display and wait until it shows "7.0 NM". Now turn the knob labeled HDG until the target setting shows "83".
5	Middle information display	A round knob is located to the right of the central display. This is necessary to extend the landing gear. Slightly tighten the small release on the top of the lever and push the entire lever downwards.
6	Autopilot control unit	In the front area of the cockpit, in the middle above the large screens, there are four small displays. Below the second from the right is a button with the inscription Approach Button (APR). Wait until the purple display on the large screen shows "6.0 NM" and then press this button.
7	Middle console	On the rear part of the center console, between the two seats, the flaps lever is in position "1". The position of this lever can be changed by pulling the release. Set this lever to position "2".

Table 2.4: Steps one to seven of the 14 individual steps to successfully complete the task for landing.

Step	Cockpit position	Task
8	Autopilot control unit	In the front area of the cockpit, in the middle above the large screens, there is a knob with the inscription SPD. The initial value is "180 kt". Now turn the knob until a target value of "150 kt" is displayed.
9	Middle console	On the rear part of the center console, between the two seats, the flaps lever is in position "2". The position of this lever can be changed by pulling the release. Set this lever to position "3" as soon as the speed indicator falls below "155 kt". At the front of the cockpit, in the middle above the large screens, there is a knob labeled SPD. The initial value is "150 kt". Now turn the knob until the target value of "140 kt" is displayed.
10	Middle console	On the rear part of the center console, between the two seats, the flaps lever is in position "3". The position of this lever can be changed by pulling the release. Set this lever to the "Full" position as soon as the speed indicator falls below "144 kt".
11	Autopilot control unit	Now search the screen in front of you for the indicator Above Ground Level (AGL) and wait until it shows "100 ft".
12	Primary flight display	In the front area of the cockpit, in the middle above the large screens, there are four small displays. Below the second from the left is a button labeled "A/THR" (Auto Thrust). Press this button.
13	Middle console	On the front part of the center console, between the two seats, the "SCB" levers are in position "CL". Set these levers to position "0".
14	Middle console	The "Spoiler" lever is located at the rear of the center console. The position of the lever can be changed by pulling the release. Pull the lever backwards.
End		You have landed successfully if the speed indicator (SPEED) on the screen in front of you displays a speed of less than 10 kt.

Table 2.5: Steps eight to fourteen of the 14 individual steps to successfully complete the task for landing.

Figure 2.7: Middle front view of the cockpit with labeling.

If all steps are executed in the correct order, the scenario ends with a "perfect" landing on the runway. However, there are also time components. If the average time is exceeded, but all correct steps are taken, a landing is still possible. However, no longer on the runway, but off it. If steps are omitted, executed too early or too late, a landing is not possible and the simulated aircraft continues to fly at a constant altitude in the last flight direction set. In this case, the scenario can be aborted and paused by the test instructors. This operationalization makes it possible to check the effectiveness of the instructions for the action, since only a limited number of possible outcomes are possible. To land the airplane at the airport there are two different error types:

- *Unknown error*: The single actions by the subjects performed for the first time. Example: The 2nd step change the heading position form "0" to "45" for the first time.
- *Known error*: The single action by the subject performed one or more times before. Example: The 4^{th} step with change the heading position form "45" to "83".

2.3.1 Preparation of the operating instructions

This chapter shows how the three different instructions for actions to be compared were constructed. Due to the given flight simulation scenario, the action steps to be taken for a successful landing are identical for all three action instructions. The instructions for action therefore differ only in the way they describe the steps to be taken. The 14 steps (see Table 2.4 and 2.5) are only different in the presentation form, not in the content.

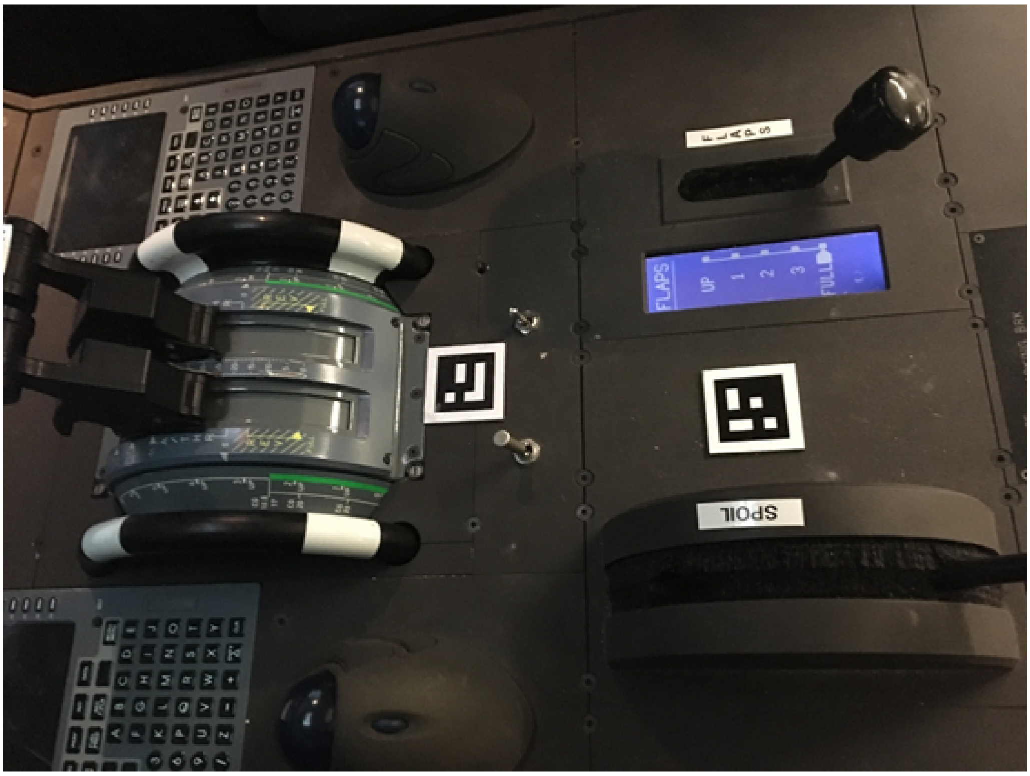


Figure 2.8: Middle of cockpit between the two seats with the controls for the spoiler and flaps.

In general, there are three different forms for instructions each with the same content, but each of which have a different presentation form. These three variations are the most common types of instruction forms:

- Algorithm presentation
- Image presentation
- Text presentation

In the following three sections, only these different ways of presentation are explained. For the complete sets of instructions see [HKF20b].

Algorithm form

The idea for the algorithm form comes from the area of rescue medicine for paramedics and fire teams. The aim is in time critical situations to save lives in a quick and efficient way. The algorithm form presentation is defined by a meaningful and consistent process of symbols [Int85]. It is taken into account that even complex work processes can be made visible. The instructions contain white diamante for decisions, yellow rectangles for commands and blue arrows for further information. Figure 2.10 shows an exemplary of an algorithm.

Figure 2.9: Front display of the cockpit with the standard knobs and buttons for adjusting the functionally of the aircraft.

The algorithmic representation of the statement was created using the free software yEd Graph Editor®. It comprises a total of four DIN A4 pages.

Image form

The second instruction form is the standard image presentation. These image form presentation variations are typically used for instructions for furniture or LEGO®. Every single step shows images in the same way and is printed on separate DIN A4 pages. The left image is the "actual or present" state and the important step in red. The right image is the "should be" state with the action or treatment step in red. In the middle, you see a red arrow for the subject to follow from the starting image through to the end image. The two black boxes are needed for the eye tracking system. Figure 2.11 shows an exemplary of a step, at 7 NM the button "HDG" must be turned to 83.

Text form

Checklists are the used from of technology for instructions in aviation. There are many high quality level publications in textual presentation forms for flight systems, the leading institution is the NASA [DW94]. However, the subjects in the test were alone, so that the classic format cannot be used. Therefore, the typical two man design has been modified and

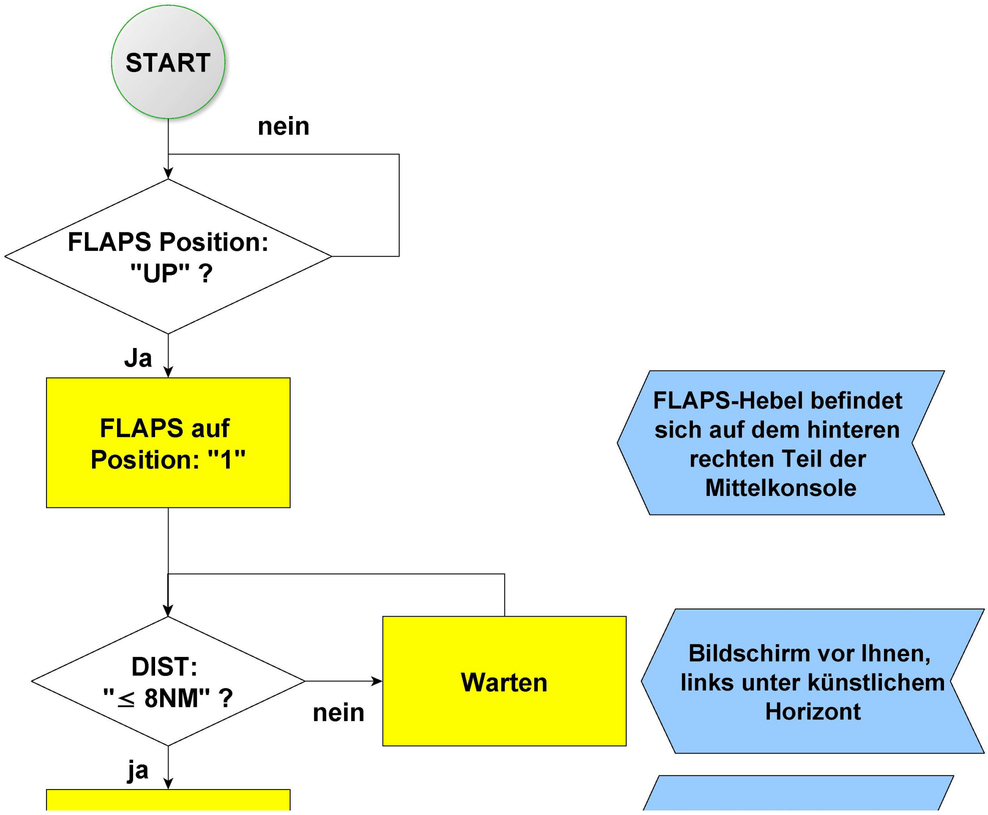


Figure 2.10: Exemplary excerpt from the algorithmic presentation form for the probands.

adapted, so that the text form can be executed by one person. The instruction (see figure 2.12) shows the first four steps for landing at the airport. On the left, the initial state and on the right, the target state.

2.3.2 Experiment expiry

The experiment consist of five parts. A short overview can be found on Figure 2.18. The five steps are:

1. *Welcome and Introduction*

   The experiment starts in the foyer of the Flight System Dynamics Department of the Technical University of Munich with the greeting of the subject and the introduction to the experiment. At the same time, the experimenter introduces the task to the subject: which is to land an aircraft at Munich Airport, they are instructed to do so quickly and precisely, step by step. The experimenter also briefly discusses the use of the Dikablis Eye Tracking System, as well as how to unlock levers, as well as, the announcements and warning tones in the cockpit. In addition, attention is drawn to the low brightness of two display displays, but which can be read by changing the seating position.

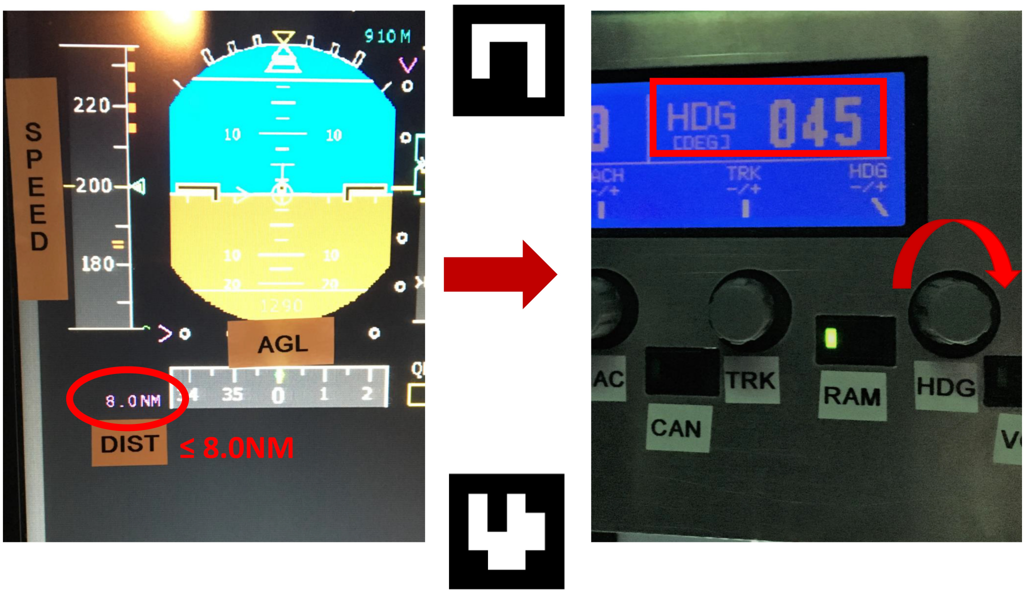


Figure 2.11: Exemplary excerpt from the image presentation form for the probands. On the left, the initial state, on the right, the target state, the middle figure is for the eye tracking system.

Initialisierungszustand	**Auszuführende Handlung**
1. **FLAPS** (Hebel Mittelkonsole hinten rechts) auf Position: **„UP“**	**FLAPS** auf Position: **„1“**
2. **DIST** (Bildschirm vor Ihnen, links unter künstlichem Horizont) zeigt: **„≤ 8.0NM“**	**HDG**-Regler (mittiger Frontbereich) auf**: „45“**
3. **HDG-Regler auf: „45“**	**SPD**-Regler (mittiger Frontbereich) auf**: „180“**
4. **DIST** (Bildschirm vor Ihnen, links unter künstlichem Horizont) zeigt: **„≤ 7.0NM“**	**HDG**-Regler auf**: „83“**

Figure 2.12: Exemplary excerpt from the text presentation form for the probands. Left the initial state, on the right the target state.

2. *NASA Questionnaire and consent form*

   Subsequently, the subject is given a declaration of consent, which informs them about data acquisition, processing and storage. After signing the document, the subject receives a second form with demographic questions and a test for interaction related affinity. In the demographic part age, sex, activity, experience with action instructions, experience with complex systems and flight experience are queried.

3. *Preparation*

   Afterwards, the experimenter leads the study participant into the room with the flight simulator and asks them to take a seat in the cockpit on the left side. As soon as the subject sits down, they put on the Dikablis ® eye tracking system and it is individually adjusted as required. For this purpose, the experimenter must align the eye cameras to the subject's eyes and coordinate the field cameras with the field of view of the subject. Next, the system is calibrated with the "Calibration Wizard" in D-Lab so that the gaze behavior can be recorded during the experiment. After completion of the calibration, the subject receives the instructions assigned to them and is asked to only read the cover page. Meanwhile, the experimenter launches the simulation software and adjusts the autopilot setting to the output parameters. Afterwards, the subject receives instruction as to which areas in the cockpit are relevant for the experiment and how the given instruction manual is structured. If the subject does not have any questions about the course of the test flight, it is again pointed out that the steps of the handling instruction work are to be completed as quickly and precisely as possible and the recording of the eye tracking system is then started. During the test preparation, the experimenter takes care that the subject has little time to look around and memorize the cockpit, in order to create the same experimental conditions for all subjects. This is made possible through the fact that the subject first takes a seat on the pilot's seat, which has been retracted. This physical location in the cockpit makes it impossible for the subject to read the labels on the controls. Then, the subject gets the eye tracking system turned upside down and then has to hold the DIN A4 sheet used for the calibration with outstretched arms in front of their face and fix different points on the sheet. When the calibration of the eye tracking system is complete, the subject moves the pilot's seat forward to the final test position. Only then, does the subject receive the instruction to read the explanation on the starting page of their instruction form.

4. *Experimental Procedure*

   The test flight is started by the subject themselves by pressing the pause button on the overhead panel. Then, the flight simulation immediately starts and the subject begins to work through their given instruction form. Meanwhile, the experimenter does not answer any further questions and only intervenes if the following situations occur:

- The subject actuates an incorrect key without noticing, e.g. by slipping the specially constructed cover, then the original condition is restored by the experimenter.
- The subject misses the instruction to extend the landing gear, then the experimenter takes over this step to prevent a crash of the simulation model.
- The instructions are executed too slowly, which makes a landing impossible, then the attempt is aborted by the experimenter at step 11.

The experimenter sits next to the subject during the entire experiment and logs their mistakes and special occurrences. After the end of the test, the landing of the aircraft or the termination of the flight, the experimenter stops the simulation and the recording of the eye tracker. The duration of the flight amounts to 4 to 6 minutes depending on the aptitude of the test person when following their given set of instructions and their orientation in the cockpit.

5. *Completion questionnaire*

   In the final part of the experiment, the subject is allowed to discontinue the eye tracking system and receives the NASA TLX questionnaire, which examines the subject's perceived workload during the flight simulation. Finally, the focus and the topic of the study is explained to the subject and sweets are offered as a thank you for their participation.

2.3.3 Data acquisition from cockpit with error types

With Simulink from MathWorks®, all variables were recorded with 100 Hz , in order to be able to evaluate them afterwards. The aim of the test is to perform the necessary steps as quickly and precisely as possible. The errors were defined according to [SG83]. A step is only to be executed when the initialization conditions are fulfilled. In the case that a subject needs so long for first action step that the initialization condition for the second action step is already falsified during the conversion of the first action and the result for second action step is falsified. The time at which these two conditions are fulfilled is the time $t_{PreInit}$ for each action step. The time at which the required action was successfully performed corresponds to the time t_{succ}. For the evaluation, the difference between t_{succ} and $t_{PreInit}$ is now calculated for each action step. This then corresponds to the difference $t_{succ} - t_{PreInit}$. A metric is defined in the second to answer the question about the temporal differences between the occurrence of the required action and the execution of the action. The difference between the time at which an action step becomes necessary and the time at which the action is successfully implemented $t_{succ} - t_{PreInit}$ is produced for each action step. The complete data set of the experiment can be found in digital appendix of the published paper [HKF20b].

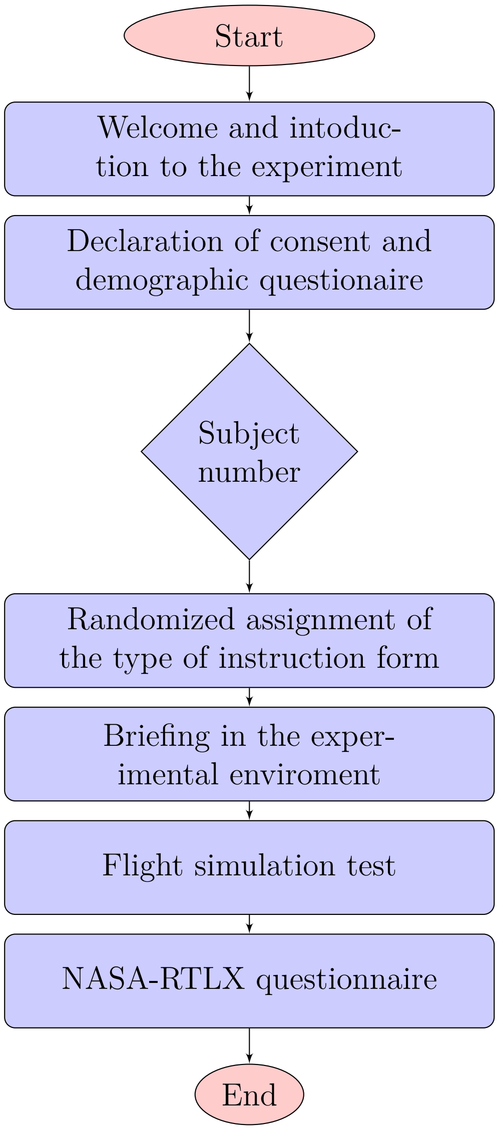


Figure 2.13: Presentation of the experimental setup as a flow chart from start to the end.

2.4 Results from the flight simulator

Data and overview of the test population:

- The study included n = 93 subjects (Sex: 73 male, 20 female).
- Each of the 93 test persons was randomly assigned to either the group algorithm n = 31, image n = 31 or text n = 31.
- Age between 18 and 61 ($\phi = 29.04$ with an $\sigma = 9.32$ years).
- 79 subjects did not have any experience with simulators (PC etc.).
- 24 test persons had flight experience (6 test persons had already operated a flight simulator).
- Technical affinity with ATI questionnaire is 4.721 (scale from 1 to 6). There are no significant differences in technical affinity between the three groups (algorithm = 4.771, image = 4.633, text = 4.756).

2.4.1 Frequency of top event

A successful landing depends on the facts that the steps are correctly executed in the simulator and in the correct chronological sequence. Therefore, a distinction is made between landing on the ground (correct sequence of steps in the simulator) and landing on the airport runway (correct sequence of steps in the simulator and appropriate time). Figure 2.14 shows how many of the test persons managed to prevent the top event of the "no landing" and how many caused the occurrence of a top event.

The chi-square test was conducted between the type of instruction and successful landing. No expected cell abundances were less than 5. There was a statistically significant relationship between instruction type and successful landing, $x^2(1) = 11.586$, $p = .003$, $V = 0.353$. Since $p = .003$ is smaller than $\alpha = .05$, there is no significant difference in landing frequencies between the three instruction forms. With a V of 0.353, the choice of action instruction has an average effect on the number of landings. The null hypothesis is assumed with:

$$H_{1\ (Top\ event\ ground)} \tag{2.12}$$

There is no association between the type of instruction and successful landing on the ground.

Figure 2.15 shows how many of the test persons managed to prevent the top event (the non-landing or landing next to the runway) or managed to land on the runway.

The chi-square test was conducted between the type of instruction and successful landing on the runway. There was no expected cell frequency that was less than 5. There was a statistically significant relationship between the type of instruction and successful landing, $x^2(1) = 15.040$, $p = .001$, $V = 0.402$. Since $p = .001$ is smaller than $\alpha = .05$, there is a

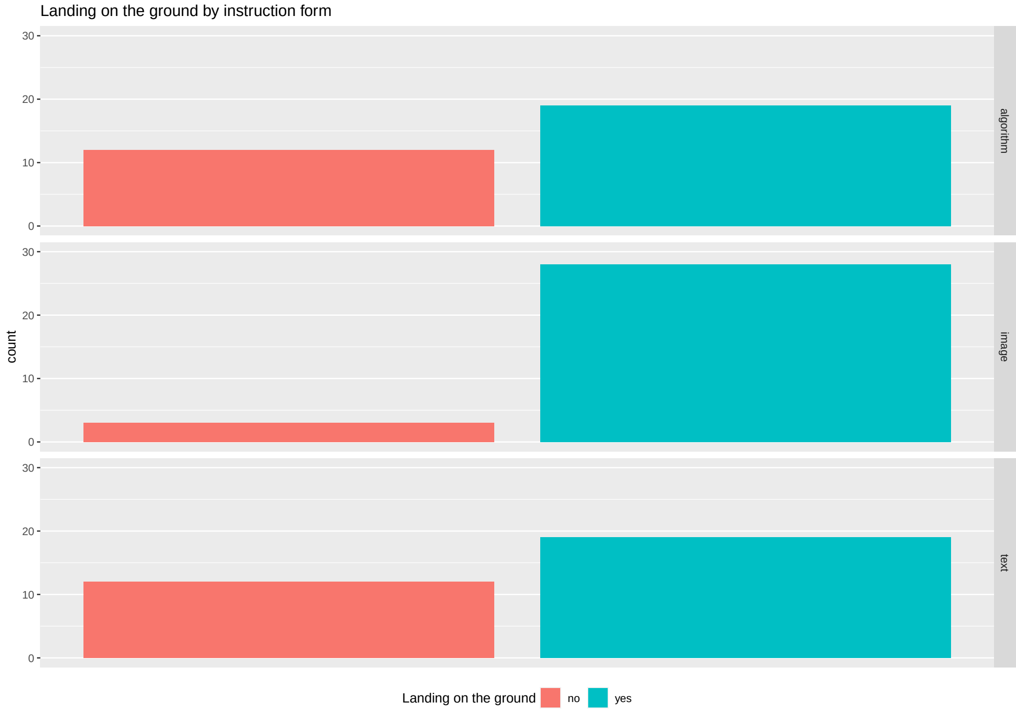


Figure 2.14: Face sheet with number of landings on ground. The graph shows the division of the three groups (each group algorithm, image and text has 31 subjects in it). The "count" on the y axis is the number of subjects per instruction form. Blue indicates a successful landing on the ground and red an unsuccessful landing.

significant difference in the frequency of runway landings between the three samples. With a V of 0.402, the choice of the action instruction has a medium effect on the number of landings on the runway.

$$H_{0\ (top\ event\ runway)} \tag{2.13}$$

There is no association between the type of instruction and successful landing on runway.

2.4.2 Number of errors

The following section describes the results for the three hypothesis pairs in terms of the number of errors made. Figure 2.16 shows a box plot on the x axis as the representation of the action instruction and on the y axis the number of errors. The definition of known and unknown errors, see on the chapter 2.2.1. All errors are split in these two categories, because the results are different, if the subject does the operation for the first time or the second or more.

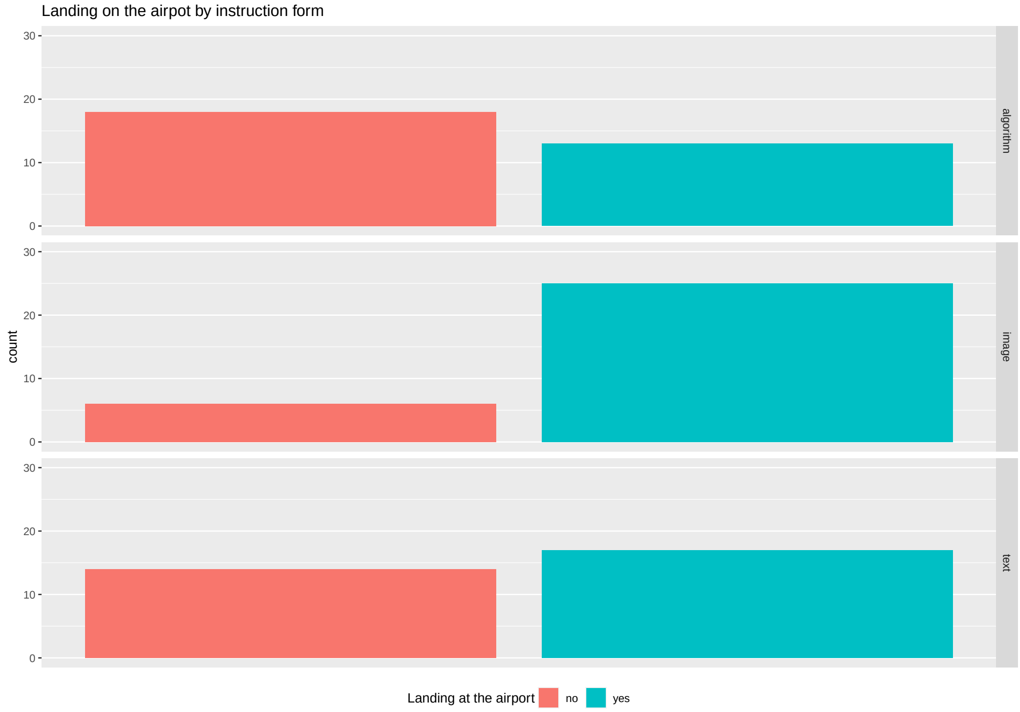


Figure 2.15: Face sheet with number of landings on the runway. The graph shows the division of the three groups (each group algorithm, image and text has 31 subjects in it). The "count" on the y axis is the number of test persons per instruction form. Blue indicates a successful landing on the ground and red an unsuccessful landing.

Analyzing all errors (known + unknown)

In the following section the cause of all errors is analyzed, including both known and unknown errors. Firstly, all errors together. The mean number of all errors (including the known and the unknown errors) is in the group with the algorithm instruction form $\phi = 1.74$ errors ($\sigma = 1.527$), with the image form $\phi = .81$ errors ($\sigma = 1.138$) and the text form with $\phi = 1.55$ errors ($\sigma = 1.502$).

Statistical tests for all errors:

- Normal distribution of the three samples of $p < .05$ with significant Kolmogorov-Smirnov test result for all three samples.
- The effective strength with $\eta^2 = .79$ corresponds to an average effect.
- Variance homogeneity with Levene's tests with $p = .382$ shows that a variance homogeneity of the three samples can be assumed.

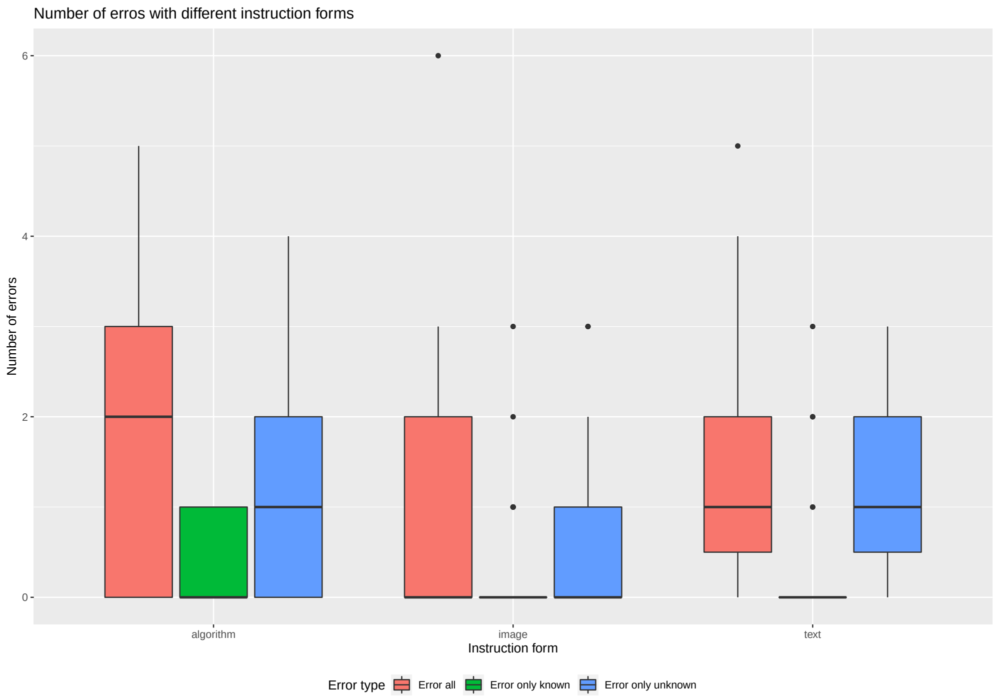


Figure 2.16: Number of errors, divided into all known and unknown errors according to display form.

The alternative hypothesis with:

$$H_{1\ (Number\ error\ all)} \tag{2.14}$$

is assumed. The number of errors differs significantly between the instruction forms for the total number of errors.

Analyzing only unknown errors

In case of the analysis of only the unknown errors (A single action step that is executed for the first time) the results shows that the group with the algorithm form had $\phi = .35$ errors ($\sigma = 1.124$), the group with the image form $\phi = .55$ errors ($\sigma = .850$) and the group with the text form $\phi = 1.26$ errors ($\sigma = 1.064$).

Statistical tests unknown errors:

- Normal distribution of the three samples of $p = .002$ with significant Kolmogorov-Smirnov test result for all three samples.
- The effective strength with $\eta^2 = .113$ corresponds to an average effect.
- Variance homogeneity with Levene's tests with $p = .082$ shows that a variance homogeneity of the three samples can be assumed.

The alternative hypothesis with:

$$H_{1\ (Number\ error\ unknown)} \tag{2.15}$$

is assumed. The number of errors differs significantly between the instruction forms for the total number of errors.

Analyzing only known errors

If calculating only the known errors (Steps that were carried out before and are now carried out again) in the group of algorithm form $\phi = .39$ errors ($\sigma = .715$), the group with the image form $\phi = .26$ errors ($\sigma = .514$) and the subjects with the text form $\phi = .29$ errors ($\sigma = .6934$).

Statistical tests known errors:

- Normal distribution of the three samples of $p < .001$ with significant Kolmogorov-Smirnov test result for all three samples.
- The effective strength is smaller with $\eta^2 = .007$ corresponds to an average effect.
- Variance homogeneity with Levene's tests with $p = .392$ shows that a variance homogeneity of the three samples can be assumed.

The null hypothesis with:

$$H_{0\ (Number\ error\ known)} \tag{2.16}$$

is assumed. The number of known errors does not differ significantly between the representation forms.

Human error probability

So far, only the errors of the subjects have been analyzed depending on the respective group. However, how the errors change when an action is performed several times is also of central importance. The HEP describes the data in a more understandable way. The table 2.6 shows the percent of HEP between the unknown and the known errors. The data describes the error probabilities and shows that the probability of making an error is more than twice as high for algorithmic and textural instruction than for image instruction. The difference between unknown and known steps of HEP in the table is much smaller with a rate of below of 4 %.

Instruction form	$HEP_{unknown}$	HEP_{known}	$HEP_{unknown} - HEP_{known}$
Algorithm	22.58 %	7.74 %	14.84 %
Image	9.14 %	5.16 %	3.98 %
Text	20.97 %	5.81 %	15.16 %

Table 2.6: Comparison of HEP for unknown and known actions with the reduction of the first operation (unknown) to the repeated operation (known).

Instruction form	n for all ϕ in s / σ in s	n for unknown ϕ in s / σ	n for known ϕ in s / σ
Algorithm	242 15.289/12.718	132 18.989/15.077	110 10.848/6.925
Image	297 12.61279.799	162 13.777/11.239	125 11.512/7.532
Text	275 15.531/15.080	150 19.293/17.658	135 11.016/9.494

Table 2.7: Time analysis for all steps of operation and in dependence of the instruction form with the mean (ϕ) and the standard deviation (σ) for known and unknown.

2.4.3 Time for operation

This analysis focuses on the time of the operations. All of the following data is only calculated for probed events with a complete data set. Table 2.7 shows the overview with the number of analyzed individual action steps executed by the test persons with the average time in seconds for each action instruction with the mean value and standard deviation. As with the analysis of the errors, a distinction is now also made in the analysis of the determined times according to known and unaccounted for actions.

Time for all operations

The time required for all operations (known and unknown together) to perform the required actions were statistically significantly different for the three different instructions forms for all actions, Welch Test $F(2, 502.587) = 5.608, p = .004$. To find significant time differences between all possible combinations of algorithm, text or image, a Games-Howell post-hoc test is used. The most significantly different results are between algorithm and image form with $p = 0.020(2.676, 95\% - CI[.335, 5.018])$ and on a further combination between text and image with $p = 0.018(2.919, 95\% - CI[.397, 5.440])$. The one way ANOVA results performed single sector ANOVA without repeated measurement shows that the times required to execute known action steps do not differ significantly statistically for the three different action instructions, ANOVA $F(2, 367) = .063, p = .939, \eta^2 < .001$.

The null hypothesis "There is no time difference between the types of instructions":

$$H_{0\ (time\ all)} \tag{2.17}$$

is therefore assumed. Correspondingly, there is no time difference between the different types of instructions.

Time for unknown operations

The result for unknown operations time is for all three instruction forms different. The Welch Test results in $F(2, 271.174) = 8.305$, with a significance level of $p < .001$. The Games-Howell post-hoc test does not find any significant differences between the algorithm and image form with only $p = .003(5.212, 95\% - CI[1.482, 8.943])$. Furthermore, the relation between the text and image form is $p = .004(5.517, 95\% - CI[1.530, 9.503])$.

Time for known operations

If analyzing only the known operations, there are no statistically significantly differences between any other combinations of the three groups (algorithm, image or text).

2.4.4 Workload analysis

The following analysis is the result of the answers of the questionnaire by NASA-TLX workload score. Generally, there are scores of:

- Algorithm: $\phi = 8.935, \sigma = 2.809$
- Image: $\phi = 7.817, \sigma = 2.910$
- Text: $\phi = 9.978, \sigma = 2.551$

In NASA-TLX score it is possible to give a response of between 0 and 20 points for the effort, frustration, mental requirement, performance, physical requirement and the time requirement depending on the different instruction forms. Figure 2.17 shows the answers regarding the three different instruction forms and the feedback on the perceived amount of workload.

There are significant differences between:

- Image and algorithm (1.118, 95%-CI[-.553, 2.789])
- Algorithm and text (2.161, 95%-CI[.490, 3.832])

No significant difference in workload between Levene's test (p = .615) and Tukey's post-hoc test with medium effect strength $\eta^2 = .095$ only for text and image with $p = .008(2.161, 95\% - CI[.490, 3.832])$.

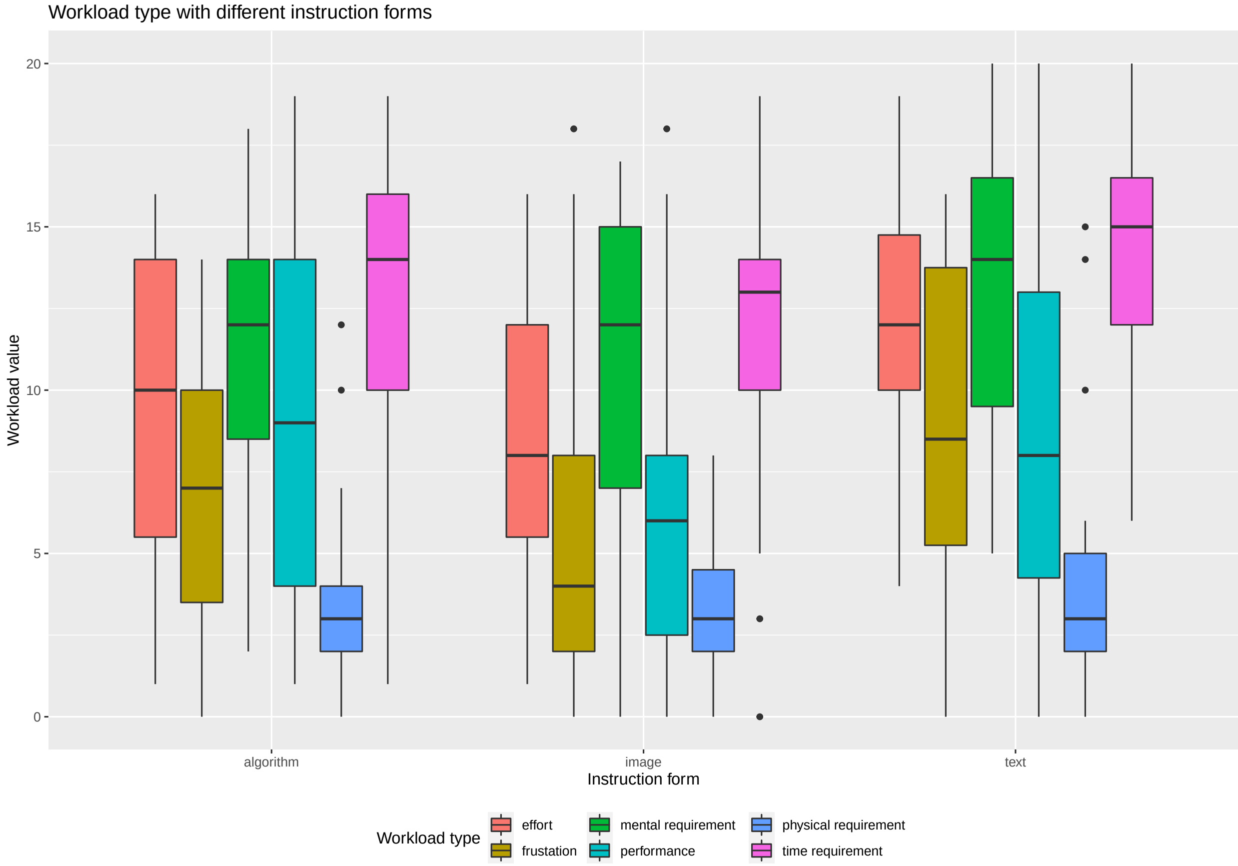


Figure 2.17: Analysis of questionnaire answers by a boxplot with the workload score. The workload is split by the three different instruction forms (algorithm, image and text).

2.5 Discussion of the organizational part

Chapter 2 describes the possibility of quantifying different instructions. It describes the development of the method, the test setting and the results. In the following, these sections are critically examined as to whether they serve their purposes, which improvement steps are available and which options further studies may follow.

The test procedure has proven to be a good method to compare different types of instructions. The three most common forms of instruction (text, image and algorithm) also form the majority of instruction forms worldwide. However, there are other ways to transfer information. Influencing factors such as light, temperature or noise were not taken into account in the study. The research field "Light and Health" offers complete conferences [RBPB19]. They only examined the influence on nighttime melatonin suppression and show that the effects when illuminating areas of the retina in the lower and nasal parts of the retina are more pronounced [LKE99, SKEY02]. The experimental setup had exactly this influence so that the screen of the measuring instruments was bright and located in the lower area. It

Instruction	Flight experience	Complex system experience	Sex female
Algorithm	10	6	3
Image	8	13	8
Text	6	9	9
Σ	24	28	20

Table 2.8: Distribution of the test subjects to the respective instruction form of algorithm, text and image. In addition, the division of people and questions. A total of n = 93 subjects.

has to be discussed here that in further tests attention is paid to uniform illumination of the test scenario in order for it not to have an influence on them.

In general, it must also be considered whether the result can be transferred to the general public. It is striking here that the proportion of women among all test subjects is very low (see Table 2.8). The sample has a female portion of 21.50 %, while in the general population it is 50.64 % [Sta20]. The call to the study was probably mostly received by TUM students, where the female population is also underrepresented. In future investigations, the real result could definitely be better determined here, if the gender distribution would correspond to reality.

Likewise, the result was influenced by a purely random selection, the distribution of people with experience in complex systems or flight experience. Table 2.8 show the distribution of a total of n = 93 subjects with previous experience in complex systems and experience in flight simulators. The finding that almost twice as many people in the group of algorithms are present who have flight experience compared to the subjects in the text group must of course also be critically examined. This factor should also be recorded differently in a new study. One possible way would be to change the test process or the group selection process to ensure an even spread of said subjects. Although, this would mean that subjects would not be randomly assigned to a group (see figure 2.18).

This process would no longer be completely random, however it would have the great advantage that shifts in the statistical evaluation would be far less likely. A maximum of one subject per instruction is shown. The study analyzes the quantification of the different forms of instruction. When processing the 14 individual test steps, a specific instruction was always followed. In very complex systems, other forms of action can of course also be divided. Here, the algorithm would probably again outweigh the other forms of instruction.

The statistical operations are analyzed below. The significant results of the Chi^2 test with p = .003 and p = .001, respectively, result in the conclusion that the different results for the frequencies of landings and landings on the runway are not accidental. $H_{0\ (Top\ event\ landing)}$: $\mu_1 = \mu_2 = \mu_3$ is discarded and $H_{1\ (Top\ event\ landing)}$: $\mu_i \neq \mu_j$ is assumed. This applies to landing on the ground and landing on the airport runway. Therefore, the following conclusion is made: Instruction forms have an influence on the avoidance of top events. The most successful landings (landings next to the runway/landing on runway/total number of subjects) are the image group (29/26/31), followed by the text (19/13/31) and finally, the algorithm group with (18/13/31). The results of the ANOVA on error frequencies show that

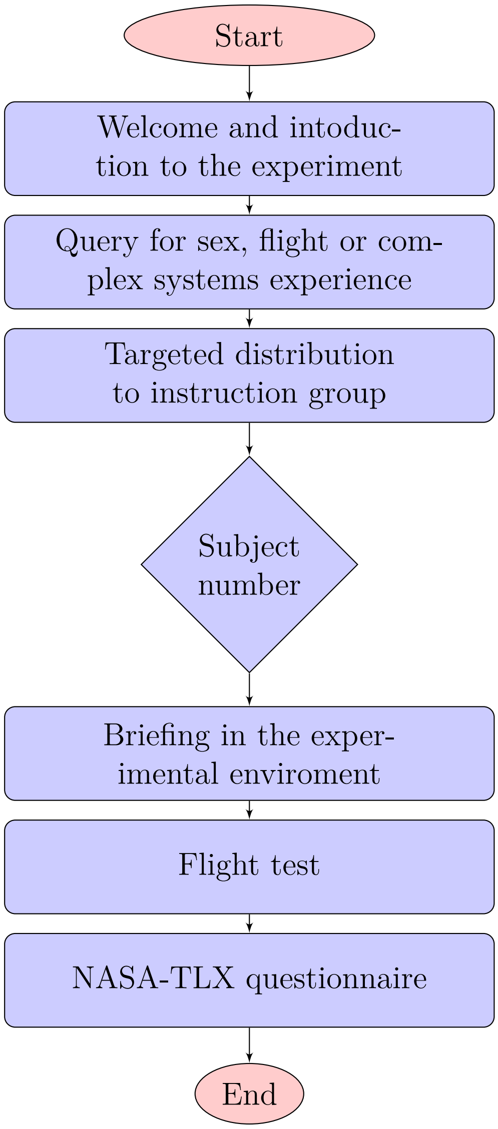


Figure 2.18: Modified version of the experiment. First query about sex, flight experience and experience with complex systems, then assign the groups into image, algorithm or text instruction form.

there is a significant difference between the 11 usable, considered action steps with regard to the error frequencies between the three action instructions. The individual frequencies differ between the three samples to the extent that it appears that these results are not of a random nature. However, the post-hoc tests conducted show that this significant difference can only be demonstrated between algorithmic and imagine instructions for action. A similar outcome can be seen when considering the unknown action steps. The conducted post-hoc tests show that there are significant differences between image and text instructions as well as between image and algorithm instructions. Here, there is a clear tendency that the imagine instruction causes fewer errors in unknown action steps than both algorithm and text instructions. When only the known steps of action are considered, a different picture emerges: error frequencies do not differ significantly between the types of instruction form. Thus, none of the three instruction forms used seem to be superior with regard to error avoidance. An explanation for this could be the fact that the image instruction is the only one that visually supports finding the required operating elements by visually describing the position of the operating elements. The other instructions only contain this description in text form. In addition, the examination of the prerequisites for carrying out the ANOVA shows that the assumption of a normal distribution of the samples cannot be assumed on the basis of the Kolmogorov-Smirnov test performed. Since the ANOVA of large samples ($n <= 30$) is very robust against a violation of the normal distribution, this can be performed and interpreted as in the present case [PS18].

The results of the Welch ANOVAs on the execution times show that there are significant differences in the execution times of the action steps between the three different instruction types, across all action steps. In addition, there is also a significant difference in the execution times of the unknown action steps. For the known action steps, however, there is no significant difference. It should be noted in advance that, in contrast to the previous hypotheses, the sample sizes are no longer identical. Only complete data sets are included in the evaluation, which means that only 22 test subjects are included in the algorithm instruction, 27 in the image instruction, and 25 in the text instruction. This procedure, the elimination of incomplete data sets, can be viewed critically. There are various ways of dealing with missing values. These range from the elimination of incomplete data sets to imputation, which is equivalent to estimating missing values [Fli07]. For the following reasons, an estimation of missing values is dispensed with, and the procedure of eliminating incomplete data sets is chosen. It is also conspicuous that the algorithm instruction on average achieves better execution times in the known steps than the text instruction. However, this must be put into perspective insofar as the algorithm instruction with 22 test subjects has the smallest sample for this test, the worst test subjects are already excluded. However, since no significant difference between algorithm and text instructions can be determined, this fact plays a rather subordinate role. The comparatively high standard deviations across all hypothesis tests are a further sign that the interindividual and intraindividual differences are very large. This makes it more difficult to interpret the results unambiguously.

The results of the evaluation of the NASA-TLX questionnaire show that there is a significant difference in the amount of perceived stress between text and image instruction. However, a significant difference between the text and algorithm, as well as the algorithm and image instruction form, is not to be found. The text instruction for action is shown to be the highest regarding perceived load during the work task. This is followed by the algorithm instruction, which is evaluated as somewhat less stressful than the text form. However, since the difference between the NASA-TLX scores achieved is not significant for these two forms of instruction, a precise statement cannot be made about the causes of the difference. The image instruction for action yields the lowest value and is thus the "least stressful" type of instruction. It is shown that there are substantial differences with regard to the perceived stress. Since the success of the accomplished task must also be evaluated in the NASA-TLX, this may also be a reason for the good results of the image instruction. This was highlighted by the results of the "top event" hypothesis. The image instruction also results in the most successful landings, which may be related to the lower perceived load. The use of the algorithm form of instruction tends to be classified as less stressful compared to the text form of instruction. With regard to the NASA-TLX scores evaluated with a single-sector ANOVA, it is questionable whether the ANOVA requirement for a dependent variable with at least interval scaling is fulfilled. The problem here is whether the NASA-TLX score represents such an interval scaled variable. To achieve this, the difference between two different intervals would have to be interpreted in exactly the same way [Tsc14]. In research practice, it has become established to assume multilevel questionnaire items as being interval scaled [HDMG14]. The implementation of a single step ANOVA is thus a tried and tested means of evaluating the NASA-TLX scores [Jac07].

Another goal of the work is to generate impressions of the interaction of the test persons with the different instructions by using the eye data recording. Gaze data analysis, time-to-marker analysis and analysis of operating behavior could produce interesting observations. However, this does not apply in this work. In view of the poor quality of the gaze data and the resulting omission of the presentation of the results from this data, the discussion of these results is also dispensed with. In addition to recording the flight data, the gaze data of the subjects is also recorded using the Dikablis Professional Eye Tracker from Ergoneers GmbH®. This is a head frame that is worn similar to glasses and records both the eye movements and the wearer's field of vision via three cameras. Two of the cameras, the so-called eye cameras, are aimed at the subject's eyes and document the pupil movements. The third camera, the field camera, films the surrounding area. The recorded videos can be stored one above the other using the D-Lab software from Ergoneers GmbH ®. This creates the subject's gaze, which provides information about their gaze behavior. An evaluation and interpretation of this data will most likely lead to incorrect statements. As a result, no results are presented here. The results generated in the preliminary test are subject to very strong individual fluctuations, so that a trend cannot be discerned in the small number of subjects present in the preliminary test. This is due to two factors of influence. One factor is that the lighting in the flight simulator is not strong enough. Secondly, the frequent changing of the viewing direction despite the new eye tracking systems could not be reliably evaluated. This can be improved in another study.

The tested procedure is exclusively defined for a fixed processing of steps (14 individual actions). A new exciting hypothesis arises from the question of which form of instruction is the best for a decision. Statements such as "If the parameter is larger than x, then if the parameter is smaller than x, then that" would be a very good improvement of future test settings. Here, differences could be worked out even more. Very complex systems can also be analyzed.

At the end of the chapter with the organizational measures, it must be stated that the scientific quantification of human measures in fire protection is an important step in the right direction. The forms of instruction described (text, algorithm and image) play an important role, especially in fire protection, in order to improve the quality of the negative fire protection.

Chapter 3

Technical quantification with probabilistic system

In 2018, Prof. Rost as a keynote speaker at the largest European fair for fire protection in Nuremberg - Germany said: "Higher construction costs are not caused by fire protection in buildings (as many headlines suggest), but by engineers, planners and authorities who fail to implement correct fire protection and/or approve it, even though there is a lack in their expertise. Over the last 30 years, the fire protection requirements in building law have been significantly reduced [1] [Ros18]". Of course, one has to ask the question of the efficiency of fire protection versus the costs. In the following chapters, the answer to calculate the effectiveness and cost ratio of fire systems.

The proportion of fire protection costs has risen steadily in recent years. To make a statement about the separate costs for fire protection in buildings in Germany is very difficult. The building regulations are only devised in larger groups without specifically focusing on fire protection [Deu18]. This chapter describes which gaps exist in risk quantification in technical fire protection and the methodological approaches to be used. Chapter III is split up first, into section 3.1 with an explanation of the basis of FTA and technical fire systems, secondly section 3.2 describes the important input values with the developed quality level, in the third section 3.3 the DFT with time dependent is examined, the fourth section 3.4 looks at the advanced input values, the fifth section 3.5 exhibits a developed algorithm for the new methodology and to analyze quality levels, section 3.6 describes the RIAAT® application and finally the last section 3.7 contains the discussion of the technical part.

Specifically, there are three aspects of FTA to be analyzed as described in this chapter:

1. The first main topic is the dynamic of technical systems with time dependent of an FTA method analysis in chapter 3.3

2. The second main topic explains which input values are needed for advanced results and it is explained in 3.4

[1] Own translation of the keynote speaker, the original was "Höhere Baukosten entstehen nicht durch den Brandschutz (wie viele Schlagzeilen suggerieren), sondern durch Ingenieure, Planer und Behörden, die den Brandschutz aus Mangel an Fachkenntnissen nicht optimal umsetzen und genehmigen. In den letzten 30 Jahren sind die Brandschutzanforderungen im Baurecht erheblich reduziert worden".

3. The third main topic explains the development of an algorithm to accurately interpret the results of an FTA and find the correct mathematical calculation method for it in subsection 3.5.

In order to present an application case, the individual parts are implemented in the software package RIAAT® and its use is explained in section 3.6. The chapter ends with a critical examination of the developed models. Before presenting the topic in detail, the definition of some terms is needed. There are two options for defining safety requirements in fire protection or in other disciplines with a high risk consequence in the case of failure, such as in nuclear plants and emergency control center dispatches or on aircraft. To generally describe the requirements there are two different ways:

- *Descriptive Based Code*: The first way is the classical version with simple and clear conditions in a Descriptive Based Code (DBC). Here, the requirements are defined with exact words with fixed meanings, for example, a classical fire wall is needed every 40 m [Bau12]. The term "fire wall" is defined in national regulations with five characteristics in a national regulation based on national statistics [Bay19]. This is that fire walls are needed every 40 m, the building materials have to be inflammable, if there are bulkheads, the fire resistant class needs to be at the same level, they must be resistant up to 90 minutes in a standard fire and they have a height that exceeds the top of the ceiling by at least 30 cm. Here you can build with fixed standardized building components such as doors, bulkheads and so on. This is a brief explanation of some of the standards that exist in the German building industry and generally throughout the EU.
- *Performance Based Code*: The second possibility to create a safety concept is through the use of a Performance-Based Code (PBC). This code indicates a required level of performance. It allows the designer and project owner to determine the solution and method to achieve their end goals. In fire protection, this method is not yet possible across borders. However, DIN 18009-1 [Deu16b] is currently being developed to enable a standard in this methodology for the basic model. DIN is currently working on a standard to standardize security concepts. This should then be published under DIN 18009-4. In the subject of technical mechanics, statics and further classical PBC disciplines these methods are state of the art [Sch18, Din18]. For the calculation of the ultimate limit state for the load bearing capacities of a cross section of components or connections, the following can be applied:

$$E_d \leq R_d \tag{3.1}$$

with:

$$E_d = load\ factor\ value\ for\ the\ destabilizing\ effect \tag{3.2}$$

$$R_d = load\ factor\ value\ for\ the\ stabilizing\ effect \tag{3.3}$$

A safety factor is then added when calculating the load bearing capcity for a structure according European codes [Deu10a]. The safety factor S_d is multiplied by E_d depending on the building class.

Both options offer a comparison of the safety requirements for a building. These requirements can describe for an example the safety of people in a building in the case of a fire, the safety requirements for the structural engineering in the case of a earthquake or the structural engineering requirements in the case of heavy snow loads on the roof, so that it does not collapse. The DBC system is an easy way to build, based on precisely defined regulations. Unfortunately, however, the origin of the regulations can almost never be exactly determined. Strong political influences are sometimes at fault, such as the introduction of timber construction in buildings [Fac08]. In this current building trend, it is not about the adavantageous properties of timber as a building material in construction, but for the political sake of promoting timber construction and the timber industry. Although, this makes sense to legislators, in classical engineering it does not, since it does not include quantifiable influences. In order to fulfill a purely scientific approach, the focus here is on PBC, because PBC describes a system on a purely mathematical background, while DBC describes a system on the basis of regulations. However, these regulations always have other internal influences. For example, the economic interests of associations can have an impact on certain content within a regulation and the way is the applied.

The aims of this chapter are:

- To enable objectification and quantification of measures.
- To increase the national ability for fire safety engineering.
- To enable further development of FTA software tools for a comprehensive risk assessment.
- To create a summary of important indicators for comprehensive risk assessment.

To enable the analysis of significant breakdowns, the probability failure or possible interventions and other influence of the breakdowns, the risks involved must be examined. Section 3.1.3 defines the risk of influencing factors and the extent of their damage. The Reliability Availability Maintainability Safety (RAMS) describes the process to identify and analyze potential failures. RAMS methodology with an FTA is state of the art in aircraft engineering [Luf15] and in nuclear technology [Ges01b] and in the new field of building engineering [SMR16]. Using acRAMS allows for the analysis for the probability of failure and the analysis is broken down into 4 parts:

- R = Reliability: The probability that an item can perform a required function under given conditions for a given time interval or period.
- A = Availability: The dependability of a system to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval or period, assuming that the required external resources are provided.

- M = Maintainability: The probability of a system to be in a state or to be reset into a state where active maintenance action is carried out, for an item to be maintained so that it can operate under its given conditions of use. The maintenance can be carried out within a stated time interval, if maintenance is performed under stated conditions and using stated procedures and resources.
- S = Safety: Mitigation of risk to the health and physical integrity of people.

The life cycle of a system consists of its commissioning, maintenance, repair and improvement through to its decommissioning. Furthermore, the whole life cycle of a system [Deu11] can be analyzed, to find opportunities for improvement [LRU09]. The goals in conducting RAMS analysis are the evaluation of the soundness of a system, through the means of modeling complex scenarios, which fosters a better understanding of context, causes and effects of failure, strong visualization of understandable system models, support of probabilistic methods to model uncertainty and the compliance with relevant standards and guidelines [SMR16].

3.1 Basic concept of Fault Tree Analysis and fire systems

In order to provide all of the foundations and basics regarding this new methodical approach to calculate the risk benefit ratio, a basic knowledge of FTA and technical fire systems is needed, which now follows. Since a distinction must be made in the field of technical fire protection between a hypothesis and the verification of a hypothesis, the differences between the descriptive and inductive statistics are described in table 3.1. Generally, in the methodology concerning the science of mathematics and specifically FTAs there is a lot of special terminology. The meaning of the definitions is always transferable to other sciences. The following enumeration describes the most important terms [ESH15]:

	Inductive methods	Descriptive methods
Basic principle	A certain situation is observed and events are noted, then an explanation for its occurrence is found.	A preliminary explanation (hypothesis) of an event or situation is defined and then it is checked as to whether it is true.
Statement	Prognosis	Description
Hypothesis	Only set up	Check possible
Relevance	Creation of new hypotheses	Logic can be formalized
Application	FTA, Network analysis, Boolean algebra	If-Then relationship, Operationalization
Example	72 people were killed in the fire at the Grenfell tower ⇓ That can happen again ⇓ People die in fire	People die in fire ⇓ 72 people were killed in the fire at the Grenfell tower ⇓ Then it can happen again

Table 3.1: Overview of the two general approaches in research methodology, each with the application, fire game logic screen layout.

- *Event*: Occurrence of a condition, activity or action of the system under consideration.

- *Primary event*: Elementary event that cannot be further subdivided or which is deliberately omitted.

- *Logical gate (brief: gate)*: General term of all linked elements, when at least two elements are connected. The word gate does not define in which way elements are connected, only that they are connected.

- *Top level event*: An event, the possible cause of which is examined by an FTA. It is represented by a gate that has no output.

- *Multiple Occurring Event (MOE)*: Primary event, the output and input of which is on more than one super ordinate primary event. Also named as "Common cause" within FTA.

- *Multiple Occurring Branch (MOB)*: Gate, the output and input of which is on more than one super ordinate gate.

- *Minimal cut set*: Set of primary events that occur together when the main event occurs.

3.1.1 Basic concepts in probability

To calculate the probability, a basic concept of stochastic is needed. Classical statistics is traditionally divided into descriptive and inductive statistics. Descriptive statistics describe the facts with empirical models to analyze and visualize measured data. In simple cases, for example, error or characteristic outlines can be recognized by their presentation alone. The second part of classical statistics is inductive statistics, which is based on probability calculus. In this system, by analyzing a random sample of a population, our findings and conclusions can be applied to the whole population [HPSW13]. The population is the set of entities to be studied, while the sample includes only a subset of the objects. If all elements of the sample are captured for the experiment, it is run for a full survey. If only part of the total is collected, this is a partial survey. Since a full census is either very expensive or even impossible depending on the subject, conclusions about characteristics of the population are then drawn from the partial survey on the whole. In this chapter, methods of inductive statistics are mainly used, so that the introduction of this topic lies in focus. Generally, the random variables are defined with A, B, C and the complementary of A is called $\bar{A}$. The result of A and B is AB. The event A or B is $A + B$ and the probability of a result of A is $p(A)$. *Andrej Kolmogorov* defined three basic axioms (equation 1 to 3) and five extended axioms (equation 4 to 8) out of the first three basic axioms [Kol33]:

1. The probability cannot be a negative real number:

$$p(A) \geq 0 \tag{3.4}$$

2. A certain event S has the probability of 1:

$$p(S) = 1 \tag{3.5}$$

3. If A and B are mutually exclusive, then:

$$p(A + B) = p(A) + p(B) \tag{3.6}$$

4. For an event and its complementary to be valid:

$$p(A) + p(\bar{A}) = 1 \tag{3.7}$$

5. For any independent A and B are:

$$p(A + B) = p(A) + p(B) - p(AB) \tag{3.8}$$

6. If A and B are mutually exclusive, then:

$$p(AB) = 0 \tag{3.9}$$

7. If A and B are independent then:

$$p(AB) = p(A)p(B) \tag{3.10}$$

The rules 3, 6 and 7 are used for more than two values. Exclusively A, B and C, results from rule 3 and 6 are $p(A + B + C) = p[(A + B) + C] = p(A + B) + p(C) = p(A) + p(B) + p(C) = p(ABC) = p[(AB)C] = 0$.

8. If A, B and C are independent, follow form rule 7 [BSMM15]:

$$p(ABC) = p((AB)C) = P(AB)p(C) = p(A)p(B)p(C) \tag{3.11}$$

3.1.2 Risk analysis and Boolean algebra

The aim of probability quantification in risk analysis is to identify risks, analyze their possible impact and with this information, help to make decisions to minimize them. In this method, the probability of occurrence and the extent of damage are again taken into account as influencing factors. The first option to evaluate the influencing factors is the qualitative method and second is the quantitative method [San12]:

- In the qualitative method, risk is assessed by estimating non-standardized data and their evaluation. Here, the estimation of the empirical relative risk is transferred to numerical values. The relative risk means that this is a comparison of two systems so that an assessment can be made. Thus, the qualitative statements are converted into a measurable scale (numerical values). Now, comparisons can be made between the numerical values. A fixed relation between the numerical values is then set [PS18]. However, in order to obtain a qualitatively high quality and a usable statement of risk, this model may only be carried out by specialized personnel. The reason for this is the subjective evaluation of influencing factors. Specialists are defined as people who have been performing this task for several decades and thus, have a great wealth of knowledge. Figure 3.2 shows a typical qualitative method matrix with the influence of the probability and the consequence of an event.

Probability				
	IV	II	I	I
	IV	III	II	I
	IV	IV	III	II
	IV	IV	IV	III
	Consequences			

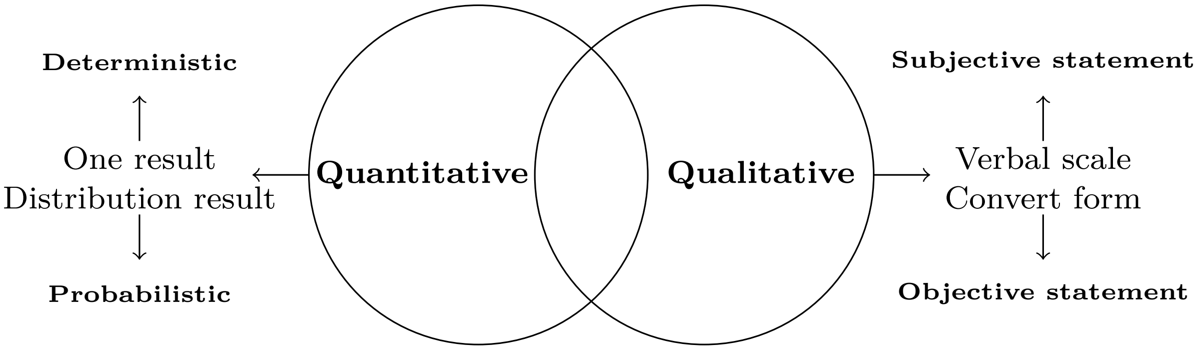
Table 3.2: Matrix with possibility presentation of the probability and the consequence of risk. I = Unacceptable, II and III ALARP, IV Acceptable.

Fixed relation number	Probability of an event	Consequence of the event
1	Low event probability	Low level of consequence
2	Middle event probability	Middle level of consequence
3	High event probability	High level of consequence

Table 3.3: Table shows three examples to connect the verbal risk to a fixed relation number.

- The qualitative method results in the production of two quality statements. The first resultant statement is in the verbal level of the ordinal scale with high, middle or low probability for an event. The second connects a subjective estimate of probability of high, middle or low that can approximately describe reality. Table 3.3 shows a connection between the fixed number of relations and the probability and the consequence of an event. Now, it is possible to link the ordinal scale to ratio scale.

- In the quantitative methodology, the risk of an event is presented as a purely mathematical variable $r(E)$. In this methodology, risk is calculated in the classical way with the product of the probability of an event $p(E)$ and the consequence $c(E)$. When using probabilistic methodology, the result is not only one value, it is possible to describe the result as a probability distribution. This possibility offers a direct comparison of the probability of the occurrence. In comparison, various types of constructions can be compared with regard to their probability of failure. Another aspect is the ability to evaluate the effectiveness of systems. The Monte Carlo method [Gla03], which is the state of the art, should be specifically mentioned here. It offers the possibility, through the large repetition of possible outcomes, to give a system a prediction of the probabilities (for further information regarding the Monte Carlo (MC) method see subsection 3.5.1).



To clarify further, there are not only the classic qualitative or quantitative approaches. Mixed forms have also been developed over the years to compensate for the advantages and disadvantages of various methods. The following enumeration shows the intersection between the methods [San12]:

1. Qualitative method [PS18]
2. Semi-qualitative method [Lek17]
3. Semi-quantitative method [Dre12]
4. Deterministic method [Alb12]
5. Probabilistic / quantitative method [Fac15]

Qualitative method

Qualitative methods are not always suitable in research. One always has to determine when it makes sense to apply it. A comparison is needed to determine whether it is appropriate or effective. Influencing factors of the evaluating person always strongly depend on their world-view and their personal attitudes and opinions. There are many controversial discussions regarding this method [Fli07]. When using this method, the scientific analysis and process used by researchers is based on a three step approach in the following order. The first is the qualitative analysis, with the definition of the question, the definition of terms, categories and the analysis‘ instruments. The second step is the data acquisition with the adaption of the analysis methodology depending on the target. Finally, there is the interpretation of the result with its connection to the defined question and its interpretation [PS18]. In the case of building risk analysis at the level of process management, this method is used with a three step analysis to estimate the failure probability for the procurement procedure, political surroundings or proceeds from property sales [San12]. The subjective assessment of influencing factors and the subsequent interpretation are often open to misinterpretation and have a high probability of delivering a false statement.

Semi-qualitative method

In general, the semi-qualitative method is the first higher level step-up from the classical quantitative method. In this version there is a mixture of only qualitative questionnaires, expert testimonies and other influences including little conversion to other scale levels, such as the ratio scale. Since the semi-qualitative method is a mixture of qualitative and quantitative methods, several different types of scales are required. For example, data from a qualitative method (text) cannot simply be converted into qualitative processes (numbers). Table 3.3 shows an example of converting text into a numerical value. Here, fixed numbers are connected with fixed verbal statements. On the basis of this combination, relationships can also be defined in the later process using mathematical statistical procedures [Lek17]. However, with this method it is particularly important to note that resealing can quickly lead to errors, since both the influencing factors dependent A and independent B can be interpreted incorrectly [PS18]. In one of the appendices (see subsection 6.1) an excellent algorithm to determine the influencing factors in a correct way is shown. This procedure is used in the cost risk assessment of large construction projects [SW13]. The combination allows a good overview of construction project risks, which can be quickly defined. However, the evaluation of this method remains subjective, since the data is also collected subjectively through human influence.

Semi-quantitative method

The next level of risk assessment is the methodology of semi-quantitative analysis. In this method the calculation is determined by index. In the area of the application of this method, the directive in Austria should be highlighted here [Aus16]. This methodology was used when constructing the number 6 highway in Austria [San12]. The method is based on the fact that the probability of risk occurrence and the consequence of each is described with an index from 1 to 5. The index for each individual influence is defined, so that there is no absolute numerical value, but always an estimate. This method is state of the art in the classical risk consulting in structural and infrastructure projects.

Boolean algebra

The development of Boolean algebra is a split off from the classical linear algebra [Whi35]. The basis for this is to interpret complex systems with fixed operators and to logically link primary events. It is therefore a logic statement that allows three relational operators acting on the events to be identified:

- Operator $\wedge$ for AND
- Operator $\vee$ for OR
- Operator $\neg$ for NOT

Peano's redundant axiom system describes Boolean algebra as a set with a zero element (0) and a one element (1). The table 3.4 shows all possible combinations with the Boolean algebra with their opposites [RS15a].

Rule	n	Primary term	n'	Opposite term
Commutativity	1	$a \wedge b = b \wedge a$	1'	$a \vee b = b \vee a$
Associativity	2	$(a \wedge b) \wedge c = a \wedge (b \wedge c)$	2'	$(a \vee b) \vee c = a \vee (b \vee c)$
Idempotent	3	$a \wedge a = a$	3'	$a \vee a = a$
Distributivity	4	$a \wedge (b \vee c) = (a \wedge b) \vee (a \wedge c)$	4'	$a \vee (b \wedge c) = (a \vee b) \wedge (a \vee c)$
Neutrality	5	$a \wedge 1 = a$	5'	$a \vee 0 = a$
Annihilator	6	$a \wedge 0 = 0$	6'	$a \vee 1 = 1$
Double negation	7	$\neg(\neg a) = a$	7'	not possible
De Morgan	8	$\neg a \wedge \neg b = \neg(a \vee b)$	8'	$\neg a \vee \neg b = \neg(a \wedge b)$
Complementary	9	$a \wedge \neg a = 0$	9'	$a \vee \neg a = 0$
Duality	10	$\neg 0 = 1$	10'	$\neg 1 = 0$
Absorption	11	$a \vee (a \wedge b) = a$	11'	$a \wedge (a \vee b) = a$

Table 3.4: All possible combinations of n and the opposite of the rule of n are n' in the Boolean rules by *Genocchi*[Gen99].

a	b	$a \wedge b$
0	0	0
0	1	0
1	0	0
1	1	1

a	b	$a \vee b$
0	0	0
0	1	1
1	0	1
1	1	1

a	$\neg a$
0	1
1	0

Table 3.5: Truth table with all possible combination of two input ways a and b with the operator $\wedge$, *lor* and $\neg$.

The described eleven possible combinations of n with their mathematical opposite n' are the basis for further calculations in today's Boolean algebra. If one now wants to represent a complex system with the three operators $\wedge$, $\vee$ and $\neg$, the primary events are connected by gates. Figure 3.1 shows these combinations to connect two events by using Boolean algebra with an FTA. With the combination of the three operator forms $\wedge$, $\vee$ and $\neg$, it is possible to create a truth table (see table 3.5). In these basic models of Boolean algebra with the operator and the axioms lies the mathematical anatomy of FTA.

3.1.3 Model anatomy of FTA

At the beginning of FTA in the year 1961, nobody believed that the tool would be so powerful. The development of the FTA method, like many other technologies, has a military background. That is how the launch control system for Boeing LGM-30 reactors was simulated for safety and reliability. Since then, scientific publications have increased regularly, FTA is a recognized rule of technology development [Eri99]. The reliability of a system or a component is its ability to meet the requirements of its intended use within the given limits, which relates to the behavior of its properties during the given time period. A failed unit can no longer provide its functionality, which is why classical reliability analysis shows the

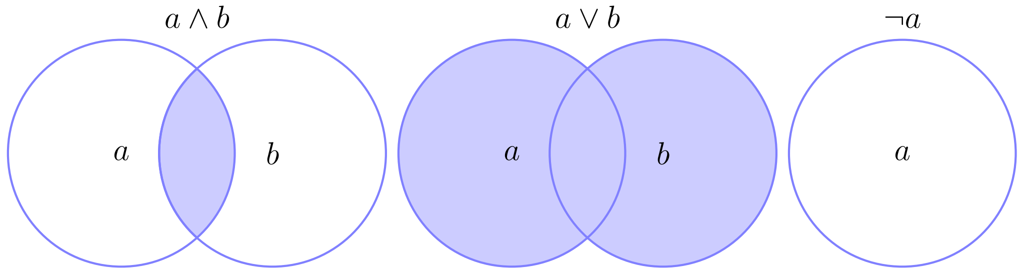
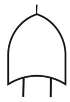
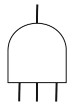
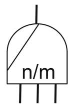


Figure 3.1: Venn diagram with the possible operators of Boolean algebra to connect two events in an FTA.

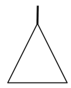
failure behavior the units considered. This analysis essentially consists of the following tasks. It supports the development of new systems by comparing future oriented system concepts and enables the objective evaluation of development criteria (reliability prediction, reliability comparison, reliability tracking, and vulnerability identification). Moreover, it enables proof of reliability for existing systems and concepts. The same methods and analysis methods are often used to fulfill these tasks. Unlike reliability analysis, safety analysis focuses on the subset of such systems and component failures that result, with safety defined as freedom from unacceptable risks. The safety relevant reliability of a unit is therefore its characteristic or, in quantitative terms: the probability within a defined period that it does not cause any dangerous effects (damage) under the specified conditions. The safety relevant reliability also takes the effects of damage into account when failures occur [Sch09]. The application of FTA is found in the nuclear technology [MUBH19, Fac15], in the flight systems on aircraft [Luf15] and a multitude of other technologies [RS15b]. The aim of the an FTA is to calculate the probability and the consequence of failure as accurately as possible. It is possible to generate the Fault-Tree to ensure the safety of systems and processes, to determine the break down times of individual parts, to calculate their reliability and other important statistically relevant parameters in a technical system. However, if there are cost influences or technical limitations for redundancy, then further methods are required to include them in the overall risk determination. In order to express the mathematical model into a clearer visual representation, standardized symbols are integrated in the acFTA methodology. Unfortunately, the symbols are not completely standard internationally, although often they are very similar. One of the first sources for the symbols dates back to 1981 and they are described by the U.S. Nuclear Regulatory Commission [SG83]. For the current state of the art with the most important symbols to connect gates see following enumeration [FE14, ESH15]. A summary of most important FTA logical symbols to connect gates or events with a brief definition are:

-  *OR gate*: Logical "OR" connection of inputs. The succeeding event happens if at least one of the preceding events has occurred.

-  *AND gate*: Logical "AND" connection of inputs. The succeeding event happens if all of the preceding events have occurred.

- 

N gate: Possible combination of n out m inputs. The succeeding event happens if at least n of the preceding events have occurred.

-  *T gate*: Transfer event link to a further FTA. The values of this primary event were exported from another FTA.

In general, there are more than the symbols shown in the enumeration, although they can always be defined by the explanations of the four that are described in the table. For example, the XOR gate, describes an exclusive "OR" for the events A or B, but not both events nor both properties. The same result of the XOR gate can be described with one OR gate and two AND gates, so that the four symbols described are sufficient to represent all operations in FTA with Boolean algebra. A further aspect of FTA is the independence of events. For the analysis and the quantification, it is very important that the primary events are completely independent. If independence does not apply, the statement can be completely wrong. The definition of independence in an FTA is that the probability of occurrence of each primary event is not influenced by any other primary events [ESH15]. This is a strong limitation for the use of classic fault trees. However, there are now also very good options for modeling dependent events. These are:

- Multiple usage of Common Cause Errors [Vau03]
- Definition of fixed conditions and events for modeling [ESH15]
- Mutual exclusion of events (especially in nuclear technology) [FE14]
- Sequential dependency of events and errors [ESH15]

3.1.4 Summary of technical fire protection

Since the new methodology for the optimization of processes taking into account the various influences on a technical system has been defined, it is now applied to fire protection as proof of principle. Technical fire systems include the individual components and the linkage of all elements involved. Since this subject covers an extremely large range of information and explaining everything in depth would exceed the scope of this thesis, only a brief summary is presented here.

The term technical fire protection is a sub-term of Technical Building Equipment (TBE). The networking of technical, structural and organizational measures is becoming increasingly important as the complexity in the construction of buildings and the operation of them also increases. Every year there is an increase in the electrical and technical elements in classical preventive fire protect engineering [KMMJ19, NJF09]. The individual components of a building are constantly influencing each other. In order to create a technical system that meets all requirements for security, reliability and clarity, all relevant factors must be included when planning a building. The technical development within buildings is now taking on a variety of different forms. For example, nowadays, a building can be programmed and a dynamic escape route can be displayed within the building for people fleeing in the event of a fire [KMMJ19]. On the other hand, the probability of survival is simulated using Monte Carlo methods [ZLMH17]. The first approaches for calculating the probability of failure for sprinkler systems are also widely available, however they do not calculate the cost benefit for such systems [MIK19]. The most important components of technical fire protection are described below.

Fire extinguishing systems

Extinguishing systems are part of TBE in fire protection and, as with automatic fire extinguishing systems, reduce and prevent the spread of fire. Depending on the extinguishing agent (water, foam or gas), the effect of this system is to extinguish a fire in the most effective way. The most commonly used form of fire extinguishing system is the water sprinkler system. Contrary to what the term may indicate, the system does not extinguish a fire, but suppresses it and prevents a large fire from breaking out and engulfing the building. These systems are normally used in:

- *Skyscrapers*: Here through the help of water sprinkler systems, critical structural components are not exposed to extremely high temperatures, to minimize the risk of building collapse [Fac08].
- *Underground parking garages*: Similar to high rise buildings, firefighting in an underground parking garages is also difficult and the temperatures in the event of a fire are high. Additionally, there are requirements for a certain size and type of water sprinkler system for them dependent on their size [Bay93].
- *Industrial buildings*: The maximum area that can be combated by the fire brigade in the event of a fire is fixed in Germany, it is 1,600 m^2. However, if this area is exceeded in an industrial area or in large warehouses, compensation measures must be taken, such as the installation of a water sprinkler system. System sections of up to 10,000 m^2 can be set up to combat fire [Fac19].

- *Department stores*: Similar principles to that of an industrial area apply in these buildings. Here, too, larger fire combating system sections are often required in these types of buildings [Fac14].

Water sprinkler systems are simple and efficient. There are pipes, which are mostly filled with water, with openings. Water outlets with nozzles are attached to the pipes. Each nozzle is secured by a glass vial that shatters when the temperature exceeds a certain level. This will cause the water to be released and then the system starts to suppress the fire. Before the water is released, it is pre-heated in a large tank and accelerated with compressed air. Its efficiency in regard to fire protection and the probability of failure of such systems is sometimes controversially discussed [But08].

Fire detection systems

Smoke is much more dangerous than fire, most people die from smoke in a fire, not from the fire itself. In Germany, there have been around 400 fire deaths in recent years, 95% of the dead were not burnt, but suffocated by toxic smoke gases [Sta17]. Fire alarm systems fulfill the following protection goals [Deu20]:

- Discovery of fires in its early stages through smoke and fire detection
- Alerting building occupants
- Automatic control and triggering of fire protection devices such as bulkheads and vents
- Fire alarm forwarding to the fire department
- Localization of the fire with detailed route to the fire for the fire brigade

Fire alarm systems should detect fires at an early stage, potentially reducing risk, warn people and notify the fire department of the emergency. In addition to automatic fire alarm systems, fires can also be discovered and help called for with the installation of manual call points (Push button) and the alarm, which is activated manually, is then automatically forwarded via the fire alarm system to the fire department or to another help center. In order for this system to work, many influences have to be analyzed. Every fire alarm system needs durable and reliable components, plus an electrical supply and they are only needed in case of fire for information transfer to people in the building and the fire department. In order to automatically detect the outbreak of a fire, a room must also be monitored by smoke and fire detectors. Each element is in turn assigned a certain probability of failure, they can be clearly represented in an FTA. Figure 3.2 shows an example with influencing factors for a functional fire detection system with a common cause of information transfer error.

The difficulty in simulating such systems is the reliability of the input data. In order to obtain real data, standardized quantification of the data must also be carried out. There are already a great many differences that currently exist in EU countries regarding standardization. Even within Germany, it is not uniform, because the federal states make cities

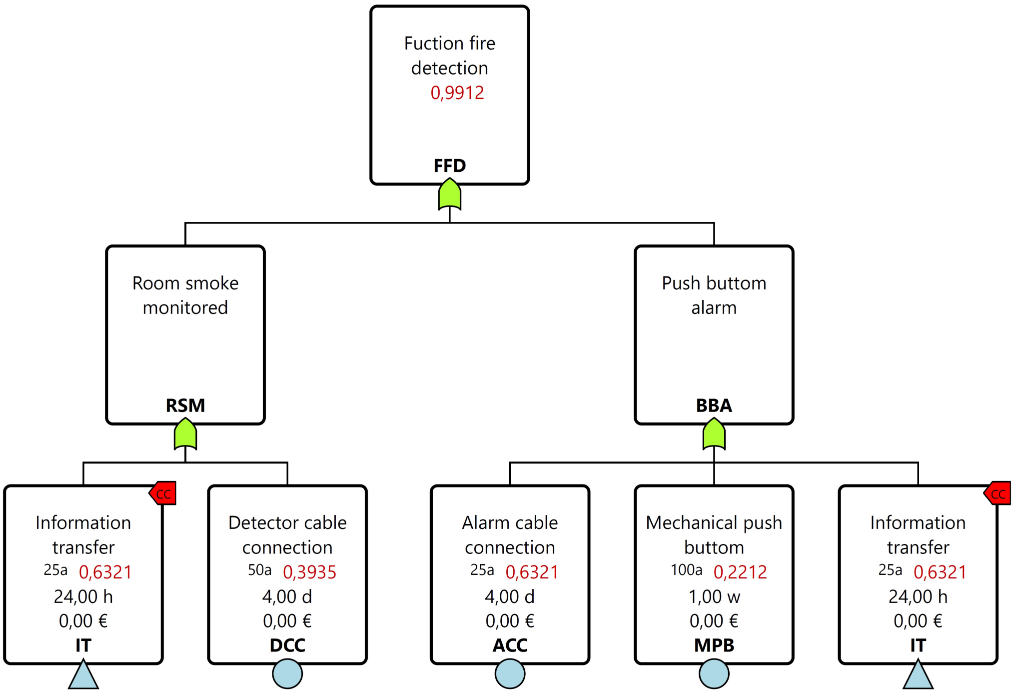


Figure 3.2: A simple example of an FTA for the failure rate of an automatic fire detection system with a common cause (red) for information transfer error. The analyzed period is 25 years with a result failure rate p = 0.9912. There are two primary events of a sub-system (Triangles for information transfer) implementation by RIAAT®.

responsible for fire protection. Possible uniform sources can be found in the nuclear industry, which is a very high quality source of standardized data [FE14]. In addition, China also collects uniform data with high quality and in large numbers [XH13]. It must always be checked whether the data can be used by the concrete model.

Ventilation systems for smoke and heat

Smoke extraction from buildings plays a central role in fire protection, since most of the deaths in fires are caused by toxic smoke gases [Sta17]. In addition to the protection goal of the residents' safety and the safety of the fire service, the protection goal of property protection is added. Fire smoke has a highly toxic effect [SKR+16] and additionally, it is very difficult to remove from walls. The theme of smoke extraction from buildings is essentially defined by fluid mechanics [EGH+11]. In general, heat and fume hoods must be manufactured in a reliable and stable manner. The systems must also be equipped in such a way that smoke cannot be transferred to other unaffected rooms or fire compartments. The basis for the installation of smoke and heat exhaust systems in Germany is the pipe systems directive [Fac16]. There are different levels of ventilation systems and openings that can assist smoke and gases to leave a building. In simple cases, it can be as basic as a window on the top floor of a stairwell that can be opened by the fire department, if necessary. In more difficult cases, it can be the case that ventilation systems discharge hot combustion gases and funnel them outside a building. Accordingly, the requirements are much higher here. The subject is becoming increasingly complex, as new low energy houses increase the effort to maintain heat, but at the same time the flue gases have to escape out of a house faster in the event of a fire [SK17].

Bulkheads for gas, water, air and electricity

In the area of planning TBE, the specialist planners are particularly challenged. As described in the section 1.3 introduction, there are walls with and walls without requirements. A hole can simply be drilled in the walls without requirements and additional cables can be laid through them. In walls with requirements (e.g. fire walls, walls in stairwells, walls in main corridors), cables must be secured using bulkheads. These measures can prevent the fire from spreading from one area to the other. Depending on the fire protection requirements, bulkheads are available in a standard that guarantees 30, 60 or 90 minutes of fire resistance.

In order to meet the protection goal of fire protection, it is very important that the wall requirements are truly met. If the bulkhead is defective, the fire can spread quickly and endanger the users of the building. The classifications of these bulkheads correspond to the classic requirements of DIN EN 13501 [Deu19], as described in table 1.3. Figure 3.3 shows an overview of the bulkhead in a classical building with the penetration of the floors and figure 3.4 the possible installation of the cables or pipelines.

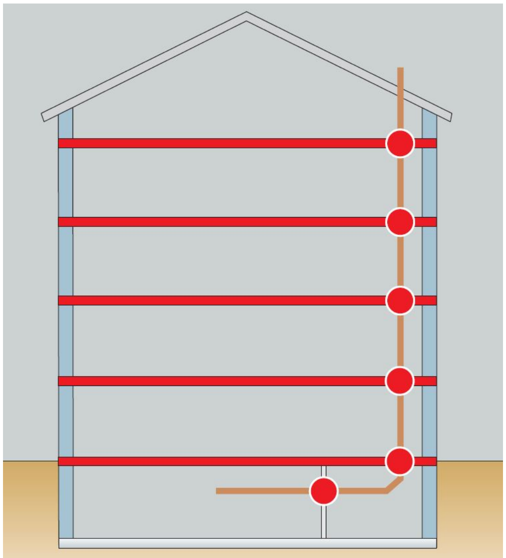


Figure 3.3: An example of bulkheads in a building showing their penetration into floors [HKS+14].

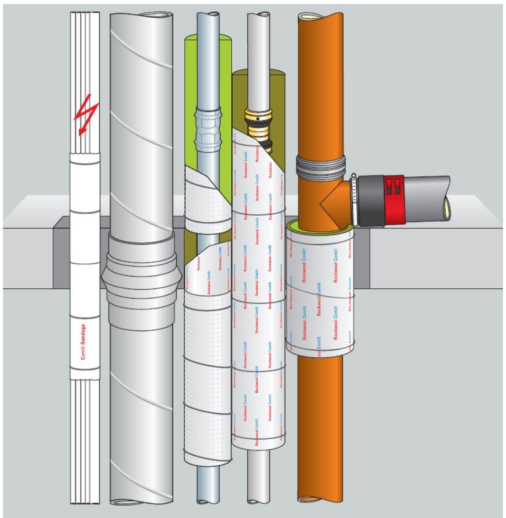


Figure 3.4: System drawing of bulkheads as detailed images going through a floor [HKS+14]

3.2 Important input values and quality level

An essential part of this work is the research of data in technical fire protection. For this purpose, a scientific quality level of the collected data has been developed. So far, only the methodological options and the components of FTA have presented. Various input variables are required to insert primary events as a data basis. As the first improvement of FTA is development of a standard quality level for the input data of primary events, including a summary of the most important failure probabilities. Very comprehensive literature research determined that there are many key figures, although they are not grouped and summarized. These key figures are summarized in Appendix 6 so that various systems can be simulated. The quality of the data with the failure probability of individual components is very different. Therefore, a classification system was created in this thesis work to quickly achieve excellent quality. A three level system is described in a short concise way:

- *Quality +*: The first level of the quality scale states that the data comes from recorded individual tests. The acquisition was understandable and repeatable, but can also come from manufacturers or other non-governmental organizations. Furthermore, it has the quality level +, this applies to all regulations like DIN, DIN EN etc. because the data is influenced by the industry without any traceability of the collection process.
- *Quality ++*: The values of the probability of failure come from a peer reviewed journal and are recognized by the scientific world. Additionally, there are failure rates at this quality level in professional books from international publishing houses.
- *Quality +++*: The highest quality level of the variables for the probability of failure is assigned to saved data. These come from technical reports from governmental organizations, audit authorities or other international specialist organizations for the quantification of the probability of failure.

The data collected is only applicable to preventive and defensive fire protection. If better data is available, the better quality standard has always been used. Other subjects such as building physics, heat penetration of components and the like are not part of this thesis and are therefore not listed. The tables with the variables in the appendix were all independently checked by two other scientists, so that a total of three scientists are involved. The following list shows an overview of the most important input values headings used this chapter. The values of the probability of failure are always associated with a quality statement. As explained, there is a three level system with + for the lowest quality level and +++ for the highest quality level. For a better overview, the brief data structure of the data is shown here with connections to the appendix chapter:

1. Preventive organizational fire protection
   - Lay fire extinguisher: Page 166
   - Non-detection failure rate: Page 166
2. Preventive technical fire protection
   - Fire alarm system reliability: Page 167
   - Stationary extinguishing system: Page 168
   - Occupancy sprinkler reliability: Page 168
3. Preventive structural fire protection
   - Fire door reliability: Page 169
   - Bulkhead failure rate: Page 170
4. Defensive fire protection for fire brigade
   - Fire fighting technical equipment: Page 171
   - Defensive fire protection failure rate: Page 171
5. Fire starting frequency
   - Fire causes in Germany: Page 172
   - Fire per unit of use: Page 172
6. Fire spread data and death risk
   - Probability of fire spread and of deaths: Page 173
   - Number of spread and their spread: Page 173
   - Incident of deaths and numbers: Page 174

All probabilities described were always checked by at least two scientists as peer review. However, the current status refers to when this thesis was written and when the data is used in the future, it must be checked for its current status.

3.3 Dynamic FTA analysis

So far, the previous subsection has described the development of a uniform quality level. In this subsection the second improvement follows, which is to improve the expressiveness of FTA. In this case, this expressiveness describes simulating a system in such a way that the calculated result of the top event in an FTA also represents the reality as precisely as possible. An FTA always represents a system at a defined point in time. The reliability of the individual components (primary events) changes differently within one. There are primary events which the probability of failure hardly changes over the live time and others that change very significantly. The next section describes how this additional information can be integrated into an FTA. The reliability of a system is the ability, within the given limits, to meet the established system behavioral properties, which are set during the given fictional by there life time time for a technical system [Deu90]. When a part of the system can no longer perform its function, the system's reliability is affected and the failure may or may not lead to the failure of the entire system. The determination of the reduction of reliability or of the probability that the system fails under these conditions can be calculated by classical reliability analysis. [ESH15]. The analysis not only includes the probability of failure, it also supports of the development new systems.

In contrast to reliability analysis, safety analysis is a way to identify weak points in a system in order to increase overall safety. Here, safety is understood as a component of an accepted residual risk that must not be exceeded. Safety related reliability also takes into account the effects of failure rates of a top event in an FTA. Safety analysis therefore requires further definition in regard to the question of which risk or which type of damage is to be considered. In the context of classical safety in regard to the safety of technical systems, this is the risk to life and limb or the injury / death of people. In principle, the same analysis and methods are also used in other considerations, for example in the field of security regarding the safety of technical systems [SSP+02]. The exception to this is the concept of knowledge safety, which refers to the reliability (confidence) of data and models. The following model of dynamic time analysis in complex modeling FTA in this thesis is based on Schilling's research [Sch09].

The dynamic behavior of a system is given according to [SSP+02] if the system response to an initial fault develops over time, while the system components interact with each other and with their environment. In contrast, classical fault tree analysis treats undesirable events (system failures) as a static, fixed and time invariant consequences of a certain combination of component failures. In a world full of dynamic influences and interactions, all technical systems generally also remain dynamic. Static methods and models for reliability and safety analysis of systems therefore only approximate their actually dynamic behavior. Due to this simplification, static analysis such as FTA or reliability block diagram are comparatively easy to utilize. In fact, in many cases, the assumption of static behavior makes analysis possible. The question relevant to practical application therefore is, which static approximations are able to actually map the dynamic failure behavior well enough. It has been shown here that the conventional FTA is very well suited for the logical and probabilistic analysis of systems whose failure behavior can be described, at least to a first approximation, as being free of time dependencies or dynamic interactions between the individual components. However, from the middle of the 20th century onwards, researchers and users have been complaining about the comparatively rough view of static analysis regarding the failure behavior of technical systems [Uni75]. Science and research are therefore looking for opportunities for accident modeling such as FTA to expand the most important dynamic effects [Sch09].

In order to better illustrate the ideas and the methodological approaches, a technical system (e.g. a sprinkler system for extinguishing fires) has been analyzed, which includes an analysis time of 6 years. All of the following descriptions refer to the same time period.

3.3.1 Classical Fault Tree Analysis

As already described, the mathematics of the fault tree is based on Boolean algebra, which in connection with an FTA represents the connection between system components. The top gate to be analyzed (or TOP) is the result. It enables a qualitative and quantitative perspective on reliability. Each primary event is assigned a probability of failure with a distribution including the respective down time. A FTA demands two tier status as essential restrictions of events, the fulfillment of the monotony or coherence condition [ESH15] and the independence between their base events. Furthermore, an FTA can only map dynamic failure and repair behavior to a very limited extent. This results from Boolean logic, which does not have a time concept and therefore only covers the structural aspects of failure combinations [BSMM15]. It does not make any statements about the order in which events or other time dependencies occur [Sch09]. When calculating the probability of failure, the time dependent probability is an important influencing factor. A typical influencing factor is the aging process for technical components, so that the longer a component is used, the more likely it is to fail. The failure rate of components in systems in the field is assumed to show a typical bathtub behavior, as is sketched in figure 3.5. Three regions can be seen; first, the early life regime with a relatively high and in-time decreasing failure rate; secondly, the working life with a constant failure rate; and, thirdly, the increasing failure rate in the wear-out regime. These three phases are then called burn in, useful and wear out and the typical *Weinbull* failure probability distribution with operating time for technical components is created (see Figure 3.5) [ESH15].

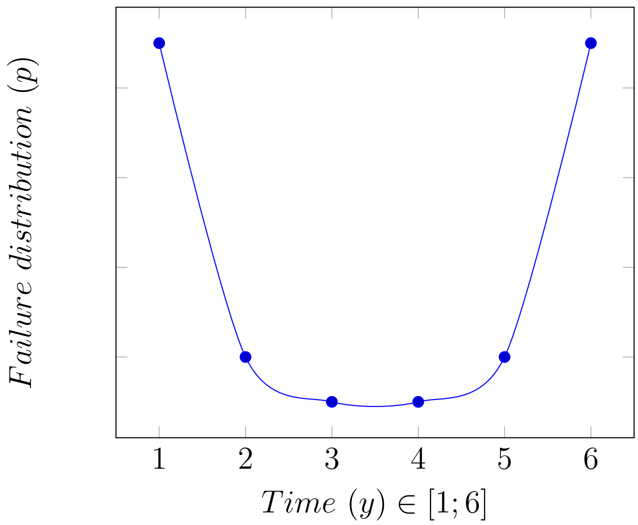


Figure 3.5: Example of a typical U-distribution of the failures of technical components depending on the time. Including the burn in phase, the useful phase and the wear out phase as a blue line.

The classic error model for technical components with the U-curve is of course not applicable to every case. There is a different distribution of deaths in humans, when they are broken down by age. Here, the probability of death decreases shortly after birth and slowly increases over the years up to the natural average age of 77 years [FKS18]. A distribution shifted to the right can then be determined here (see figure 3.6).

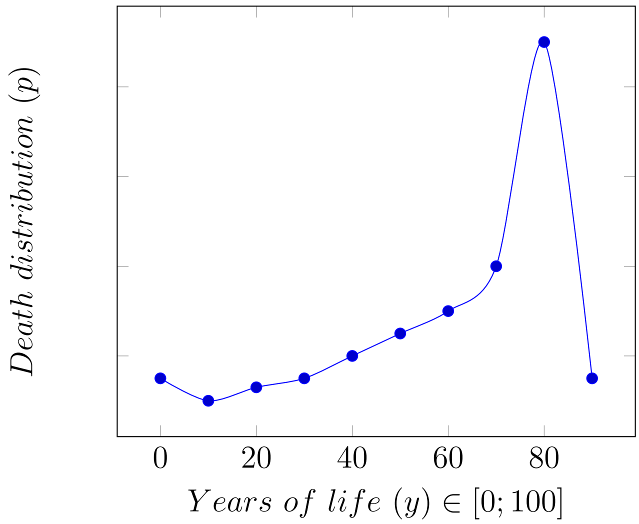


Figure 3.6: Death rate with the probability (p) in dependent on years of life (y).

In general, the failure rate r of a component is defined as the relative rate of change at a time t with:

$$r(t) = \frac{P\{Failure\ in\ [t + dt]\}}{P\{No\ failure\ to\ time\ t\}} \tag{3.12}$$

Furthermore, it is possible to calculate the cumulative failure rate F. It indicates the probability that the component will mostly like fail in time, up to a certain time t [MUBH19]:

$$F(t) \stackrel{\text{def}}{=} P\{Failure\ time \leq t\} \tag{3.13}$$

In the classic fault tree, this failure rate is illustrated in a U-curve (see Figure 3.5) only as a classic average. This is valid for wear models, but not all components behave in the same manner. They may have failure distributions which follow other curves. If you add the respective fault tree to include the time variable in the mathematical description of the fault tree, a 3D space is established.

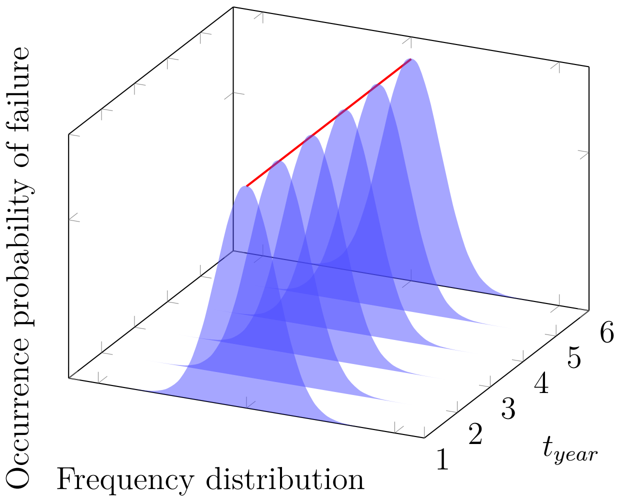


Figure 3.7: 3D plot with probability of failure and the normal distribution of occurrence of a failure (blue). There is no modification in the error rate over time between the analyzed period of 1 to 6 years (red line).

The 3D plots used these axes:

- *x-axis frequency distribution*: Relative frequency of occurrence of a failure within a primary event of an FTA.
- *y-axis occurrence probability of failure*: The occurrence of probability of failure within a primary event of an FTA.
- *z-axis time*: The z-axis reflects the time course over the 6 years of the analyzed period.

Figure 3.7 shows the occurrence of probability of failure with the frequency normal distribution of the FTA (blue), including same failure distribution over all of the six years as a normal curve (red line). The occurrence of an error is normally distributed [Dhi18]. In order to carry out good analysis by means of an FTA, also dependent on the wear of the system, a new fault tree has to be created with different probabilities of occurrence every year, such as in this example. The missing link between a static error tree and the changed probability of failures occurring over time is now the goal of expanding FTA analysis. This means that when a technical system is analyzed by an FTA, "now" is very precise. The more time passes, the less precise the FTA becomes, since the failure probabilities of the primary events are not all the same. In general, it determines that a component is functional (Reliability R) or failed (Failure F) at the time t. Therefore:

$$1 = R(t) + F(t) \tag{3.14}$$

The density function of the two factors $F(t)$ and $R(t)$ is enriched. The occurrence of probability over the time interval $[0, t]$ over the integral follows:

$$F(t) = \int_0^t f(u)du \tag{3.15}$$

Conversely, reliability can be defined as [ESH15]:

$$R(t) \stackrel{\text{def}}{=} P\{Time\ for\ error > t\} = 1 - F(t) \tag{3.16}$$

Also $F(t)$, $f(t)$ and $r(t)$ form a mathematical connection in which the failure of a component is clearly described by one of the FTA analyzing functions [ESH15]. Now, the question of the time dependent components in the course of the aging of a system remains. So far, the time dependent of failure has been implemented with the input data of the $F(t)$ for the failure of error. The expansion of this component will now be described in more detail.

3.3.2 Dynamic Fault Tree

According to the state of the art, FTA includes the time dynamic approach. In general, however, a distinction is then made between the classical FTA (without change in the probability of failure with increasing time) and time dependent FTA (with temporal sequences) [DSB92]. The *Markov* chains are used in the time dependent FTA to expand the dynamic perspective of a classic FTA. This enables the sequence dependencies to be modeled and solved analytically. This can be defined over the term by the dynamic of the result sequence. By only using Boolean algebra with its "AND", "OR" and "NOT", it is impossible to express the relationship between the inputs and the dynamic relationship. Every gate has at least two connected relationships (further gates or primary events). For calculation with a dynamic process in FTA with a time dependent the main question is, what happened first or happened at the same time. In the case of a classical "AND" gate with two components called A and B, the succeeding event occurs, when two of the preceding events have happened. Moreover, the question is now expanded by "In what order?". Did the A fail first, after then B or contrariwise or did they occur exactly at the same time? These three possible sequences are described in figure 3.8.

The classical FTA exclusively detected the probability that the component failed or did not fail. The DFT is additionally the answer to which kind of result occurs in a dynamic time way. A further option for calculation with time in an FTA is called Temporary Fault Tree Analysis (TFTA). This means that various other analytical options are possible [MDCS99]. As shown in figure 3.8, result always leads to the same Boolean methods, however in three possible different ways. Seeing the dynamics as a definition of different ways is a variant of FTA theory [Sch09]. The DFT model requires an understanding of the timing of a failure. There are three different ways of describing the real influences (for example aging of components):

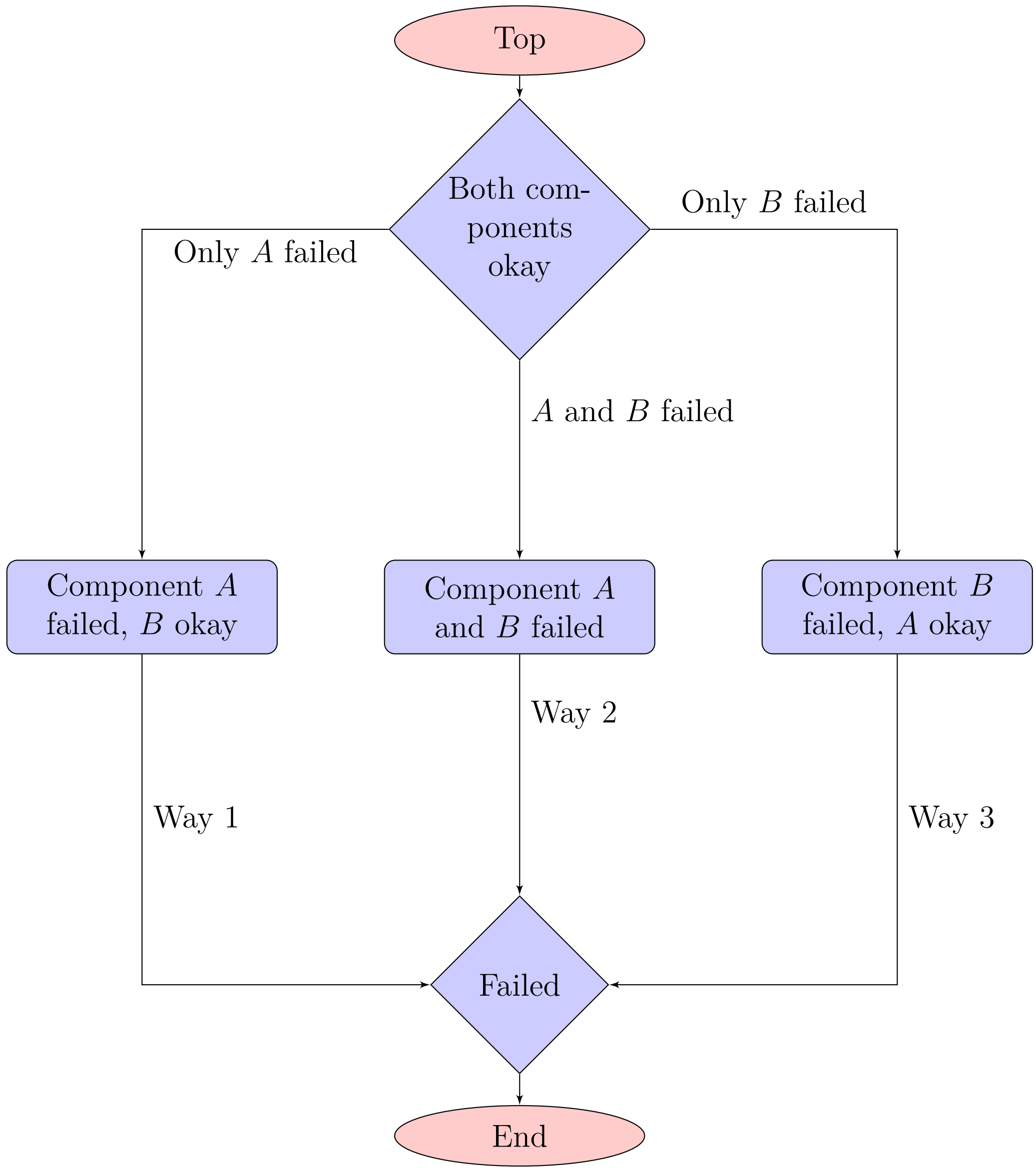


Figure 3.8: The figure describes the three possible ways of state transition from "Both components okay" to "Failed" independent of the order of failures.

1. FTA: The classical methods can only model systems in which a combination of failed components results in a system failure, regardless of when each of those component failures occurred [RS15b, ESH15]. Generally, there are "OR", "AND" and "NOT" gates in basic Boolean algebra. The analysis in this step relates exclusively to the failure probability of the top event within an FTA.

2. TFTA: The next step describes a balance between an FTA and a DFT. Here, individual time dependent components can be displayed by expanding gates using a ordinal scale. The additional gates are [RS15b]:
   - PAND: The Priority-AND Gate output event occurs if all inputs occur from left to right.
   - FDEP: The Function Dependency output is a dummy and never occurs, but when the trigger event on the left occurs, all the other input events also occur.
   - SPARE: Represents a component that can be replaced by one or more spares. When the primary unit fails, the first spare is activated. When this spare fails, the next is activated, and so on until no more spares are available. Each spare can be connected to multiple spare gates, but once activated by one it cannot be used by another. By convention, spare components are ordered from left to right.

3. DFT: This methods allows the modeling of dynamic dependencies of system components in reliability analysis [Yev15]. Here, the dependent processes are not only defined by the processing of different gates, also moreover by the temporal context. The DFT is an expressive model catering for common dependability patterns, such as spare management, functional dependencies, and sequencing [VJK18].

With regard to fire protection, there is almost no FTA currently in use and certainly not TFTA or Dynamic Fault Tree Analysis (DFTA). This represents a very large research gap, as the dependency placed on certain events, especially in fire protection, plays a very large role. When considering the protection target "personal safety", a certain probability of failure must always be taken into account. For example, a classic way is to simulate rescuing people with an "AND" gate. Each apartment on an upper floor has at least one staircase to reach A. There are also always windows that can be reached by the fire brigade through a ladder B. This target "personal safety" in the event of a fire can be achieved, either via the stairs or the fire department ladder. A and B each have a certain probability of failure, then $p(A)$ or $p(B)$. The protection target "personal safety" T_p:

$$T_p = 1 - (A \wedge B) \tag{3.17}$$

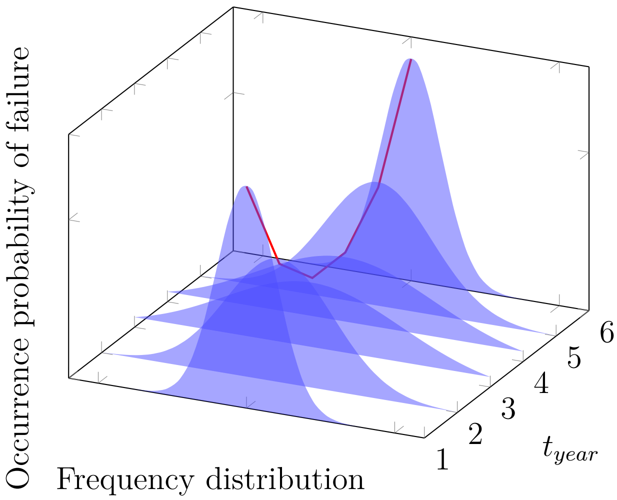


Figure 3.9: 3D plot with probability of failure and the normal distribution of occurrence of a failure (blue). There is a modification in the error rate over time between the analyzed period of 1 to 6 years (red line). The red line shows the U-curve with a high failure rate at the 1^{st} and the 6^{th} year.

A and *B* each have an extra fault tree with gates as the sub-items. The application of DFT or TFTA is a large field of research to enable the question of efficient design in preventive fire protection. When it comes to the dynamics of fire protection, there are three main cases to be considered:

1. Dynamic time dependent with the same distribution over the entire analyzed period
2. Dynamic time dependent with moved (right or left) distribution
3. Dynamic time dependent with cross moved by right to left distribution or left to right distribution.

The first version of possible time distribution has the U-curve distribution of the TOP event of an FTA at the start to the end of the analyzed period. The frequency distribution and the occurrence probability of failure have normal distribution. The distribution is varied in time. In this example at t_1 and t_6 in figure 3.9. Between t_1 and t_6 a U-curve is depicted this represents the distribution of reliability (see the technical failure distribution as a 2D plot at figure 3.5).

The second version of possible time distribution has the U-curve distribution of the TOP event of an FTA from the start through to the end of the analyzed period. The frequency distribution and the occurrence probability of failure have normal distribution. The distribution is varied in time. Here, the normal distribution begins on the left side and moved in the $1st$ year and ends on the right side in the $6th$ year. Plot figure 3.10 shows this in a 3D plot with a distribution of the 2D plot of the possible probability rate of death of figure 3.6.

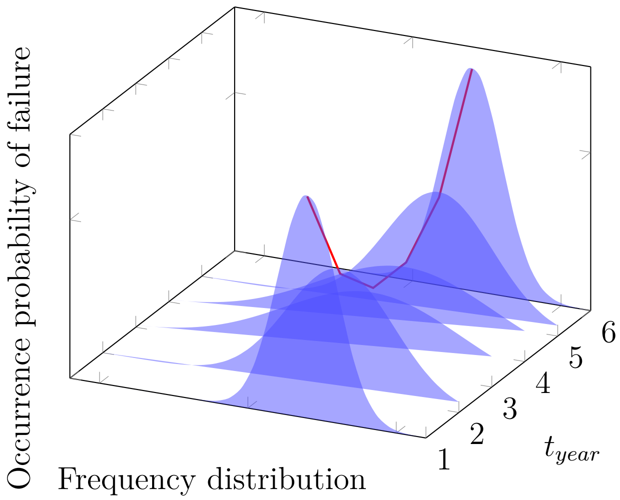


Figure 3.10: 3D plot with probability of failure and the normal distribution of occurrence of a failure (blue). There is a modification in the error rate over time between the analyzed period of 1 to 6 years (red line). The red line shows the U-curve with start at the 1^{st} year moved to left and finished at the 6^{th} year on the right side.

The third and last possible combination of distributions is shown in figure 3.11. Here it is explained with the crossing of a left moved distribution at t_1 to a right distribution at t_6. This is a special version, because the arithmetic mean distribution at t_3 and t_4 represented the mean, but not the reality.

The distribution of various distributions within fire protection plays a major role in trying to minimize the risk of system failure or the probability that it occurs. Especially, if the best ratio of financial resources to the increase in security is to be found. The time dependent change, especially in structural and technical fire protection, can be viewed more realistically with such a model. There is a special research approach here to technically advance risk quantification. In particular, it is about the question of which input data and primary events are needed so that a system can be simulated as best as possible. The three advanced variants of time distribution which illustrate the possible failure and wear of elements above are a further step in this direction.

3.4 Advanced input values

In order to be able to implement a new advanced DFTA, an essential step is to compare existing input values with extended input values. As existing input variables are available in a RAMS analysis tool like RIAAT®:

- MTBF: The expected value of the operating time between two consecutive failures.
- p(E): Probability p of an event E.

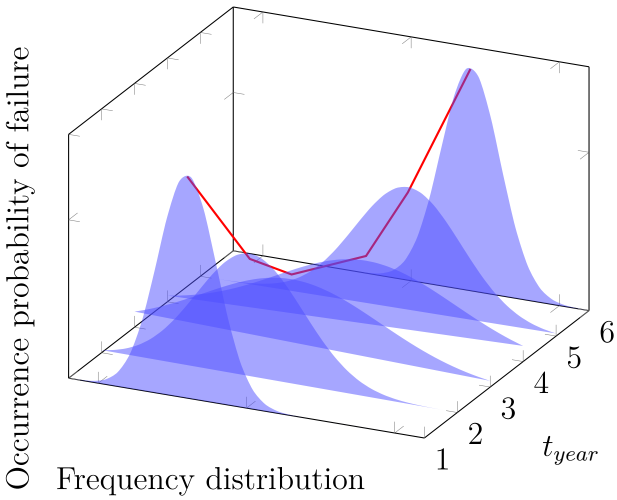


Figure 3.11: Dynamic time dependent, starting on the left distribution to the right distribution with a DFT

- Distribution type $D(p)$: Type of possible failures per analysis period. There are two possibilities to describe the distribution type. The first, is that only one failure is possible per analysis period (%) and the second, is that more than one failure is possible per analysis period ($\frown$). Since the characters already exist in the current software, these are also used again.
- Recovery time $R(t)$: Time to restore the system including a few of the possible distribution forms.
- Frequency error $F(t)$: Frequency of occurrence of the event described in each case including a few of the possible distribution forms.

$$v_{existing} = \begin{cases} MTBF & \in t[0;\infty] \\ p(E) & \in [0;1] \\ D(p) & \in [\%;\frown] \\ R(t) & \in t[0;\infty] \\ F(t) & \in error \end{cases} \tag{3.18}$$

The existing variables $v_{existing}$ are now expanded to generate new variables v_{new} value for the advanced analysis. These are:

$$v_{new} = \begin{cases} C(E) & \in Euro \\ T(E) & \in [1;\infty] \\ M(G) & \in [1;\infty] \end{cases} \tag{3.19}$$

with:

- Costs for a primary event $C(E)$: Defined costs for the implementation of a redundant system including a few of the possible distribution forms. The costs relate exclusively to the technical implementation of the redundancy of a primary event. A cost example for technical fire protection is approximately 15,000 euros for an additional secondary sprinkler system.
- Technical redundancy $T(E)$: Maximum number of technically possible redundancies in the entire system. This variable specifically describes how often a primary result should be carried out redundantly. If, for example, a sprinkler system is to be activated twice, the redundancy is available twice. The combination specifies how many combinations should be calculated from redundancies. As an example, the complete sprinkler system and the fire alarm system are to be designed redundantly. See figure 3.12.
- Multiple redundancies of gates $M(G)$: Maximum number of possible combinations to be simulated. It describes how many complete systems should be simulated in combination. Figure 3.13 shows an example of redundancy gates.

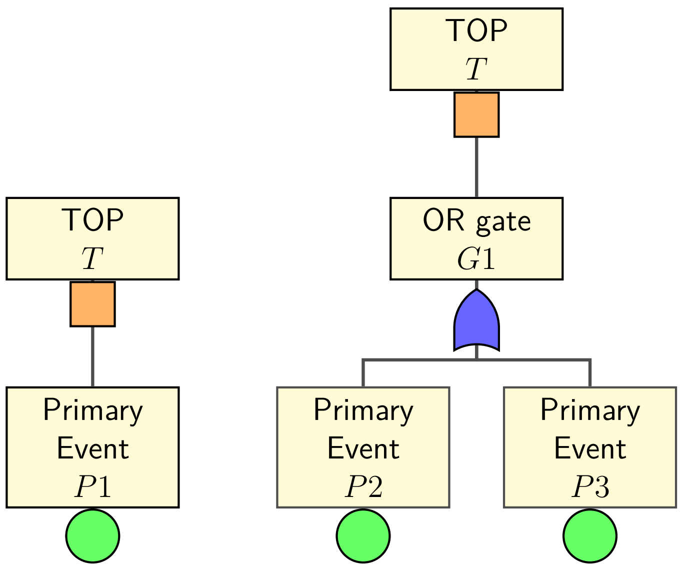


Figure 3.12: Description of the new value technical redundancy $T(E)$. On the left one primary event $P1$ exists. On the right two technical redundancies $T(E) = 2$ exist from the existing primary event to two primary events $P2$ and $P3$. Redundancies defined by the connection of an OR gate.

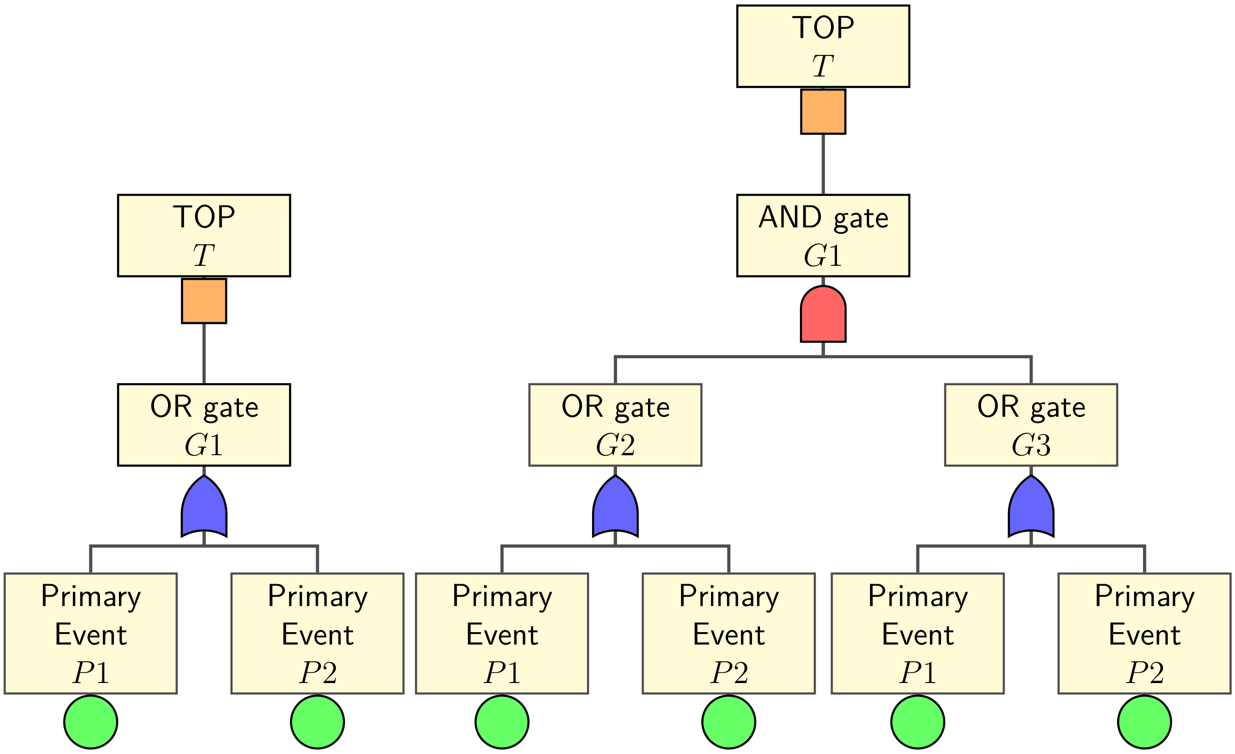


Figure 3.13: Example of multiple redundancies with gates $M(G) = 2$ on the left a classical OR gate with the primary event $P1$ and $P2$. On the right the multiple redundancies of a left distributed FTA split into two separate OR gates with the double primary events $P1$ and $P2$.

The proposed extension of the input variables was accepted at the conference "*11th European Workshop on High Performance Computering Infrastructures*" to be held on May 2021 in Munich [2] Thanks to the extended input of variables, new statements can now be made. It is now possible to calculate the best ratio from the funds invested and the increase in security in complex systems in an FTA. The mathematical basis for the minimal cut sets.

To calculate the cut set, it is necessary to transfer an FTA to a Boolean representation form. Figure 3.14 shows a simple FTA with five primary events ($P1$ to $P5$), an input probability of a subsystem of another system ($S1$) and the three gate forms (AND gate, OR gate and K gate) and the top event (T).

The probability of an OR gate P_{or} is expressed [Dhi18]:

$$P_{or}(y) = 1 - \prod_{i=1}^{m}(1 - P(y_i)) \tag{3.20}$$

[2]Due to the Covid-19 pandemic, the conference has been postponed to May 18th until May 20th, 2021 and therefore has not yet been published at the time of submission of the dissertation. The title of the presentation is "*Preventive fire protection: Official rules versus Performance based code*" from Claudius Hammann. Homepage: `https://www.euhpcinfrastructureworkshop.org`.

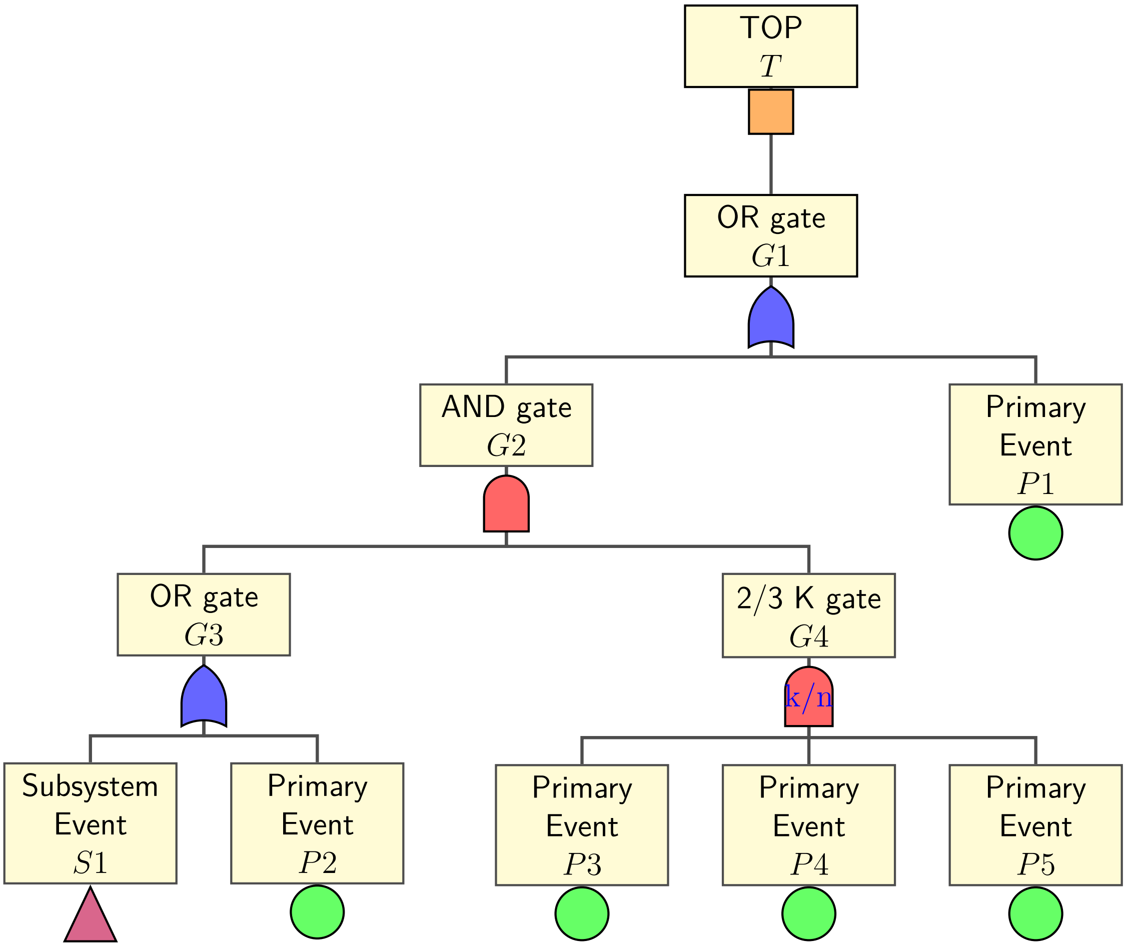


Figure 3.14: Example of a simple FTA including all possible gates (AND, OR and K) starting at top and primary events and subsystem connection.

with $P_{or}(y)$ the probability of occurrence of OR gates output in a FTA event is y. m is the number of input FTA events and $P(y_i)$ is the probability of occurrence of input FTA y_i, for $i = 1, 2, 3, ..., m$ [Dhi18]. Another option to connect two events is an AND gate. The probability of an AND gate P_{and} is:

$$P_{and}(y) = \prod_{i=1}^{m} P(y_i) \tag{3.21}$$

In case of a K gate, the probability is the result of the weight of the single primary k events in relation to the necessary n option. Now, the error tree is divided into individual Boolean algebra steps. Here, the respective gate is divided step by step through the connections to the individual gates. Table 3.6 shows the four steps to split an FTA in the figure 3.14.

Step	Boolean representation
1	$T = G1$
2	$T = G2 + P1$
3	$T = (G3 * G4) + P1$
4	$T = [(S1 + P2) * (P3 * P4 * P5)] + P1$

Table 3.6: Boolean representation with the transfer of an FTA with the reduction. OR gate = +, AND gate = * and K gate = k/n.

The main idea for the examination for the incorporation of the new variables is now to add the new variables v_{new}. By implementing the v_{new} with the existing variables $v_{existing}$, the following very important question can now be answered:

> Where is the optimal intersection between the financial resources used and the increase in the level of safety, including the dependency of time and the technically possible implementation of redundancy?

Possibilities for finding the approach to this question would be conceivable according to the *Monte Carlo* method [Gla03]. Since this calculation method already exists in RIAAT® to calculate the reliability of the top event in an FTA, it should also be used again. Alternatively, with the addition of a further dimension of such as *Esary-Proschan* [EPW67] with minimal cut set or after *Ruijters* [RS15b]. More research is needed here to find the best mathematical method for the calculation. Possible further approaches are presented in the discussion in this chapter (see subsection 3.7).

3.5 Development of FTA interpretation algorithms

The goal is to develop algorithms for standard use in an FTA. The first is an algorithm to establish a method for risk calculation and the second to determine the statistical significance of results. Both algorithms should be developed to answer which mathematical methods are the best and how exactly does thesis´ result reflect reality. The aim of an FTA is to simulate reality as precisely as possible. The calculated result should describe the real system as well as possible. In order for the description to be meaningful, two things must be taken into account when making the calculation. These are the mathematical calculation model and the quality level of the input data. The development of algorithms in these two areas increases the quality through standardization and also gives non-experts in this field the opportunity to carry out a good FTA.

3.5.1 Definition of main questions for algorithms

There are several mathematical methods for calculating a result within an FTA. While researching the possible methodological approaches for calculating the failure rate of a top event, several options are available. Probably, the most common method is the classic calculation based on the theory of probability from *Kolmogorow* in 1933 [Kol33] with an "Exact" result. Even with powerful computers and a lot of computing effort, it is not always possible to calculate an exact result. By linking the failure probabilities of the primary events within an FTA with *AND* and *OR* gates, the result can be quickly calculated to hundreds of digits after the decimal point. That does not make much sense in practice, so it makes sense to round the results. This method is then called "Exact with limit".

Another method is to evaluate an FTA using the MC-Methodology like *Metropolice & Ulam* [MU49]. Afurther method is the calculation following *Esary & Proschan* by the Esary-Proschan (EP)-Methodology [EPW67]. Every method has advantages and disadvantages with a massive amount of influences on the events being analyzed. The first step for a useful algorithm to develop the right calculation methodology for finding the optimal intersection between spent financial resources and the increase in safety is the definition of an optimal combination of all influences to differentiate the method. The questions are:

- Are the input values MTBF or probability? It is necessary to differentiate between the two input options, since one variant is a probability between 0 and 1 and the MTBF defines a time.
- Is it possible to fail once or several times? This decision is necessary so that it can be defined as to whether there can only be one failure per analysis period or whether it can occur several times. The top event defines which variant it is. There are influencing factors such as temporary power failure (this can fail for a few minutes and then come on again) or fire (after a fire, the complete fire detection system must be renewed).
- Is the data quality more than +++? The highest quality data level.
- Is the data quality more than ++? The intermediate quality data level.
- Is the data quality more than +? The data quality + represents the lowest level. However, it does not occur in the algorithm that all data is either +, ++ or +++, so that only ++ or +++ has to be asked for due to an exclusion principle.
- Are there more than 18 AND gates in the FTA? Experience shows that with more than 18 combinations of AND gates, the computing power of normal computers is reached.
- In the case where input values are MTBF, is MTBF $> 15 years$? There is a limit to the differentiation of the MTBF size this is necessary because the robustness of the calculation is to be strengthened. The robustness here relates to extremely different MTBF values. For example, AND gates could no longer correctly define the weighting when combining a MTBF of 1,500 years and 5 hours. Different calculation methods are necessary here.

- In the case that input values are $p(E)$, is $p(E) < 1 * 10^{-5}$? A similar problem as explained with the big differences in MTBF.

These main questions are split into two different algorithms for quality level and a mathematical tool. In the following there is a summary of the three different calculation methods:

- *Monte Carlo Methods*: These methods are based on applying the Monte Carlo procedure to solve statistical problems. The mathematics of measures formalizes the probability, association and event with a set of outcomes and definition of the probability [Gla03, FMF12]. The development of the methodology in its application in combination with MC methodology and the application with FTA, TFTA and DFT are by *Merle* [MRL+14].
- *Exact*: The probability of occurrence is calculated completely and precisely according to the classical mathematical rules of Boolean algebra, see chapter 3.1.1. The computing power needed is high and sometimes the evaluation takes an enormous amount of time depending on the size of the FTA. The mathematical rules are the same in "Exact", although here it is possible to limit the maximum time of calculation. These are useful with an extremely huge FTA, because of the fact that when the number of connections with different gates increases, it also affects the computing effort needed exponentially. A new basic concept for a minimal cut set in this methodology was developed by *Ruijters* [RS15b].
- *Esary-Proschan Methods*: The Esary-Proschan formula is an approximation formula used for FTA top event probability calculation after minimal cut set generation. It is able to take into account common basic events and calculate the result in reasonable time. The calculation procedure using this formula consists of several steps. The EP method includes two steps. The first step is minimal cut set generation and the second step is common basic events factor calculation [EPW67].

The definitions for development of the standard algorithm with the three different quality levels (+, ++ and +++) are taken from section 3.2.

3.5.2 Algorithm for the mathematical tool

The main task for the development of the algorithm is the logical combination of all important possible questions. The algorithm is an event tree with simple questions and only dichotomy questions. The goal is with one algorithm to choose the best mathematical methodology to calculate reliability in FTA. The symbols for the starting point of the algorithm, the question symbol and the possible answers is approached with DIN 66001 [Deu83] and is state of the art in computation engineering. For the algorithm, the open source software YEd® is used. The order of the questions is made according to the importance of the message. It starts with hard objective questions and afterwards follows little subjective questions. For example ""Are input values probability or MTBF?" is a hard question, because there is no scope for interpretation. The last question of the algorithm is about the quality of input data. Here, subjective decisions are always included. Figure 3.15 shows the development algorithm from start to the best methodology tool to calculate the top event of an FTA.

3.5.3 Algorithm for quality level

The algorithm just described now provides information to select the best mathematical method. However, the statement about the quality of the calculated result is still missing. Above all, the colloquial statement "Garbage in, garbage out" is used here. Only if the input data of the primary events have a high quality standard, will the result also have a high quality standard. The calculation by itself does not make the result better. Here too, the developed quality level is used for input data. It has a possible expression from + for low quality to +++ for very good data quality. By using the data quality standard algorithm, it is now possible to define the data quality of the result achieved within an FTA. This is particularly important because in complex fault trees, calculations are also carried out with subsystems. In the main fault tree, several subsystems are sometimes brought together. In order to be able to determine the quality of a result from a subsystem, a comprehensible basis is required for the determination of the data quality. Figure 3.16 shows the quality algorithm.

3.6 RIAAT® implementation and application

This section contains a brief instruction for using RIAAT® software and the application in a specific example. At this point, I would like to especially like to thank Mr. *Christian Hoos* for his outstanding master's thesis [Hoo20]. The master thesis was supervised by *Prof. Philip Sander* and *Claudius Hammann* at the University of the Bundeswehr, Munich at the Institute of Construction Management, and serves as a practical elaboration of the idea of dynamic fault tree analysis in fire protection in a standard building to demonstrate the powerful methodology.

The proposed improvements in the area of FTA are implemented in a β version of the RIAAT® software package from the company *RiskConsult GmbH* (Austria). A summary of the manual is shown in a brief explanation of the software in pages 181 to 183. The following section is also intended to serve as a brief guide for the RIAAT® FTA package, since a guide does not exist yet.

The FTA tool is an important part of RAMS analysis. An FTA depicts all of the relevant factors to evaluate its Reliability, Availability, Maintainability and Safety of a complete system. All components of a system are evaluated systematically and analyzed according to their roles and functions within it. FTA starts by identifying a major undesirable risk event, known as a top event, associated with the system under study. Generally, an FTA is a mathematical combination with at least two single primary events.

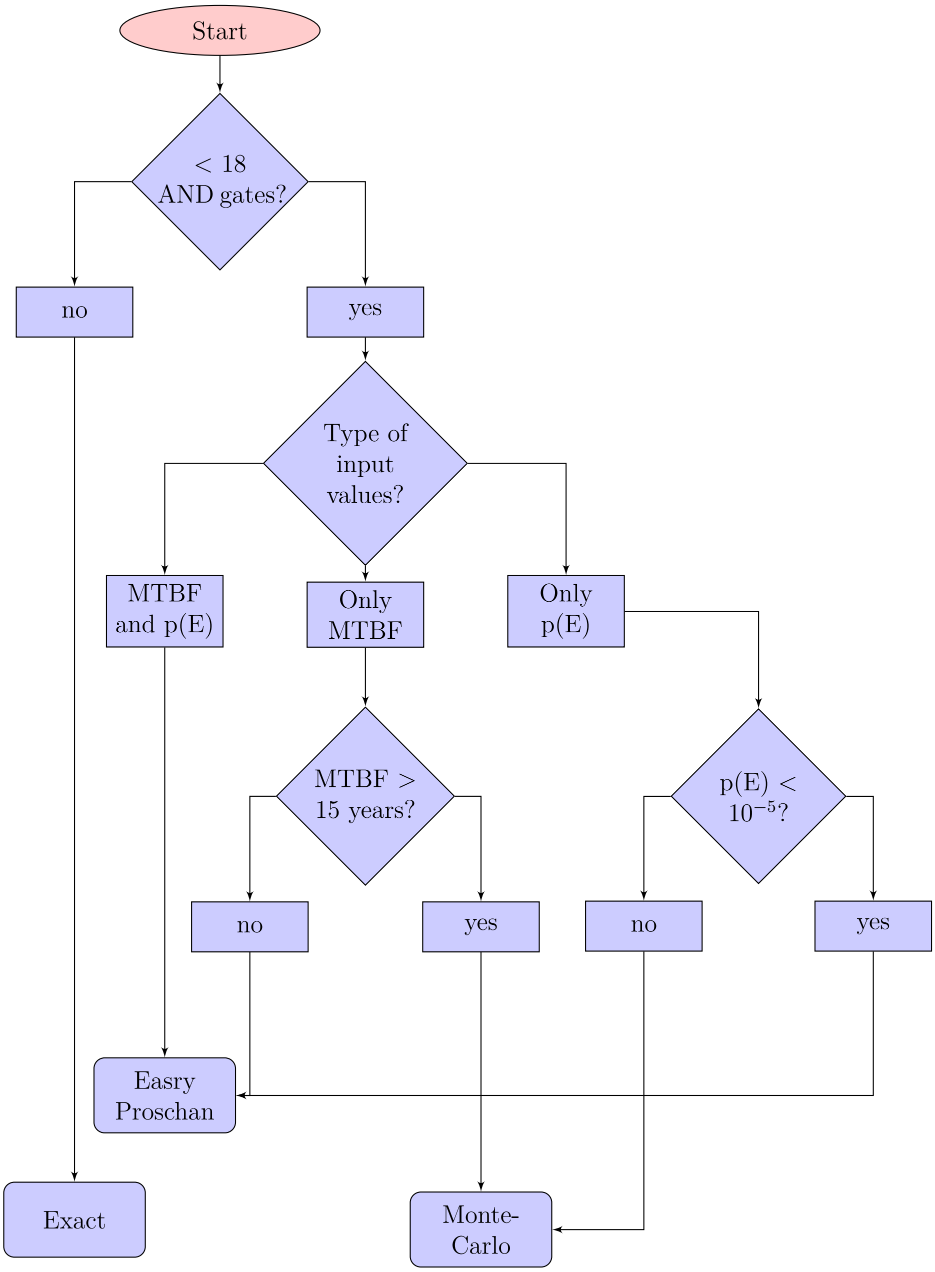


Figure 3.15: Algorithm with only simple dichotomy questions from "Start" to the three possible calculation methods in an FTA.

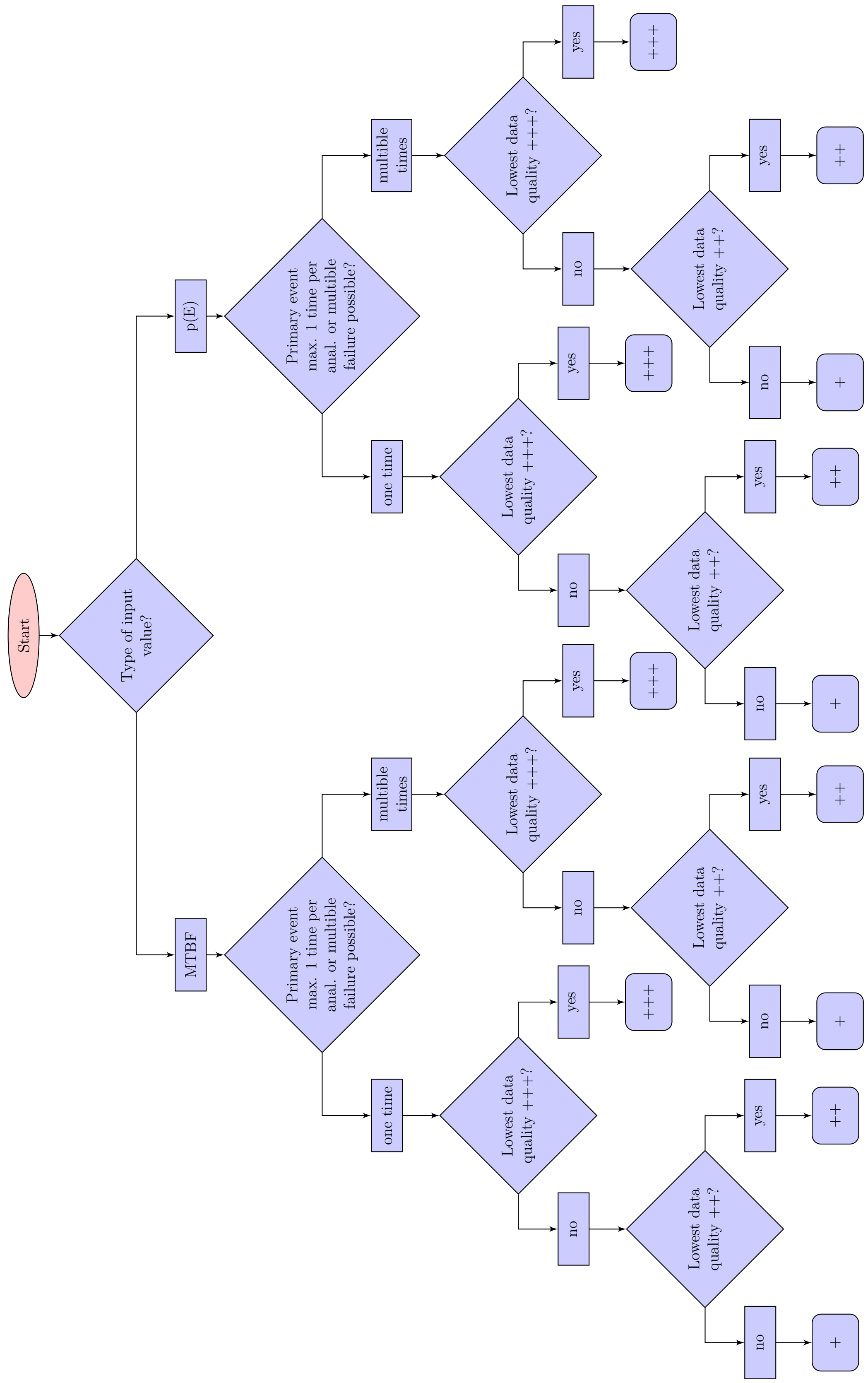


Figure 3.16: Algorithm with only a simple question from "Start" to possible quality level to evaluate the result of top event in FTA.

As already previously explained in section 3.1.3, there are three different gates of possibility to connect the single primary event:

- *OR gate*: The succeeding event happens, if at least one of the preceding events have happened.
- *AND gate*: The succeeding event happens, if all of the preceding events have happened.
- *K gate*: The succeeding event happens, if at least K of the preceding events have happened.

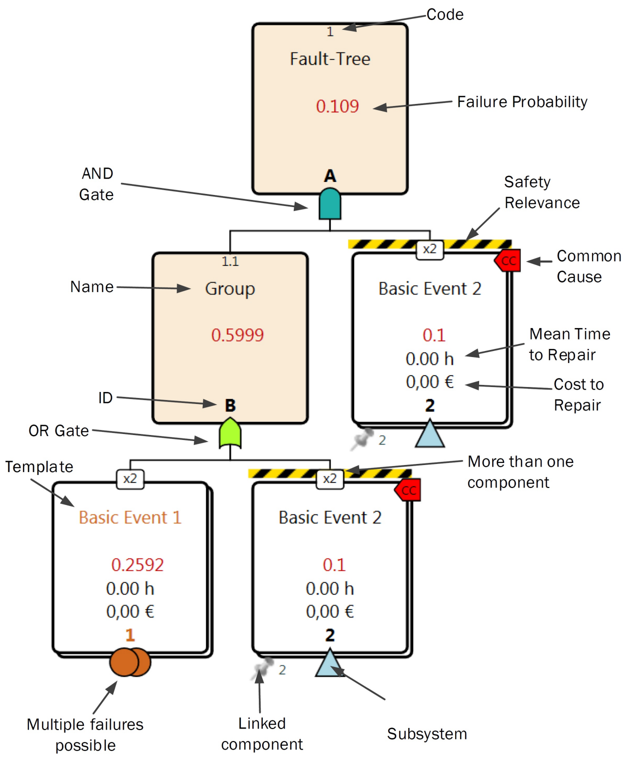


Figure 3.17: Overview of the elements, possible gates and the common causes in a Fault Tree Analysis with the software package RIAAT ® [Ris19]

With the three possible connections, the primary events can simulate the topic failure rate. Furthermore, there is a *Common Cause*, which is attached to all single primary events and is related to all failures with the same cause. Figure 3.17 shows the overview of all possible elements of the classical FTA with the software RIAAT®. There are two possible inputs for the values of the probability (p) of a primary event. The first option is the classical probability of an event (E) with a range $p(E) \in [0; 1]$. The second option is the input value with a mean time period between the two failures with an MTBF with a time $MTBF \in [0; \infty]$. The calculation of the probability of a top event within an FTA is possible with both variants. The difference lies in the analyzed period of the top event, as here, a period is always considered in which the failure of the top event occurs. Since, the MTBF defines an average time between two failures and the probability of failure is only a probability of occurrence, the MTBF is a more valuable entry form. In both cases a choice is made so that the symbol % respresents that fact that a maximum of one failure can occur for the analyzed time period and the symbol Λ,which can be possibly used for multiple failures within the time period. These are:

- *Code*: A classical FTA has clear levels to create the general failure probability. Components (primary events with AND gates, OR gates or K gates) on the same height of the FTA have the same category. The code defines the levels together with the number of elements. The main gates are the top level.
- *Name*: Here, the classical full name of the gate or the primary event is described. If the rates are to be calculated, a shortened version of the name is needed in the ID.
- *ID*: The identifier number of an event is the shortened version of the full name. This is needed for calculations of the minimal cuts set of the whole FTA. It is important to ensure that the same ID does not appear more than once in an FTA.
- *Safety Relevance*: The yellow/black bar over a primary element means that the element is safety relevant for the whole system.
- *Template*: In RIAAT® it is possible to extract primary events directly from a template. Therefore, it is not possible to change input values or names of primary events in the FTA, it is only possible in the template. It is particularly useful if different influencing factors are to be simulated and a large FTA results.
- *Subsystem*: The input data mentioned in the primary event come from another system and have been adopted.
- *Failure Probability*: The calculated probability of failure. This only appears when it has been calculated.
- *AND gate*: The linked events are connected by an AND gate.
- *OR gate*: The linked events are connected by an OR gate.
- *K gate*: The succeeding event happens if at least k of the preceding events have happened.
- *Common cause*: The event is linked to a common cause.
- *Mean time to repair*: The mean time to repair a primary event.
- *Cost to repair*: The mean cost to repair a primary event.
- *More than one component*: The primary event shown exists several times and is supplied with the same data. If the data differs, a separate primary event must be created.

- *Linked component*: The primary event shown has a direct link between the input data and other primary events in the FTA.

- *Multiple failure possible*: Multiple selection of the event is possible within the analysis period.

3.6.1 Example building and protection target definition

The basis for the specific elaboration of the example is the assessment of escape routes in terms of their probability of failure [Hoo20]. However, since only a brief overview of the methodology is given below, the topic is limited to:

- Protection target: Safety of the building residents.

- As top event of the FTA, the failure of the escape route (first escape route structurally via stairs, second escape route via ladders of the fire brigade) is simulated.

- There are three different points in time for the simulation:
  - t_0: Immediately after completion of the building when it is handed over to the residents.
  - t_{25}: 25 year old building.
  - t_{100}: 100 year old building.

- The building is a multi-family building with 25 apartments, five floors (ground floor and 4 upper floors) with an underground car park.

- There is only one internal staircase. Each apartment has a door that leads directly into the stairwell. Each apartment can also be reached from the outside via a fire brigade ladder.

- There is a voluntary fire fighting brigade.

- The entire building was built according to the state of the art (including planning and execution).

Figure 3.18 shows an example building with a side view. It shows, there are windows for each apartment that can be opened when rescue by fire ladder in case of fire is necessary. Figure 3.19 shows an example building with a view from above. It shows, there are internal stairs, which are the primary escape route for the building residents in case of fire.

Figure 3.18: Example building with the side view for the FTA simulation [Hoo20].

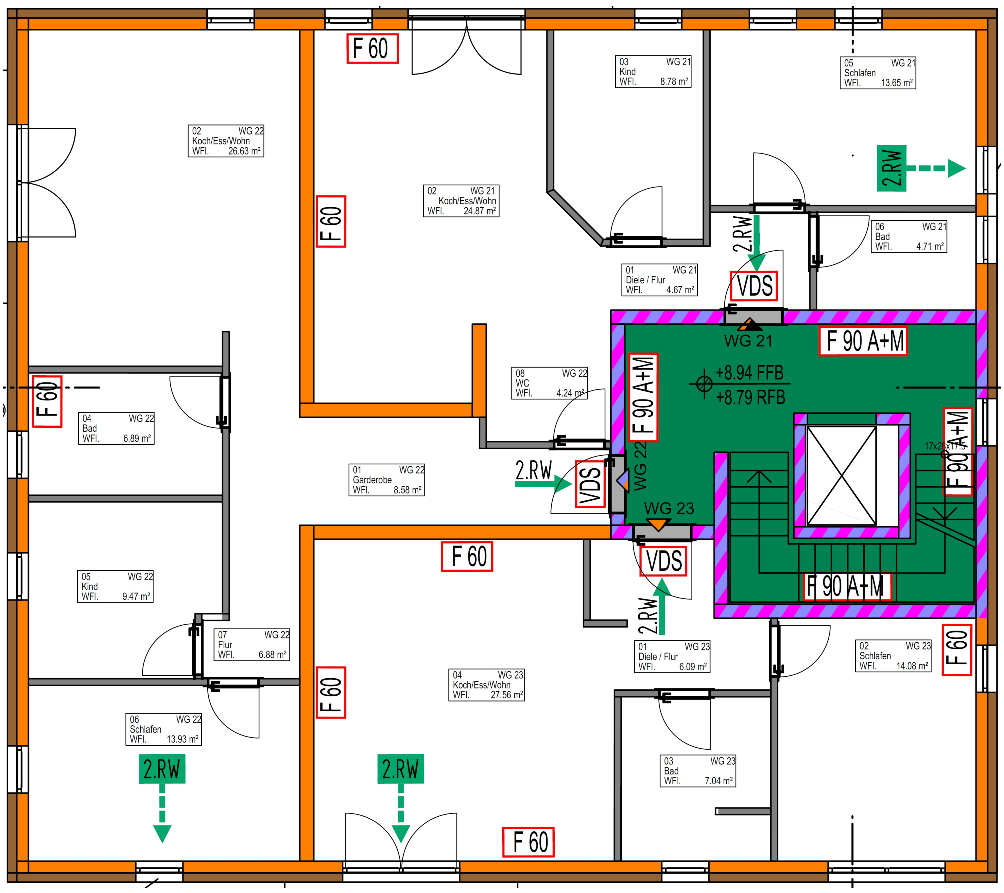


Figure 3.19: Example building with a view from above for the FTA simulation. The stairwell is colored green [Hoo20].

3.6.2 Input values

The input variable is the failure probability of individual components (primary events) that are necessary to rescue people from the building (top event). Each primary event has its own probability of failure at the time t_0, t_{25} or t_{100}. It depends on how the primary events work. There are different time dependent changes for the probability of the primary event $p(E)$. The three most important are:

$$p(E)_{t0} = p(E)_{t25} = p(E)_{t100} \tag{3.22}$$

$$p(E)_{t0} < p(E)_{t25} < p(E)_{t100} \tag{3.23}$$

$$p(E)_{t0} > p(E)_{t25} > p(E)_{t100} \tag{3.24}$$

Component / system	MTBF value	Literature
Power failure	3.5 y	annual statistics 2018
Power fuse in the stairwell	4 566 y	ALD Calculator, Siemens SN 29500-2005-1
Power fuse in the apartment	4 566 y	ALD Calculator, Siemens SN 29500-2005-1
Lighting	38 y	ALD Calculator, Siemens SN 29500-2005-1
Sensor autom. fire ladder	31 y	NPRD-95, Altitude, ALD Calculator
Hydraulics autom. fire ladder	1 200 y	DIN EN ISO 13849
Electricity autom. fire ladder	3 806 y	DIN EN ISO 13849
Mechanical autom. fire ladder	150 y	DIN EN ISO 13849
Mechanical norm. fire ladder	150 y	DIN EN ISO 13849

Table 3.7: Brief summary of the probability of failure used in MTBF values from literature researched. The table shows only a part of the data used.

Formula 3.22 applies to human systems, for example. The probability of failure for rescue by the fire brigade via a ladder does not change over time, moreover the age of the building does not have any influence on it. Formula 3.23 describes the time of the probability of failure of electrical lines. These are in very good condition when they are installed, but the probability of failure increases over time. Formula 3.24 describes the decrease in the probability of failure over time. The probability of failure when the residents of the building find the escape route is as follows: when they move into the apartment, the routes are not yet well known, but the knowledge of the routes becomes better and better the longer people life in the building.

The values for $p(E)$ from the literature are usually given for the probability at time t_0 [FE16, ESH15]. In fire protection, there are generally not many precise values for the failure probabilities to be found in the literature. The 150 most important values at time t_0 are summarized in Appendix (see pages of 165). An extensive literature review shows that there are no qualitative values for the aging of components in fire protection. To close these knowledge gaps, a semi-quantitative research method was chosen. The method consisted of a structured questioning of experts on the probability of failure. Experts are considered specialists in fire protection, if their full-time job is either the head of a fire protection department or a fire protection test engineer. A total of 12 engineers took part in the structured survey.

The survey was carried out using a standardized documentation sheet in order to ensure the comparability of the data obtained. The questionnaire for the estimation is designed in such a way that either the probability of occurrence or the number of faults can be stated. The MTBF values are calculated from the defects found per year. By choosing MTBF values for certain events, not only the reliability, but also the availability can be better calculated and different simulation periods can be used in the analysis. "The MTBF values are modeled on a Poisson distribution, since scenarios are also taken into account that show a lower or higher value than the estimated value [Hoo20]. This method was used for everyone for whom there is no probability of failure in the literature. Table 3.7 shows a brief summary of the most important input values from literature for the primary events of the example FTA.

The combination of the probability of failure from the literature and the questionnaire made it possible to supply all primary events with corresponding values. Since, there are a large number of complex FTA, only one Fault Tree is shown in the appendix as an example (see appendix 6.8). More detailed information can be found directly at *Christian Hoos* [Hoo20]. The FTA describes the rescue of residents at an example building via an automatic fire ladder in case of fire.

3.6.3 Result of the Dynamic Fault Tree Analysis

The results from the RIAAT® software are shown below. Since the DFTA is a new tool within the software, there is only one pre-alpha phase for this so far. The automated presentation of the dynamics between the time t_0, t_{25} and t_{100} does not work automatically yet. The classic FTA is already in operation. The following illustration describes the building shown and the top event "Failure of the escape by fire ladder in case of fire" at time t_0. All of the following failure probabilities always relate to one analysis year. A complete representation at point t_{25} and t_{100} would exceed the scope. However, it is sufficient to represent the DFTA system.

Downtime frequency

The simulation makes it possible to make statements about the distribution function of the failure of the escape route. Figure 3.20 shows the downtime distribution of an escape fire ladder in analysis interval of one year.

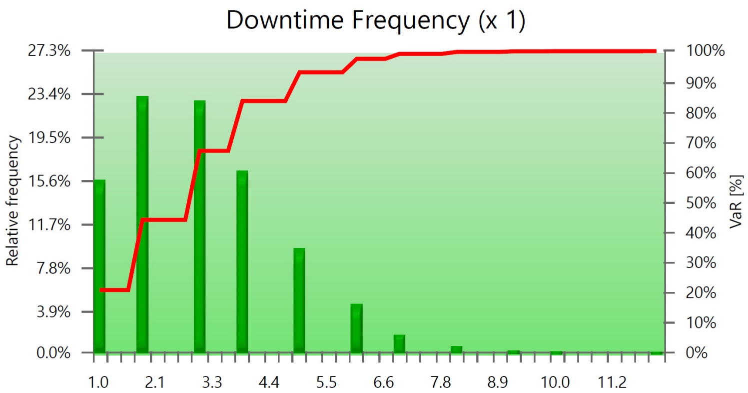


Figure 3.20: The figure shows the downtime frequency in the analysis period of one year. The relative frequency with regard to the intervals of lost days (green) is shown on the left y-axis. The x-axis shows the days with possibility failure. The right y-axis shows the values at risk (VaR). The red line shows the integral curve with which probability of the number of fault conditions in the escape route has fallen below.

Probability of falling below

A further result of the FTA is the value of risk with the days with failure of the top event. The Lorenz curve provides another representation of the distribution function. Figure 3.21 shows the value at risk on the days with deficiencies. This shows the probability with which a certain number of days with malfunctions will be undercut. For the 10% quantile, it means that there is a 95% probability that there will be six or lower deficiencies in one year. There is a 94.69% chance of at least one failure per year (no successful rescue by fire ladder in case of fire).

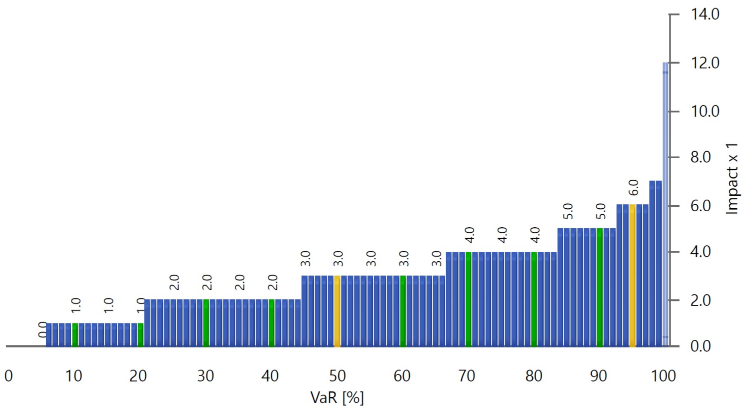


Figure 3.21: The figure shows the value at risk on the quartile respective days. The x-axis represents the fall below in %. The y-axis shows the impact.

Quartile analysis

The percentage values shows in 3.22 the percentage by which the value at risk are below or above the calculated deterministic value. The deterministic value from the calculations for the quantile is 2.901 days. This means that approximate 3 failures are expected per year. This corresponds roughly to a 50% probability of being below the limit. As a result, this deterministic value for the faulty states is exceeded with a probability of 50%.

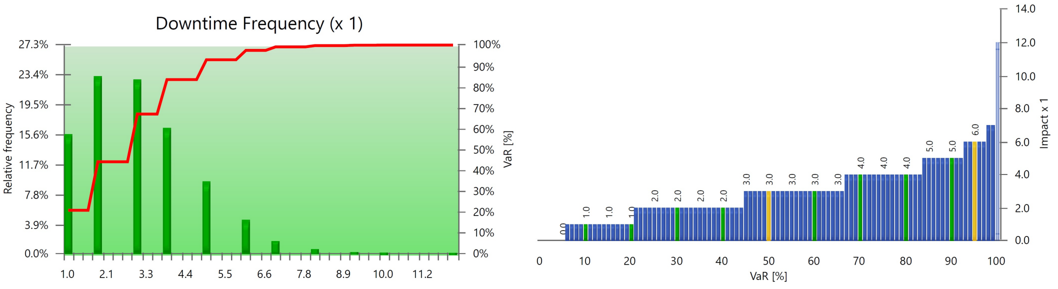
det.		0.000
VaR5	0	0.0%
VaR10	1	34.5%
VaR20	1	34.5%
VaR30	2	69.0%
VaR40	2	69.0%
VaR50	**3**	**103.4%**
VaR60	3	103.4%
VaR70	4	137.9%
VaR80	4	137.9%
VaR90	5	172.4%
VaR95	6	206.8%

Figure 3.22: Tabular representation of the quartile with a probability of falling below.

Dynamic Fault Tree Analysis

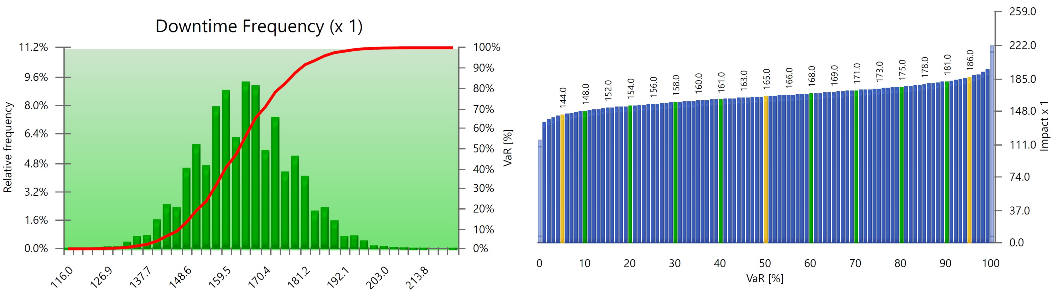
RIAAT® software is still in the alpha phase with regard to DFTA, so that an automatic time dependent analysis does not work yet. Therefore, the merging of the different analysis indicators t_0, t_{25} and t_{100} for the downtime (green graph) has to be done manually.

For this purpose, the downtime frequency at time t_0 (figure 3.23), t_{25} (figure 3.24) and t_{100} (figure 3.25) is evaluated. Each in an analyzed period of one year.



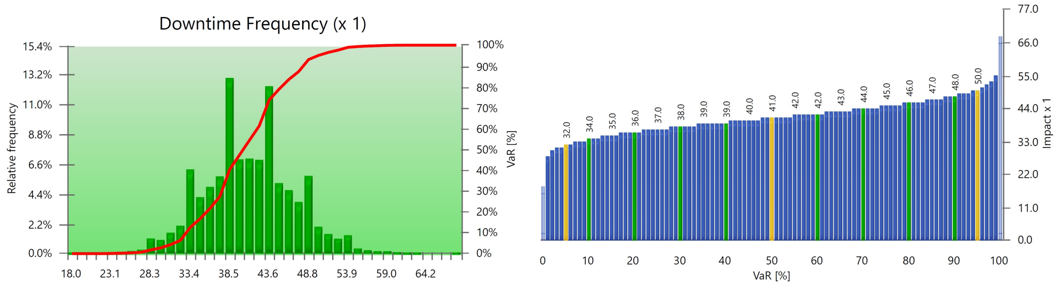
det.		0.000
VaR5	0	0.0%
VaR10	1	34.5%
VaR20	1	34.5%
VaR30	2	69.0%
VaR40	2	69.0%
VaR50	**3**	**103.4%**
VaR60	3	103.4%
VaR70	4	137.9%
VaR80	4	137.9%
VaR90	5	172.4%
VaR95	6	206.8%

Figure 3.23: Figure shows the downtime frequency with relative frequency at time t_0 on the green graph. The blue graph in the middle shows the falling below probability. The table on the right shows the value at risk between 5% and 95%. The complete analyzed time period is one year.



det.		0.000
VaR5	144	87.4%
VaR10	148	89.8%
VaR20	154	93.5%
VaR30	158	95.9%
VaR40	161	97.7%
VaR50	**165**	**100.2%**
VaR60	168	102.0%
VaR70	171	103.8%
VaR80	175	106.2%
VaR90	181	109.9%
VaR95	186	112.9%

Figure 3.24: Figure shows the downtime frequency with relative frequency at time t_{25} on the green graph. The blue graph in the middle shows the falling below probability. The table on the right shows the value at risk between 5% and 95%. The complete analyzed time period is one year.



det.		0.000
VaR5	32	78.1%
VaR10	34	83.0%
VaR20	36	87.9%
VaR30	38	92.7%
VaR40	39	95.2%
VaR50	**41**	**100.1%**
VaR60	42	102.5%
VaR70	44	107.4%
VaR80	46	112.3%
VaR90	48	117.1%
VaR95	50	122.0%

Figure 3.25: Figure shows the downtime frequency with relative frequency at time t_{100} on the green graph. The blue graph in the middle shows the falling below probability. The table on the right shows the value at risk between 5% and 95%. The complete analyzed time period is one year.

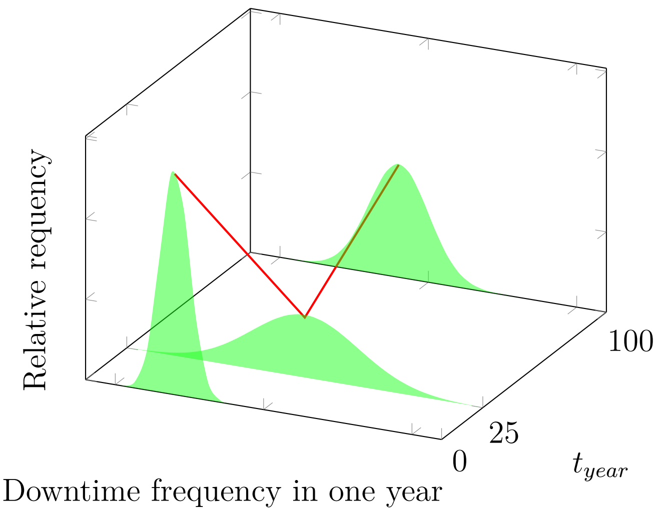


Figure 3.26: Summarized 3D graph with the distribution of the downtime at time t_0, t_{25} and t_{100} in the color green. The red line shows the connection between the respective extreme values.

The figure 3.26 now shows the chronological progression of the downtime of the failure probability of the ladder rescue by the fire brigade during the times t_0, t_{25} and t_{100} after the first use. It can now be seen here that when the building is being used (time t_0), the highest probability of failure is the rescue via fire brigade ladders. After 25 years, the lowest probability of failure exists and it rises through use to up year 100.

3.7 Discussion of the technical part

In the following, the developed method is critically questioned. Chapter 3 describes some improvements in the area of FTA. Specifically, this thesis improves:

- Summary of the most important 150 probabilities in fire protection, including defensive and preventive failure probabilities.
- Definition of three different quality levels (+, ++, +++) for the probability of failure.
- Advanced input values are defined in order to calculate the best performance ratio point between the used financial resources and the increase in safety. These are the costs to create a redundant system, the maximum sensible number of redundancies and the maximum number of calculable combinations of redundancies.
- The extension of the classic FTA by the factor of aging of the system by a DFTA. This makes it possible, even in the aging process of a system, to find the point when it makes most sense to improve the system again.
- Developing an algorithm to find the best mathematical calculation method to analyze the top event in an FTA.
- Development of an algorithm that makes it possible to combine the different quality levels of the input data from primary events in one FTA.
- Representation of the DFTA as a pre-alpha phase of the RIAAT® software to enable the DFTA.

All of the points described lead to an improvement in the informative value of FTA in general and especially in fire protection.

An FTA only works, if system links (gates) are known and the input values for the probability of failure of the primary events are available. The thesis has made an important contribution to the collection of failure probabilities in the area of fire protection. The approximate 150 important failure probabilities in fire protection have been extracted from detailed literature research and summarized. Extensive research of the literature has shown that there is no central database for the probabilities in fire protection. The data described comes from different countries, so that a critical check must always be made to determine whether the probabilities can be transferred to other systems. In order to check the transmission of the probabilities, the fire protection laws of the federal countries must always be examined [PMV10]. An essential aspect of the check is whether the material or the system from which the probabilities originate is built according to the same quality criteria. Additionally, the probability of failure of a sprinkler system from China cannot simply be compared with a sprinkler system from Germany [Fac15]. For example, there are different definitions of the testing of loads in building materials of technical systems [Sch18]. Correction factors are one way of transferring the probability of failure from one system to the other [DAN94]. Another aspect that must be taken into account is the human factor when using probabilities (for example extinguishing success with a fire extinguisher). Many factors play a role here, such as previous education, the social environment or risk awareness [Dhi18]. So people who are used to making decisions quickly and also implementing them are probably a little better suited to extinguishing a fire than people who normally only act on instruction. The probabilities of a fire in relation to the use of a building must be critically questioned [Deu10b]. Here, there are very different laws between the countries which measures must be taken to prevent the fire from starting. When it comes to defining the quality of data, there are also major differences between the various sciences. For example, data on the probability of failure from nuclear power plants are more accurate than data from a social science [Fac15, PS18]. This is due to the fact that technical systems can be simulated more precisely than human behavior. If the probabilities for the failure of technical systems (for example the failure of a pump) [Fac15] are combined with human failure probabilities (control of a operation center in a nuclear power plant) [Int08a] within an FTA, this must be analyzed in detail. In general, it can be summarized that an existing data set on the probability of failure offers a huge advantage, although the transfer of the probabilities must also be critically examined. However, if the influences are all checked and are also analyzed, this is possible.

Another aspect of this thesis is the definition of the quality factor for data on reliability in fire protection systems. The definition of three levels of quality with + for the lowest and +++ for the highest quality level now enables a selection of high quality data for an FTA. The reason for this consideration is that the transparency of data should be increased. Unfortunately, there are still important sources such as DIN standards that do not clearly cite the probability of failure [Deu10b, Deu10a]. Since DIN standards represent the interests of the economy, economic aspects and influences are also contained here. As an example, the reduction of the test period for fire extinguishers to 2 years from the original 4 years should be mentioned [Deu09]. The definition of only 3 different quality levels for the data on the probability of failure must also be questioned critically. Since, only a meaningful sequence of quality $+ < ++ < +++$ can be defined and no ratio can be calculated, it is an ordinal scale [BS10]. The definition of a ratio scale would no longer make sense here, since calculating the probability of failure with different quality levels of data would not lead to a clear result. The standardization enables a comparison, this leads to a congruence, which therefore leads to an improvement and this results in better quality [SW13]. Thus, an important contribution to the comparison of data on the probability of failure in fire protection has been made here.

The expansion of the advanced input values $C(E)$, $T(E)$ and $M(G)$ within primary events of the FTA was a further important step in this thesis in order to improve its practicality. Here, $C(E)$ represents the costs to create a redundancy system, $T(E)$ the maximum redundancy primary events that can be technically implemented and $M(G)$ the maximum sensible number of complete redundant gates. The implementation of these definitions of primary events now enables a practical application. Specifically, the FTA results that are not meaningful can be excluded directly, so that:

- The intersection between costs and the increase in safety can be defined.
- The natural limits of the engineering implementation of solutions are drawn in directly (For example, 10 redundant cables can be installed between the emergency power generator and the distribution box, but 10 generators cannot be installed).
- When calculating which gates have the greatest influence on the top event (minimal cut set [RS15b]), 10 gates are not considered.

The previous application of an FTA relates to the calculation of the failure probability of the top event, this corresponds to the state of the art [ESH15, Dhi18]. The expansion of the variable also leads to an improvement. The idea of optimizing the FTA is not a new idea [SLX07], however it is with regard to the limits of the technically possible reductions. Results of an optimization simulation are represented in this way, although they cannot be implemented in the reality. However, this work only represents the new methodology of the extended input variables. A further step is now to implement this idea in the existing software, such as RIAAT® or isograph®. In general, unfortunately, it can be said that there are various publications on the behavior of building materials in the area of statics regarding fire protection, but there is almost nothing in the risk quantification that focuses on fire protection. There is a very large field of research here to find the answer to the problem of the best possible combination of financial resources and an increase in security. Legislation in the EU means that building law is still being defined by its separate member countries [PMV10]. This makes it very difficult to find suitable means for comparing the construction planning in order to quantify risks from it. The first steps have already been taken in fire protection in a solution through DIN EN 13501 [Deu19]. *Wald* started the first approaches to fire protection costs and their risks including costs for defensive fire protection [WBH+13]. In order to quantify the reliability or probability of failure in fire protection using an FTA, the central question is whether the events are independent. These events are considered independent if their probability of occurrence is not influenced by any other event [ESH15]. For effective fire fighting and the rescue of people, several subsystems (fire brigade, smoke extraction systems, extinguishing systems, etc.) must function in the case of a fire. Since, these systems do not influence each other, they are independent. Thus, an FTA is the correct method. However, there are also influencing factors that affect several primary events at the same time. Here, the independence of the event would no longer be guaranteed. For example, a power failure in a building affects several subsystems. Here, the power failure affects the smoke extraction system and the water sprinkler system. Common causes can be used to represent this dependency within an FTA [Vau03]. This means that the top event of a fault tree can be simulated, although there are dependent and independent results.

Another important development of this thesis is the expansion of the classic FTA to a DFTA. The classic FTA represents a system at the time t_x and calculates the probability of failure in a defined analysis period [ESH15]. It is therefore a good method to represent the system status now, although it does not provide any information about how the system will behave in the future. The change in the probability of failure is the effect of the changed probability of failure in the course of the aging process. However, various publications have a different solution other than DFTA. Here, the dynamics within an FTA are defined as a time dependent course of the failure of individual components [Sch09]. Although, not the aging of the components, as described in this thesis. Thus, this type of DFTA represents an extension of the existing FTA, with the aim of better illustrating the reality (components age and change the probability of failure over time) in order to obtain a more precise result from an FTA. In order to obtain results of the calculation that represent reality very precisely, corresponding data on the probability of failure are required. Obtaining the data will be one of the great challenges of the future. It is a reliable source of failure probabilities of technical systems, but only for high quality systems like nuclear power plants [Fac15, Int08a], airplane engineering [RRF18] or for medical equipment [TK17]. In fire protection, a distinction must be made between high quality systems (fire alarm systems in nuclear power plants) and low quality systems (fire alarm systems in old residential buildings). When calculating the probability of failure in high quality systems, the data can be transferred. In systems with low quality, the data must be converted with a correction factor. Hence, in the future, research into the correction factors of technical systems will be necessary in order to obtain good data quality. Approaches from the statics of buildings can be adopted here [Sch18].

The development of an algorithm for the correct use of an FTA is also part of this thesis. One algorithm describes the mathematical calculation method with which an FTA can be carried out most sensibly, another algorithm represents the procedure for using different quality criteria for input data of primary events. These two algorithms help the user to make decisions about complex trains of thought transferable to non-experts in an FTA. The algorithms help to make the FTA accessible to a larger group of interested parties and to be able to answer difficult questions such as the correct mathematical method. However, this also harbors dangers, since errors can occur in the application that cannot be found by non-experts in the field of FTA.

In the end, it can be said that there is a big difference between practice and research. The new methods bring great advantages, although they also have to be tested in practice. This gap can only be closed by combining practitioners and theoreticians. The present work is a further step in the right direction. However, the finished path to secure "state of the art" practice is still a very long one. That will be one of the great challenges of the future.

Chapter 4

Structural quantification with Machine Learning methods

In the year 2018, renowned auction house Christie's in New York sold the first piece of art created by an algorithm for $ 432,500. Figure 4.1 shows the painting, titled "The Portrait of Edmond Belamy," it was completed by artificial intelligence managed by a Paris based collective called Obvious, Christie's stated [Chr19]. This fact alone raises the question regarding the use and possibilities of artificial intelligence. In image and text processing, these methods are already being used regularly. In fire protection and general construction, these methods are still in their infancy.

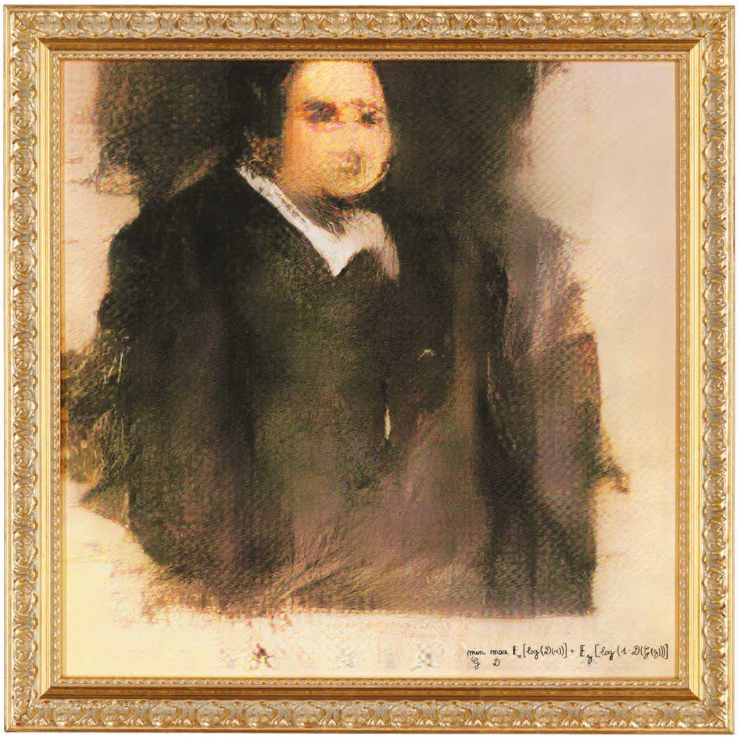


Figure 4.1: Portrait of Edmond Belamy, 2018, created by Generative Adversarial Network, sold for $432,500 on 25th October, 2018 at Christie's in New York [Chr19].

The following chapter describes the methodology for using ML in fire protection. The focus is on structural preventive fire protection and the possible application of the technology to find predictions regarding the best performance ratio between cost and the increase in safety. Essential components are laid for future research as not much is available in this area yet. The chapter is split into the first section for a basic overview of AI including the main methods of ML and basic terms of structural fire protection 4.1. The second section describes the best performance ratio concept 4.2, thirdly, the possible influencing factors 4.3, fourth the resulting result layer in the section 4.4. The fifth section describes a ML method for analyzing fire and smoke spread in a building in section 4.5 and section six shows the outlook of this chapter 4.6.

Before the chapter regarding the concrete answer to the research question is started, a point has to be considered. There are various methods for using AI in different areas that are already state of the art. Whether it is the Google® image search, Amazon®, etc. Unfortunately, despite very thorough research, there is an almost completely empty void in the scientific world with regard to the combination of AI and fire protection. There also is not much regarding the scientific consideration of the effectiveness of various fire protection measures. The following chapter is intended to lay the foundation for future research projects.

4.1 Basic terms of AI and building structures

There are a lot of different definitions of ML. One of the first was Mr. Herbert with "*Learning denotes changes in a system that are adaptive in the sense that they enable the system to do the same task or tasks drawn from the same population more efficiently and more effectively the next time* [Sim83]". However, this characterization also includes changes that obviously have nothing to do with learning. If one sees the faster processing of an arithmetic calculation as an improvement, then the definition above can be applied, as the system already uses a fast processor, the arithmetic calculations performed according to the same scheme, however a learning achievement is accomplished in a shorter time frame [CB19].

A second definition is provided in the following: "*The study and computer modeling of learning processes in their multiple manifestations constitutes the subject matter of machine learning* [CMM83]". Although this definition avoids the deficits just mentioned, it circumvents the problem of an actual definition of machine learning by directly referring to "learning processes in different forms". However, from the context of the work it is clear that not only the adequate modeling of human learning processes is meant, but also so called learning programs that pursue completely different approaches.

Learned knowledge must be represented in one form or another in order to be available for later use [CB19]. This representation aspect is highlighted in the following characterization of learning: "*Learning is constructing or modifying representations of what is being experienced* [YM90]". The performance improvement achieved through learning becomes a consequence, but closely related to the defined goals of the learner. In most practical situations, however, the assessment of learning success becomes dependent on the measure of performance improvement, since direct access and above all, an evaluation of the quality of a representation is often difficult or not possible at all.

While humans perform actions, they are usually learning at the same time, which can increase the speed, efficiency and productiveness of the performed action. Typically, computer programs are not able to experience this, as usually they are unable to improve their actions on their own [CB19]. However, this is precisely the goal of machine learning: "*Research in machine learning has been concerned with building computer programs which are able to construct new knowledge or to improve already possessed knowledge by using input information* [MK90]". Figure 4.2 shows the main differences between the classical programming and the ML methodology. With the inputs of rules and data, the computer output with an answer. In contrast, the ML output is rules from the input of data and the expected answer.

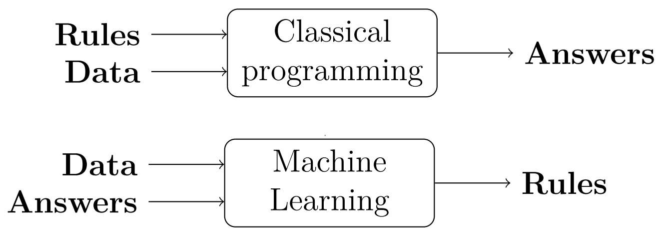


Figure 4.2: The figure shows the difference between the classical programming with input of rules and data and output of an answer. The ML methodology is described with input of data and answers and output of rules [CA18].

4.1.1 Main method to differentiate between ML types

Generally, ML methodology is split in two main classes. The first being supervised learning methods with regression and classifications and the second unsupervised learning tools with clustering and dimension reduction:

- **Supervised Learning**: A learning algorithm tries to find a hypothesis that makes the most accurate predictions possible. The method is to be understood as a mapping that assigns the presumed output value to each input value [MRT12]. If there is historical data that contains the set of outputs for a set of inputs, then the learning based on this data is called as supervised learning [Jos20]. The results of the learning process can be compared with the known, correct results [MG17]. Table 4.1 shows a brief method overview of a basic method to predict an output from an input data set. The input data set includes a pair of values with the number of used units and number of fire deaths per unit. With a supervised learning method it is possible to predict a new line of the input data set in the case of 6 units used.

  There are two main types of supervised learning methods:

  - Regression
  - Classification

Data set

n = used unit	n = fire death
3	1
5	2
8	4
9	6
...	...

=> Supervised learning method => Predict: n = death from the used units

Table 4.1: Short description of a supervised learning tool methodology with a possible prediction of the number of deaths according to units used.

- **Unsupervised Learning**: Unsupervised learning means machine learning without previously known target values and without environmental rewards. Additional labels are not assigned to the data, and the task is to identify patterns or to model the data. Unsupervised learning is used, for example, to compress information, organize data, or generate a model for it. In the following, it deal exclusively with unsupervised learning. At the moment, unsupervised learning seems to be the most developed and economically influential part of machine learning.The algorithm tries to identify patterns in the input data that deviate from structure less noise [Gha04]. There are two main methods used in unsupervised learning:
  - Clustering
  - Dimension reduction

The following demonstrates an example of an unsupervised learning method.

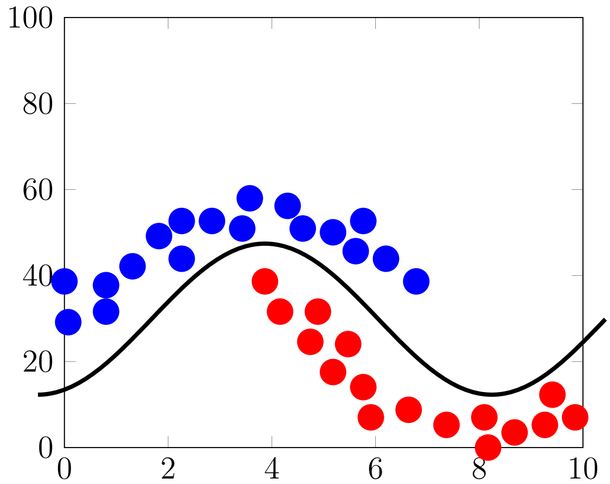


Figure 4.3: An example of an unsupervised learning method to split the red dots from the blue dots with a function.

In general, there are various different procedures in the area of ML. Only a very brief summary is given each time, since a detailed definition would go beyond the scope of this thesis. Each methodology is shown with a short text introduction and a typical figure.

Regression

The first main method in AI is regression. In general, one has to differentiate between logistic regression [BSMM15] (actually a classification algorithm) and AI methodology regression. The next section only describes the AI methodology. Regression is a popular ML algorithm tool. Linear regression is a ML model, which predicts a certain number based on training data. For this a data set is taken and the ML model is trained with it:

$$f(x) = y = wx + b \tag{4.1}$$

In the respective training, the parameters w and b are adjusted in the equation. This happens through a loss function:

$$l = \frac{1}{N}\sum_{i=1}^{N}(y_i - [wx_i + b)]^2 \tag{4.2}$$

This function presents the value of how far the predicted y value was from the real y value. The predicted y is $wx + b$. This error is optimized by a technical gradient. There are the derivatives for the parameters w and b with the formulas:

$$\frac{\delta l}{\delta b} = \frac{1}{N}\sum_{i=1}^{N}(y_i - 2(y_i - [wx_i + b)] \tag{4.3}$$

and

$$\frac{\delta l}{\delta w} = \frac{1}{N}\sum_{i=1}^{N}(y_i - 2x_i(y_i - [wx_i + b)]. \tag{4.4}$$

After a few adjustments, the minimization of the parameters w and b is obtained. Then a x input value can be taken and y can be predicted. Figure 4.4 shows the basic concept with existing input data (black dots) and the regression line in red [KBB+15].

Classification

Classification is the second basic tool of ML. It is possible, based on training data to predict a quality feature. Moreover, it is possible to classify with input values. For the first step a training data set is needed:

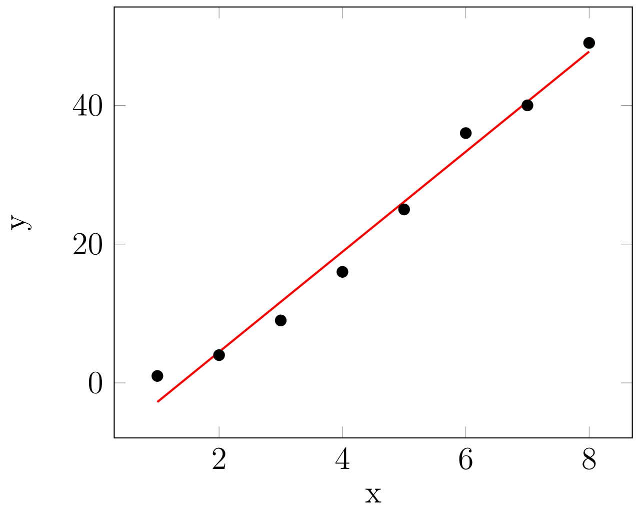


Figure 4.4: This is an example of regression function as red line to find a linear context with two different input data sets.

$$\{(x_1, y_1), ..., (x_n, y_n)\} \tag{4.5}$$

y_i is the expression of a qualitative characteristic of x_i. The classification determines a $\widehat{y}_i$ from the influencing variable x_i. The indicator value I is defined by:

$$I(y_i \neq \widehat{y}_i) = \begin{cases} 1 \; y_i \neq \widehat{y}_i \\ 0 \; y_i = \widehat{y}_i \end{cases} \tag{4.6}$$

Which means in the case of right classification between the real data set y_i and the predicted value $\widehat{y}_i$, it is 0 and in case of wrong classification it is 1. The next step is the same as the regression function to measure the incorrect I prediction with an error:

$$Training\ error = \frac{1}{n}\sum_{i=1}^{n} I(y_i \neq \widehat{y}_i) \tag{4.7}$$

The main purpose of this method is to separate the data into groups. Figure 4.5 shows an example of two simple groups of red and blue dots and they are split into two areas with a function [Sch19].

Clustering

In general, clustering is a methodology of the unsupervised learning tool. It is particularly powerful when large data sets are to be analyzed. As *Scherer* stated clustering is "... a process of organizing data sets into homogeneous groups. This organizational process is based on

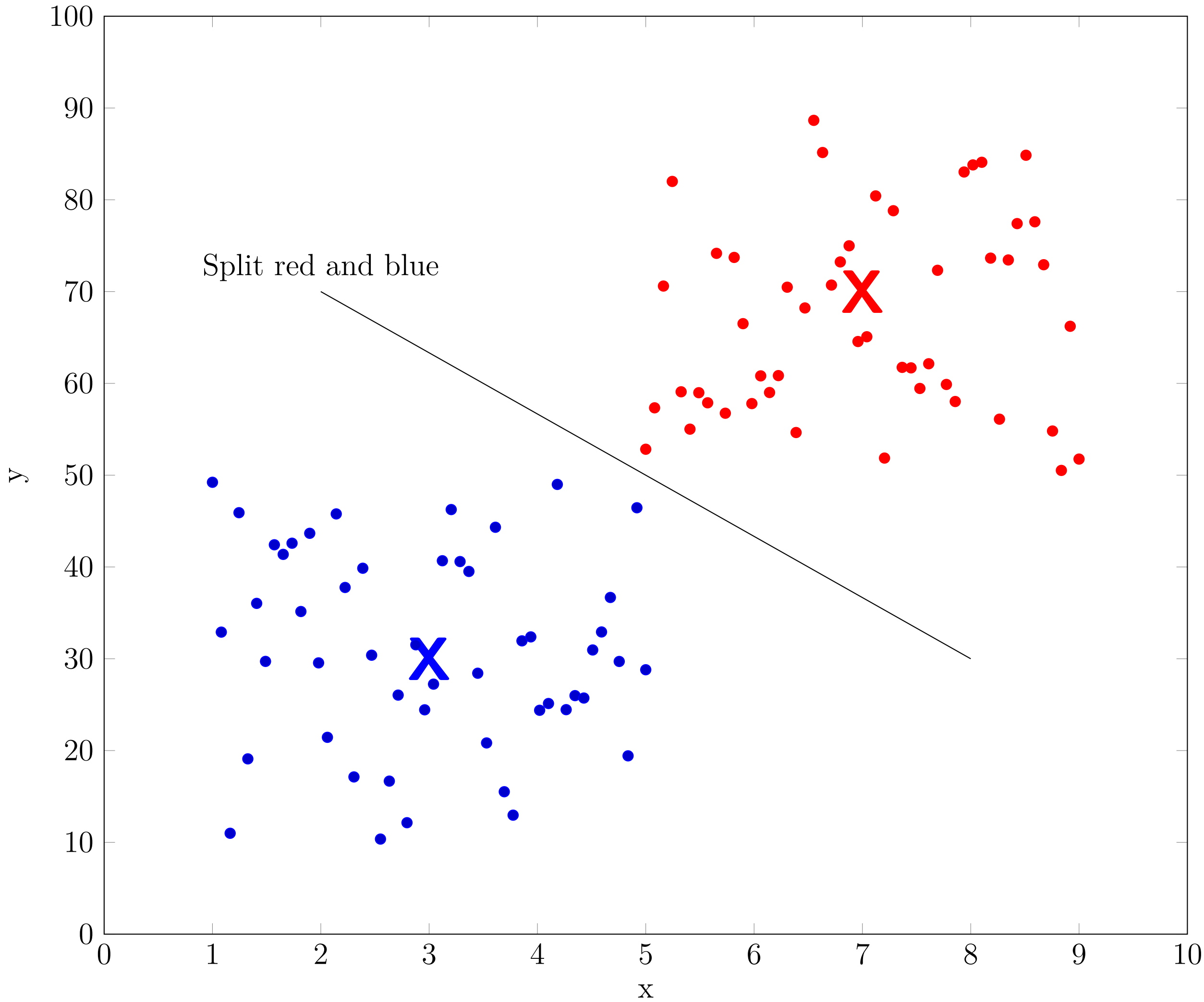


Figure 4.5: This is an example of classification, with the two influences red and blue with a black line separating the data set.

the given features of similar objects" [Sch19]. The data set or object can be described by a set of measurements or by relation to other objects [JWHT17]. One of the most common types of clustering is grouping according to certain characteristics. The most important representation form from the result of clustering is the dendrogram (see figure 4.6). A hierarchy is applied according to the characteristics. It should show how the data set is composed and at what sizes the data set can be meaningfully shared. The methodology behind this representation is the K-means. The basic concept is applicable for all of the variables of the quantitative type and squared distance values *Euclidean* with:

$$d(x_i, x_{i'}) = \sum_{j=1}^{p}(x_{ij} - x_{i'j})^2 = ||x_i - x_{i'}||^2 \quad (4.8)$$

Each observation is uniquely labeled by an integer $i \in \{1, ..., N\}$ [JWHT17].

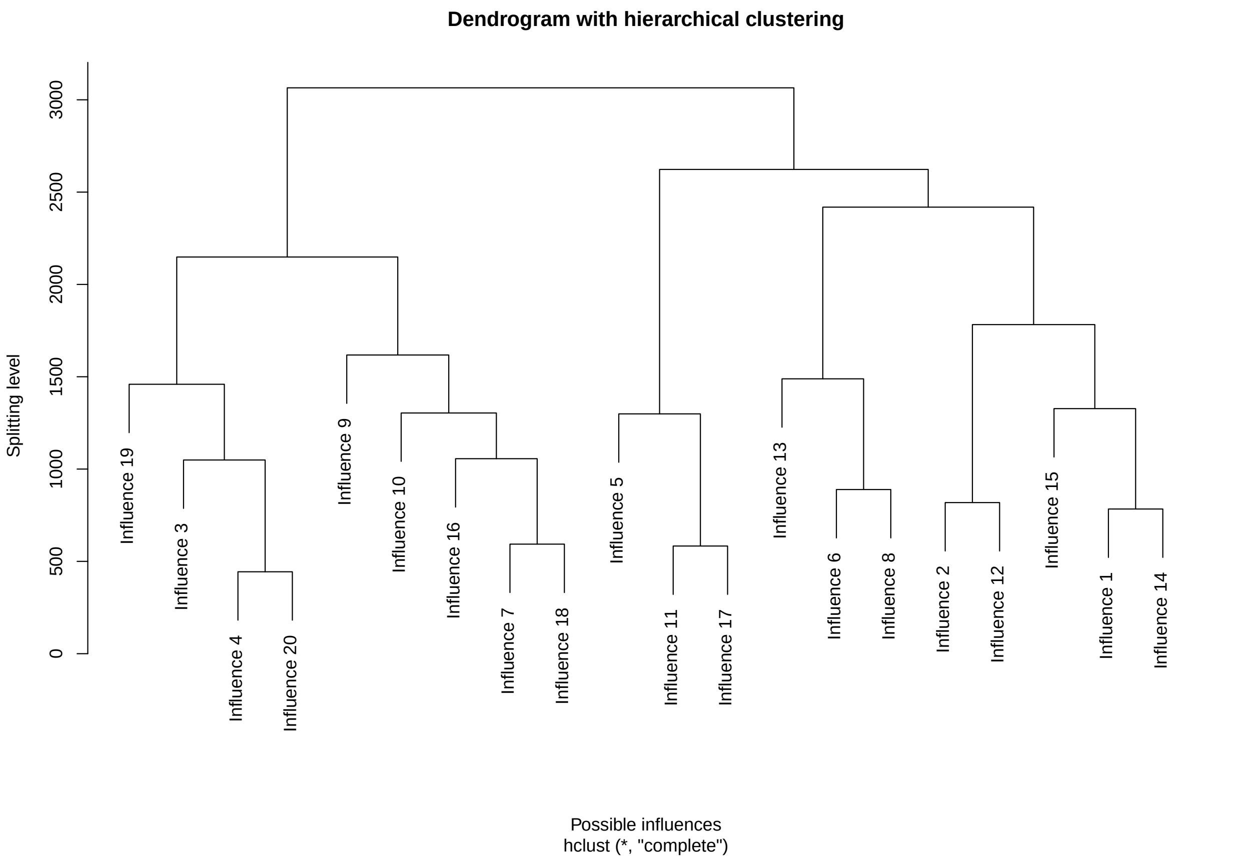


Figure 4.6: Example of a possible dendrogram as a tool of classification, possible influences are independent on a nominal scale level.

Dimension reduction

The dimension reduction is the second main methodology of unsupervised learning. The basic concept is a complex data analysis resulting in a visual representation of the data [RS00]. Today, it is standard to create huge data sets from automatic systems. A typical application for processing large amounts of data in a short time frame is autonomous driving with a car [ZLT$^+$20]. With the methodology of dimension reduction it is possible to visualize exploratory data with a reduction design. From a physical standpoint, dimension is a space of length, width and height with three coordinates to describe a point. In the example figure 4.7 shows ML field, a three dimensional space is assigned to a data set with three characteristics to describe the individual case. It is difficult to find coherence between individual cases with a huge number of characteristics. In the methodology of dimension reduction, the main objective is to reduce the number of not so important characteristics (dimensions) to find coherence. Figure 4.7 shows an example for dimension reduction from left (3D) to middle

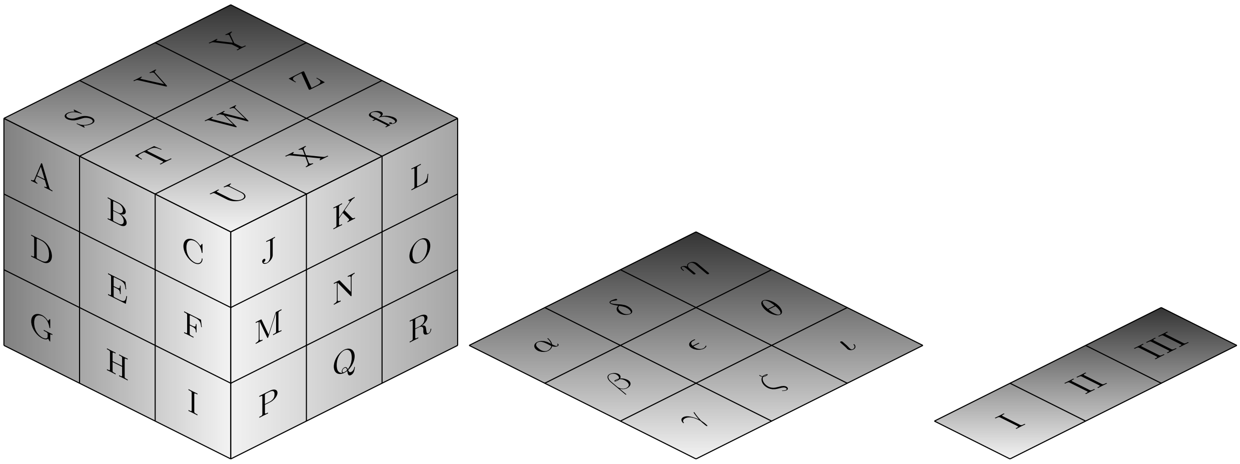


Figure 4.7: This an example of possible dimension reduction from 3 dimensions (Latin letters) on the left to 2 dimensions (Greek letters) in the middle and to 1 dimension (Roman numerals) on the right.

(2D) to right (1D) dimension. Here on the left side, it displays a data set of Latin letters via a cube with three dimensions. In the example that has been devised, the data set is then reduced from three dimensions to two dimensions in the middle, now with the Greek letters. The reduced dimension (height) is summarized here into a two dimensional square, which is only consists of length and width. In the next step, the square with two dimensions is reduced to an one dimension data set with Roman numerals, which exhibits only length.

4.1.2 Deep learning

The most powerful methodology of the sub group of AI and ML is DL. Because of the existence of neural networks, great progress has been made in the field of image recognition and in solving difficult problems. The basis for this methodology is the human brain with its functionally. Biological brains are very robust and have the mechanism to regularly learn from incomplete signals. Today, neural networks have outstanding success in AI. The DL is a more complex mechanism and neural networks are the best example of this (see figure 4.8) with more than two hidden layers. Figure 4.9 shows the basic concept with four input layers, three hidden layers and one output layer. In the year 2016, the program AlphaGo from Google® DL defeated the world's best Go player [SSS$^+$17]. Go is considered to be one of the most complex games that currently exists on the planet. The ML tool used was DL. Researchers had actually assumed that a computer could never play Go as well as a human can.

The actual methodology with the corresponding threshold value element and the weighting factors are based on a simple neural network. The basic concept has already been described in section 1.2.3.

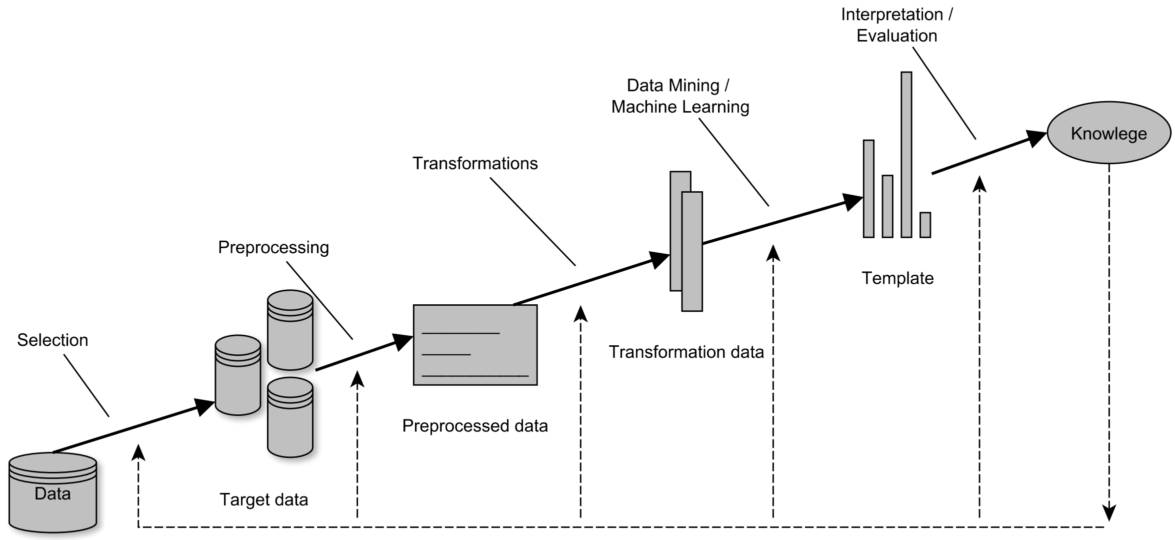


Figure 4.8: General overview of knowledge discovery of data bases with a basic process.

Figure 4.8 shows the general procedure in the ML. Starting with the data record "Data", a selection of the original data record is shared. In most cases, approximately 80% is taken as the training data set and 20% as the test data set. The data is prepared and then transformed. The transformed data is then processed using the respective DL methodology. The methodology is now very dependent on the respective data type. Various different tools are used to train DL with a data set. Typical programming languages are C ++ or Python. One of the strongest programs for training and testing is Tensorflow[1].

Deep learning is a type of machine learning in which a model learns to perform classification tasks directly from images, text, or sound. DL is usually implemented using a neural network architecture. The term “deep” refers to the number of layers in the network, the more layers it has, the deeper the network. Traditional neural networks contain only 2 or 3 layers, while deep networks can have hundreds [Mat18]. The basis of deep learning comes from *Minsky*. It dealt with the prediction of complicated credit card payments and used a methodology to predict possible payment defaults for banks [Min63]. The basic problem was that the existing data from the past should have been used to make predictions about the future. In this case, a sample was looked for which exhibited the influencing factors that effected customers who could not pay their invoices. The pattern recognition was thus born as a prediction of the DL. *Schmidhuber* [Sch15] offers an excellent overview of the history of DL from 1963 to the present day.

Today, the method is trained in a variety of different applications. The most common typical variant of deep learning probably is the suggestion tool, for example when people shop online on Amazon. Here the suggestion for further products brings an increase in profit for the company of approximately 30%. The insurance industry also predicts possible risks

[1] An excellent visualization of the Tensorflow® package is available as an online variant under: http://playground.tensorflow.org/

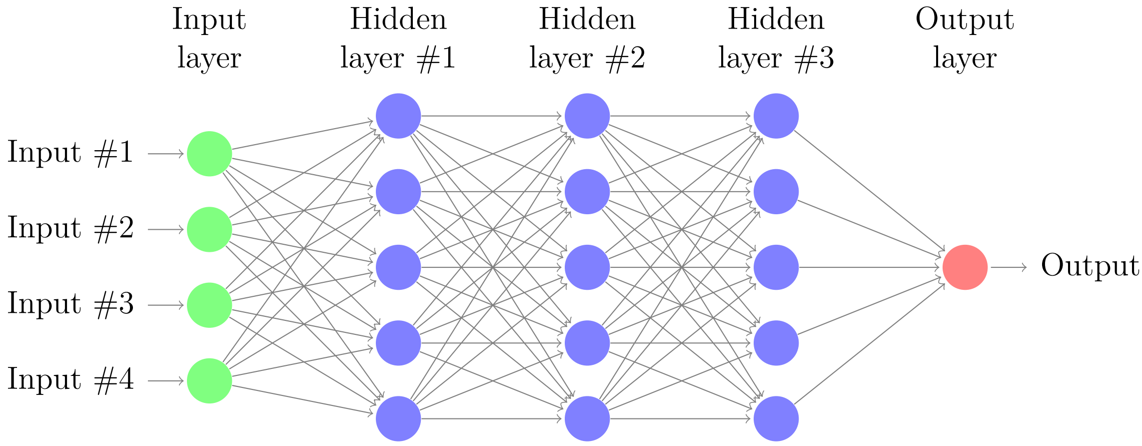


Figure 4.9: The example above displays a classical structure of a deep learning method with more than one hidden layer, three are exhibited here.

for the insured, for building insurance, life insurance and for health insurance. Here, the monthly premiums are adjusted to the respective risks of the insured person. In the area of risk prediction, it is also used for earthquake forecasts and natural disasters [HDC19]. With the completion of this work, a new topic could be opened up. Namely, the risk forecast in fire protection for extreme value statistics.

The mathematical concept of training the neuronal network is based on the adaption of all parameters in the neuronal network. The training is defined as [GBC18, KBB+15]:

- Adjustment of the weight factors of input information to the neurons.
- Adaptation of the appropriate threshold value function to define when a piece of information from the neuron should be passed on again as output information.
- Define the task of the neuronal network, if it has a fixed learning task or a free learning task.

Weight factors

The weighting factors w indicate how much the input signal x of the neuron θ should be evaluated for an output signal y. The weighting can be either positive or negative. Formula 4.9 shows the basic concept and formula 4.10 shows a brief example with a weighting for the input signal x_1 of 3 and for x_2 of 2. The threshold $\theta = 4$ means, if the sum of all inputs is more than 4, there will be an output signal for y.

x_1	x_2	$3x_1 + 2x_2$	y
0	0	0	0
1	0	3	0
0	1	2	0
1	1	5	1

Table 4.2: The table describes the possible combinations for the input information of x_1 and x_2 and the output information for y. The threshold sum function is 4. Only in case of $x_1 = 1$ and $x_2 = 1$ is there output information.

$$\begin{array}{llll} x_1 & & & \\ & \searrow w_1 & & \\ \vdots & \quad\theta & \longrightarrow & y \\ & \nearrow w_n & & \\ x_n & & & \end{array} \tag{4.9}$$

$$\begin{array}{llll} x_1 & & & \\ & \searrow w_1 = 3 & & \\ \vdots & \quad 4 & \longrightarrow & y \\ & \nearrow w_2 = 2 & & \\ x_2 & & & \end{array} \tag{4.10}$$

Table 4.2 shows which combination of input signals from x_1 and x_2 results in output information for y. The 0 stands for no information and 1 for information. Since the threshold value of 4 is only exceeded when x_1 and x_2 are entered at the same time, information is then passed on. In the case of DL, the y is in turn the input for another neuron.

Adaptation threshold function

In the example described above, the threshold function is defined with a fixed value ($\theta = 4$). Describing a threshold value with just one value is not enough in practice to train a network. Complex functions are required for training, which depend on how well the network knows the respective pattern. This is why there are different functions to describe when an output value y occurs (however, y is in turn the input value x for the next layer). Figure 4.10 shows the three most important θ functions for the adaptation threshold function.

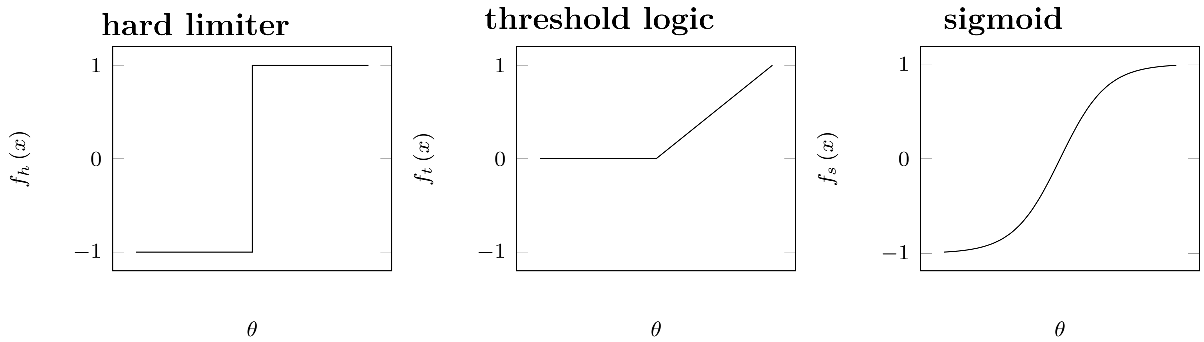


Figure 4.10: The figure describes the three most important threshold functions. The hard limiter (left) shows an output signal caused by a negative input signal. The logic function (middle) displays an output signal resultant from neutral input. The sigmoid function (right) exhibits an output signal as a consequence of saturation of inputs.

Task of neuronal network

The main task of a neural network is to train for a specific task on the basis of a training data set. The training means the adaptation of weighting factors and threshold elements. A well-trained neural network is when the adaptations are chosen in such a way that a special pattern is recognized. Depending on the training data, a distinction is made between [KBB+15]:

- **Fixed learning task**: "A fixed learning task L_{fixed} is an neuronal network with n input neurons (means $U_{in} = \{u_1, ..., u_n\}$) and m output neurons (means $U_{out} = \{v_1, ..., v_m\}$), its amount $L_{fixed} = \{l_1, ..., l_r\}$ of learning pattern $l = (\vec{i}^{(l)}, \vec{o}^{(l)})$, each consisting of an input vector $\vec{i}^{(l)} = (ext_{u_1}^{(l)}, ..., ext_{u_n}^{(l)})$ and an output vector $\vec{o}^{(l)} = ov_1{}^{(l)}, ..., ov_m{}^{(l)})$ [KBB+15]". In an fixed learning task a neuronal network should be trained, that input a learn pattern l, the the right output is described. However, this optimum is almost never reached in reality, so that one has to be satisfied with an approximation. An error function e_{fixed} determines how well a neural network describes the entered pattern. The error function is usually defined as the sum of the squares of the deviation from the desired and actual output across all learning patterns. Thus:

$$e_{fixed} = \sum_{l \in L_{fixed}} e^{(l)} = \sum_{v \in U_{out}} e_v = \sum_{l \in L_{fixed}} \sum_{v \in U_{out}} e_v^{(l)} \tag{4.11}$$

with:

$$e_v^{(l)} = (o_v^{(l)} - out_v^{(l)})^2 \tag{4.12}$$

The square of the deviation strengthens the determination of how large the error is.

- **Free learning task**: "A free lean task L_{free} is an neuronal network with n input neurons (means $U_{in} = \{u_1, ..., u_n\}$) is amount $L_{free} = \{l_1, ..., l_r\}$ of learn pattern $l = (\vec{i}^{(l)})$, which consists of an input vector $\vec{i}^{(l)} = (ext_{u_1}^{(l)}, ..., ext_{u_n}^{(l)})$ of external inputs [KBB+15]". While learning patterns contain a fixed learning task and a desired output, another criterion is needed to assess how well the neural network solves the task. The aim of a free learning task is for similar inputs to deliver similar outputs. To achieve this, each input variable is normally scaled so that it has the mean value 0 and the variance of 1. For this purpose, the learning pattern l of the learning task L is calculated from the input vector for each input neuron u_k with:

$$\mu_k = \frac{1}{|L|} \sum_{l \in L} ext_{u_k}^{(l)} \tag{4.13}$$

4.1.3 Structural building terms

This section describes the most important terms in structural fire protection and the basic concept of the evacuation and rescue systems in buildings [MB20]. In general, buildings are systems made from construction materials and there is a connection to the ground, even if the system rests on the ground due to its own gravity or has limited mobility on fixed tracks or if the system for its purpose is intended to be used in a stationary position, but movable [Bau12]. Although, this is the German version for the definition of a building, the EU definition is very similar.

Fire protection in buildings is to be arranged, installed, modified and maintained in such a way that the occurrence of a fire and the spread of fire and smoke are prevented. Additionally, in the event of a fire, people and animals are able to be evacuated, rescued and effective fire extinguishing work is possible. This is understood as a general protection goal in fire protection. How exactly the implementation of this protection goal works in the individual EU countries differs from country to country. Since this thesis contains a basis for future research and is not just a national document, a short explanation of the different definitions in the fire protection follows.

One of the main tasks of structural fire protection is to ensure the protection goal of personal safety. The different building laws in all EU countries give various options to achieve this. In the example of an escape route, the following combinations with the redundancy for the failure of an escape route are possible:

- *Two independent separate building escape routes*: These are separate escapes route for the residents of a standard building. In the event of a fire and where it is not possible to use one escape route, the second alternative route is accessible.

- *One building escape route, plus a temporary one via a fire ladder*: This is the most common system, where there is a structural escape route and a second escape route is temporarily provided via the portable ladders brought to the emergency location by the fire brigade. The concept here is that, if the structural escape route fails or is inaccessible, people can be rescued via the fire brigade ladders.

- *Fire safety stairwell*: The security stairwell is a special construction form for high rise buildings or other civil engineered objects. There are not two independent escape routes in these types of buildings, it is also impossible for the fire department to reach the upper and subterranean floors via ladders, therefore evacuation and rescue via this alternative is not an option. Accordingly, very high quality requirements are placed on fire safety stairwells. Some of these include, safety emergency lighting, an enclosed room system with at least two fire doors between the stairwell and the floors, plus positive pressure ventilation, etc. These features are complex measures and are only built where it is deemed necessary, due to the expense.

In addition, there is the topic of reducing the spread of fire and smoke throughout buildings. The protection goals "personal safety" and "effective firefighting measures by the fire brigade" are linked here. In the effective extinguishing measures, so-called usage units can be built in the building. For example, each building unit or section is completely separated from the next by a wall with a certain fire resistance duration. For more detailed information on the fire resistance duration refer to section 1.3 in the introduction. The aim of this is to impede a fire, so that it cannot easily spread from one usage unit to the next. Typically, in normal residential buildings, the apartments are separated by a wall with a fire resistance duration of 30 minutes. In order to separate the building into larger sections, there are so called "fire walls". For example, buildings with a maximum area of 1,600 m^2 in Germany, are required by law to have walls with a fire resistance of 90 minutes. Regarding personal safety, this law should give building users the possibility to leave the building safely over a reasonable distance. According to German building regulations, a maximum escape route length of 35 meters is determined for every apartment entrance point to a stairwell. As soon as building users are in the stairwell, they have entered a safe area, because the stairwell is a separate construction.

Figure 4.11 shows such an example, which is a hotel with several bedrooms. Where requirements are not necessary, for example within bedrooms, it is colored white. The hallway, colored light green, represents that here, the walls of the necessary hallway must have a minimum fire resistance of 30 minutes. The stairwell has a fire resistance of 90 minutes, it is colored purple. In order to check the described requirements, there are very different systems in the EU [PMV10].

Figure 4.11: Basic concept of a fire protection plan for a hotel with a necessary hall and a stairwell with the required wall fire resistance class.

4.2 Best performance ratio in fire protection engineering

The basic concept of the performance based code has now been presented several times within this thesis. The following section will deal with the concrete design of the research idea to use AI technology to improve fire protection. In particular, the method should lead to the following improvements:

1. Development of methods to make risk prediction possible in fire protection
2. Research the efficiency of various fire protection measures
3. Lay the basis for further research and identify areas that have not been researched

At the beginning of this research work, it was assumed that there is already extensive literature on the field of risk engineering in fire protection. This turned out to be incorrect. It depends very much on the respective sub-area. There are various peer reviews from publications on blaze simulation [BE19], statics in the case of fire [Deu19], person simulation [ZWSZ12, Maa04], fire behavior of building materials [BVL+20], etc. However, the question of the efficiency of the individual measures has almost never been considered [XGB06]. Chinese scientists have made further progress in the efficient design of such measures.

The research idea is based on the combination of artificial intelligence as a prediction tool in fire protection applications. The Fire Department of Atlanta started with the first and almost only approach in 2016 [MCH+16]. Here, the combination of real operations and fire inspections was made possible with the help of ML tool predictions. In general, it can be said in any case that there is still not a complete systematic workup in fire protection. That is why a step by step processing and quantification of possible influencing factors in fire protection now follows in order to be able to use concrete methods.

As a first step in this research work, it must first be determined which generic terms can be considered as influencing factors in the event of a fire. These are:

- *Structure of defensive fire protection*: An essential factor when considering risks is the entire structural analysis of fire protection. So there are many influencing factors such as training, time, number of emergency services, etc. that affect the performance of a fire brigade.
- *Real fire operation*: Another factor influencing the prediction of risks is the analysis of real fires and the use of the fire department. This allows conclusions to be drawn about effective fire protection measures and the interplay between defensive and preventive fire protection.
- *Fire protection plan*: The planning of a building, especially regarding the area of fire protection has been identified as a further general influencing factor. The fire protection plan for the construction of a building contains key indicators for fire protection. These include fire resistance classes, rescue routes, building materials, etc.

- *Building fire inspection*: The fire inspection of a building is defined as the last major influencing factor. The aim here is to regularly check a building to see whether the planned measures are being complied with. This measure is not available in all countries.

Each point of the influencing factors again has various sub points. The scales for the variables are very different, so that several hundred influencing factors have to be brought together at different levels. Classical statistical methods (see section 1.2.1) are no longer possible. A statement can only be found here through ML tools. Figure 4.12 shows the basic scheme of the developed theory to combine all influencing factors and to find efficient measures. In addition, fire protection always represents a risk and it is important to achieve a certain level of minimized risk. This is defined as an acceptable residual risk by society.

As already stated, the research field of "Influences in fire protection" is very small. Therefore, the possible influences for each level are now defined and explained in more detail the next section.

4.3 Influencing factors

The following section now describes the possibility of influencing factors quantification at each level shown in figure 4.12. To calculate with ML tools, Bayes methodology or classical statics, fixed influences are needed. Only in this way it is possible to find the connections between all of the possible combinations of influences. The next sub chapters explains the standard process of fire protection influences based on a questionnaire regarding real fire operations and the results of building fire inspections. First, a short review of the used scale levels on the basis of *S. Stevens* [Ste46] as an overview at table 4.3.

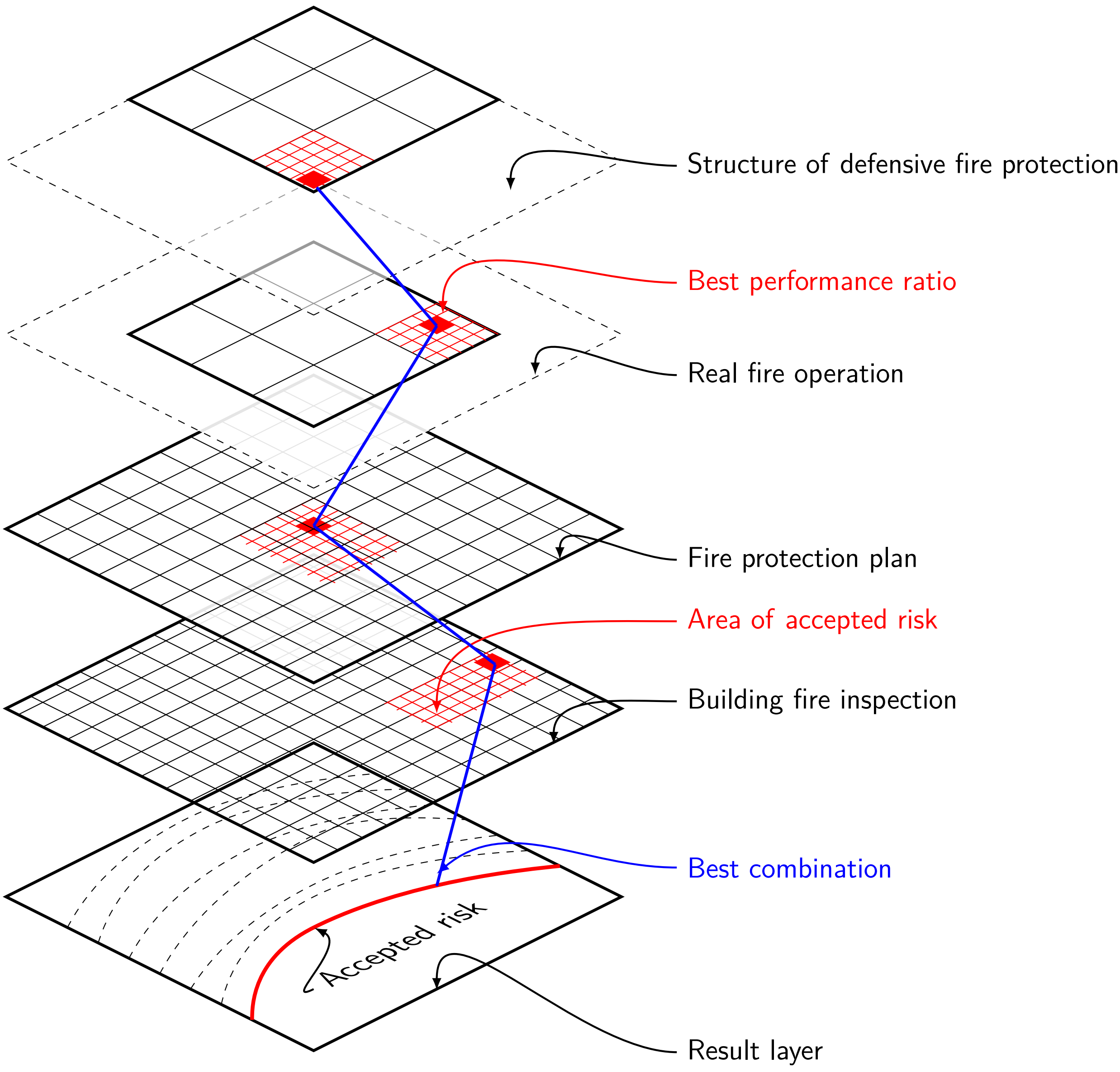


Figure 4.12: Overview of the possible input influences for the result layer of the ML level in black and the optimal performance point for ratio performance in red.

Scale level	Abbr.	Possible ratio operator	Measurable property distribution
Binary	B	0; 1	Apply
Nominal	N	$=; \neq$	Frequency
Ordinal	O	$=; \neq; <; >$	Frequency and ranking
Interval	I	$=; \neq; <; >; +; -$	Frequency, ranking and distance
Ratio	R	$=; \neq; <; >; +; -; / ; *$	Frequency, ranking, distance, natural zero

Table 4.3: The table shows the used possible scale levels for the questionnaire and the results of fire inspections with the ratio operator and distribution [JWHT17].

4.3.1 Structure of defensive fire protection

The structure of the fire protection system is regulated very differently in many countries. In general, however, a distinction can be made between:

- *Full time public fire department*: In larger cities there are mostly professional fire brigades. They are full time task forces and civil servants in many countries.
- *Volunteer fire department*: Voluntary fire services are mainly available in rural areas. Here, local residents apply to be part of their local voluntary fire brigade. In the event of an alarm, the firefighters leave their respective locations (work, school, university, etc.) drive to their local fire station and then they deploy from that location.
- *Plant fire department*: Factory fire brigades are specifically designed fire brigades for large companies (airports, chemical production plants, manufacturing facilities, nuclear reactors, etc.) and the people employed there are full time firefighters for a special area of the company. Normally, the firefighters have a specialization in the respective area.

The various types of fire departments also have different fire protection goals. For example, public fire departments have the task of saving people and animals. Protection of material assets does not usually have any particular significance. It is different with plant fire department firefighters, here they have a particular focus on property protection and personnel security. The availability and response time of the different fire departments also varies greatly. For example, by highlighting the differences between professional and voluntary fire departments, both have very different deployment and response times, as well as different alarm systems. However, since the structure of protective fire protection and its real use are very strongly related to each other, the quantification of protective fire protection is combined in the following section.

4.3.2 Real fire operations

The basis for the mathematical quantification of real fire operations is a questionnaire. This was completed by special fire protection engineers from the fire service after deployment to a fire emergency. The data includes only the size of more than one burning room. A first version is already available in Germany [Bac17]. However, the questionnaire has some weaknesses in the scientific quantification of the scale levels. Therefore, a new concrete question, responses, a scale level and variables were defined on the basis of the existing one. Furthermore, addition concrete important questions to calculate the risk are needed. The general protection goals have been more specifically defined. The protection targets are:

1. Building fire resistance class and time management
2. Hinder the spread of smoke and fire
3. Effective extinguishing by firefighters
4. Rescue and evacuation of people
5. Safety of firefighters
6. Environmental protection

At the beginning of the questionnaire, there needs to be some general information to connect the real fire to the number of safety statistics. It must be possible that each use can subsequently be assigned to a data record. Numbers can also be used for the combination. The following enumeration presents the influences of fire protection and the description of all values.

Protection target: Resistance building class and time management

The text that follows describes, in general, the information about building classes, time management and the type of fire in Table 4.4. Generally, buildings are categorized into fixed fire resistance classes by DIN EN 13501 [Deu19]. The categorization is based on the differences between the load bearing and statically stiffened parts of the various buildings. There are only four time resistance classes of 0, 30, 60 or 90 minutes. If the building in question is positioned between two classes, then the lower class is assigned to the structure.

Time management describes the operational period between when a fire starts and then progression into further events such as initiation of alarm, deployment time, arrival of the first fire engine with firefighters and then the damage and destruction after the fire begins. Through the use of the ratio scale, it is possible to correlate all other scale levels. A further general piece of information is the type fire ventilation as well as the size of the effected area. Ventilation also has to be factored in, how it is controlled and how effective it is, which is essentially determined by the amount of fuel (fire load), room volume and the positioning of ventilation units and the fire itself, e.g. localized fire in a large hall or outdoors. However, room fires have to be considered as well, even though the ignited fire load is relatively low compared to the volume of the room. If a O_2 occurs as a result of the course of the fire, a ventilation controlled fire occurs (e.g. full room fire with closed openings or a large fire in an enclosed building). The question of "Important years" needs to connect the real date of actual building regulations with the year of their implementation. This may also show the characteristic, pulsating (pulsating) flames [Bac17]. The satisfaction level regarding the success of the fire fighting action is very important, however it is only used in the binary scale for the opinions of the fire chief and the group leader. It is assumed in the quantification that it is difficult to obtain concrete impressions from the head of operations. However, further influences can also be raised. The possible parameters are described in more detail in organizational fire protection in the flight simulator (see chapter 2).

Resistance and time

Main question	Sub question	Answer	Scale	Value
Building resistance class	Minutes	0/30 60/90	R	1.1.1.
	Unknown	0/1	B	1.1.2.
Building resistance class enough		0/1	B	1.2.1.
Time management	Fire starting time	hh:mm	R	1.3.1.
	Alarm after fire start	X min	R	1.3.2.
	Arrival of fire brigade after alarm	X min	R	1.3.3.
	Fire damage after alarm	X min	R	1.3.4.
Type of fire	Ventilation controlled	0/1	B	1.4.1.
	Material controlled	0/1	B	1.4.2.
	Unknown	0/1	B	1.4.3.
Successful operation	Fire chief	0/1	B	1.5.1.
	Group leader	0/1	B	1.5.2.
Size of fire		small middle large	O	1.6.1.
Important years	Building year	XXXX	R	1.7.1.
	Last general remodelling	XXXX	R	1.7.2.

Table 4.4: The table shows the main questions regarding the resistance class of a building, the time management and special fire operational influences. The sign "/" splits the column for possible answers.

Protection target: Hinder the spread of smoke and fire

Table 4.5 describes the possible spread of fire and smoke throughout building spaces. These events are the most important influences. The spread is written as a positive feature when the fire or smoke penetrates a wall or ceiling. If the components have a fire resistance class, they must be able to withstand and endure a certain time period in the event of fire. The spread of smoke and fire can be further defined. In the case of smoke, only fire gases are spread through walls, corridors and other building spaces. The gases created by combustion are toxic and have a high proportion of CO. When the fire spreads, heat is also transferred to other building sections. In the case of a spreading fire, the transfer of heat makes it possible for the fire to spread to other rooms quickly, if the walls do not have a fire resistance class. The event of a fire or smoke spreading within a building section is not defined as a positive feature. The risk of spreading fire and smoke increases the number of deaths and injuries that can result from this emergency, additionally property damage to the building increases as well. Each of these features are defined in a binary version. In this way, possible correlations can be tested with a qui-square test.

Hinder the spread of smoke and fire

Main question	Sub question	Answer	Scale	Value
Smoke spread	To further utilization unit	0/1	B	2.1.1.
	To further corridor	0/1	B	2.1.2.
	To further stairwell	0/1	B	2.1.3.
Fire spread	To further utilization unit	0/1	B	2.2.1.
	To further corridor	0/1	B	2.2.2.
	To further stairwell	0/1	B	2.2.3.
	To complete building	0/1	B	2.2.4.

Table 4.5: The table shows the main questions regarding the different forms for the possible spread of smoke and fire. The sign "/" splits the column for possible answers.

Protection target: Effective extinguishing by fire fighters

The third protection target is the goal to make efficient fire extinguishing possible for the professional fire services. This protection target is not included in all EU countries. This is one of the latest protection targets. This requirement had been present in Germany for many years, however without any concrete formulation. Since 2008, the target has been defined in an official way[MF08]. The table 4.6 describes the main questions for effective fire extinguishing by the fire service. The first main question is difficult, as fire services need to quantify possibility correlation between the building concept and the time needed for rescue. These ratio operators are very subjective and by using the binary answer it is possible to quantify these objects. The second question concerns resource management during real fire operations, it is necessary to analyze the efficiency of defensive fire protection systems. The time period of 15 minutes has a tactical background. The first quality step of the requirements in fire protection is a 30 minute fire hindrance in the construction materials. The rescue time in the EU is connected with this time scale. The building information is an important instrument for fire services, so that they have a summary of the most important details regarding the building such as numbers of floors, available escape routes, how many persons use the building and so on. The next possible influence is the routes that are to be used by the firefighters. These are the routes to attack a fire and whether they are free of obstacles is connected with the other general protection targets in table 4.5. Here, it is possible to calculate the most used route with best performance ratio to the real cost of the building and so on. The same answer to this question looks at the most commonly used extinguishing agents by the fire service, which leads to the next question. The last line of the table describes the technical system of stationary firefighting systems.

Effective extinguishing by fire fighters

Main question	Sub question	Answer	Scale	Value
Access easy	Visible	0/1	B	3.1.1.
	Fire truck access visible	0/1	B	3.1.2.
	Fire truck access usable	0/1	B	3.1.3.
	Turnable ladder access visible	0/1	B	3.1.4.
	Turnable ladder access usable	0/1	B	3.1.5.
Operational resources	Enough for first 15 minutes	0/1	B	3.2.1.
	Enough for first 30 minutes	0/1	B	3.2.2.
	Complete operation	0/1	B	3.2.3.
Building information	General available	0/1	B	3.3.1.
	General sufficient	0/1	B	3.3.2.
	Concrete available	0/1	B	3.3.4.
	Concrete sufficient	0/1	B	3.3.5.
	Not used	0/1	B	3.3.6.
Attack routes free	Smoke	0/1	B	3.4.1.
	Fire	0/1	B	3.4.2.
Attack routes easy	Smoke extraction	0/1	B	3.4.3.
	Fire extraction	0/1	B	3.4.4.
Routes used by firefighters		Stairwell/Corridor Port. ladders Turn. ladders	N	3.5.1.
Extinguishing agent	Used by firefighters	Water Foam CO_2 Powder Other	N	3.6.1.
	Mean sufficient	0/1	B	3.6.2.
Firefighting water	Easy visible	0/1	B	3.7.1.
	Enough	0/1	B	3.7.2.
	Used	Hydrant Fountain Open source Only fire truck	N	3.7.3.
Technical system	Master key available	0/1	B	3.8.1.
	Fire alarm system	0/1	B	3.8.2.
	Sprinkler system	0/1	B	3.8.3.
	Dry riser	0/1	B	3.8.4.
	Wet riser	0/1	B	3.8.5.
	Wall hydrant	0/1	B	3.8.6.

Table 4.6: The table shows the main questions for an effective fire extinguishing operation including possible building information, attack route and technical equipment with a fixed scale level and the values. The sign "/" splits the column for possible answers.

Protection target: Evacuation and rescue of people

Evacuation and rescue of people

Main question	Sub question	Answer	Scale	Value
Self rescue	Finished before firefighters arrive	0/1	B	4.1.1.
	Used route	By direct exit By corridor By stairwell By emergency ladder Other	O	4.1.2.
	Automatic evacuation alarm	0/1	B	4.1.3.
	Local fire detector	0/1	B	4.1.4.
External rescue	Firefighter	By direct exit By corridor By stairwell By turnable ladder By portable ladder With escape hood By rescue cushion	O	4.2.1.
	Other lay person	0/1	B	4.2.2.
Injury	Injured persons	X	R	4.3.1.
	Dead persons	X	R	4.3.2.
Building rescue	By normal stairwell	Smokeless With smoke With fire	O	4.4.1.
	By corridor	Smokeless With smoke With fire	O	4.4.2.

Table 4.7: The table describes the possible influences on the main target of the evacuation and rescue of people. There is the quantification of the self rescue system versus external rescue by firefighters and further information. The sign "/" splits the column for possible answers.

Evacuation and rescue of people is the most important task of the fire brigade and as a protection goal in fire emergency planning. The reason for the first query "Self rescue" is as follows: In order to quantify the measure for the efficiency of the planned self rescue of people, it is necessary to query the type of rescue and the escape route used. A corresponding ordinal scale was used for this, the direct exit route outside is much better than via an emergency ladder. However, it cannot be said that the emergency ladder is 1/4 as good as the direct exit route outside, so that only the ordinal scale remains. The same system has also been used for external rescue. As an additional characteristic of rescue, the possible injury or death of a person is of course described on a regional scale. The last point describes the existence of different types of escape and rescue routes. Table 4.7 shows the details of the scale level and the main questions.

Protection target: Safety of firefighters

The protection goal "safety of firefighters" is still a quite newly defined protection goal. It particularly concerns the question of firefighter safety and the possibility of designing a building so that they do not injure themselves or die in the event of a fire. The first characteristic is the question of the injured or dead firefighters. Secondly, there is a possibility of falling from the building or that an object in the building falls on them, so firefighters should be able to secure themselves on roofs or other parts of the structure. An essential part in fire protection is the path between the fire engine and the location of the emergency. The further firefighters have to enter into a building, the greater the distance they have travel in reverse to exit it in the event of an emergency. This inevitably leads to errors or time delays in rescues. This also can affect the radio communication that is used by the fire department in such an emergency.

Safety of firefighters

Main question	Sub question	Answer	Scale	Value
Injury	Injured firefighters	X	R	5.1.1.
	Dead firefighters	X	R	5.1.2.
Further hazards	Risk of falling	0/1	B	5.2.1.
	Cave in risk	0/1	B	5.2.2.
	Extremely long route to attack the fire	0/1	B	5.2.3.
	Bad or no radio communication	0/1	B	5.2.4.

Table 4.8: The table describes the main target for the safety of firefighters with possible injury and further hazards, which influences the answer, scale level and the used value. The sign "/" splits the column for possible answers and X for radio scale level.

Protection target: Environmental protection

Environmental protection also plays an important role in fire service operations. Combustion also releases poisonous gases that are harmful to people and the environment. The size of the smoke haze from a fire was chosen as the criterion. In addition, when using water to extinguish a fire, it must also be considered whether this leads to water pollution. To prevent this from happening, there is a firefighting water retention system in some buildings, which has great environmental protection advantages. When extinguishing a fire, the contaminated water used in fire extinguishing is kept in the building or in an installation so that there is not any environmental pollution. Of course, such a system is also limited in regard to the respective amount of water that can be retained during the event of extinguishing a fire, so the question has been asked about the adequate dimensions of the measure.

Environmental protection

Main question	Sub question	Answer	Scale	Value
Ambient air	Normal fire smoke More than normal fire smoke Extreme fire smoke (with warning)		O	6.1.1.
Open water contaminated		0/1	B	6.2.1.
Ground water or soil contaminated		0/1	B	6.3.1.
Firefighting water retained	Available	0/1	B	6.4.1.
	Sufficient	0/1	B	6.4.2.

Table 4.9: The table describes the main target of environmental protection with the possible influences and the scale level. The sign "/" splits the column for possible answers and X for radio scale level.

4.3.3 Fire protection plans

Another point is the standardized quantification of fire protection plans. This is a special challenge, as there are very different requirements present within the EU countries. In general, a fire protection plan consists of a text section and a plan. In the text section, implementation instructions for the building are given and protection goals are defined. The respective building sections with their corresponding fire resistance duration are then included visually in the plan. Formal requirements can include:

- Legal references
- Requirements for the structure of a fire protection plan in the text section
- Requirements for the structure of a fire protection plan in the plan section

The fire protection plan has not yet been completely standardized in any EU country, making evaluation very difficult [PMV10]. However, the same pattern with the fulfillment of the respective protection goals is always included. Here, through the special strength of ML it is possible to recognize these patterns. The first approaches to automated law recognition through AI technology and its ethical principles that can be found were written by *Hildebrandt* [Hil18]. It is a suitable algorithm for searching that can recognize a text part and the matching plans with a picture of a pattern. The technology is already state of the art in the classification of images with DL processes [SXZY19]. Texts are easier to write. Only a large number of text plans need to be recorded here [Sch15].

4.3.4 Building fire inspections

As a further influence for finding connection between the four levels is the development of a standard fire inspection system. There is only a single publication about the linking of these topics [MCH+16]. The fire department of Atlanta United States of America (USA) tried to find an efficient way to decide what buildings need fire inspections. They used ML methods to find combinations about real fire operations and the fire protection requirements to find the connection between the real fire operations and required fire inspections. In Germany and most countries within the EU the task of fire inspection is transferred to individual cities. Every city has its own criteria and its own procedures for this task. Here, a standard algorithm is needed to describe the deficiencies caused by errors made during fire inspections. The following figure 4.13 shows this algorithm. The development is based on and follows the requirements of DIN EN 13501 [Deu19] and the European standard for building codes DIN EN 1990 [Deu10a], which were implemented in 2000 and in 2002 respectively. These two regulations were introduced in all EU countries. The form of the algorithm is shown in a simple way and should be used as an instruction to help finding errors made in an official fire inspection and therefore reduce them. Every error should add one more single number to the specifically identified error. The grouping within the fault tree levels in the algorithm is needed to find possible general connections by a ML tool.

The algorithm of figure 4.13 is too large for one page in this thesis. The figure shows an overview of the systematical system and the starting point. The exact algorithm with all details can be found in the appendix on pages 176 to 178 it has been split into three parts.

4.4 Result layer of best performance ratio

The result layer in a deep learning process is one of the most important layers. The patterns can then be recognized. Due to the multitude of influencing factors, variables are now defined for the individual influencing factors (i) including the scale levels:

- i_d: Structure of defensive fire protection $\in B; O$
- i_r: Real fire operations $\in B; N; O; I; R$
- i_p: Fire protection plan $\in N; images$
- i_i: Building fire inspection $\in B; N$

The very different types of scales make a normal statistical evaluation complex. During the course of this research, various options for graphical and mathematical representation have been found. The most challenging variant is the problem with a large number of layered input variables. A pattern could be more easily recognized by ML methods. More precisely, it can probably be defined by DL. The package Tensorflow®, developed by Google Brain Team®, was used. The program is based on the programming language C ++. The application is programming in *R*.

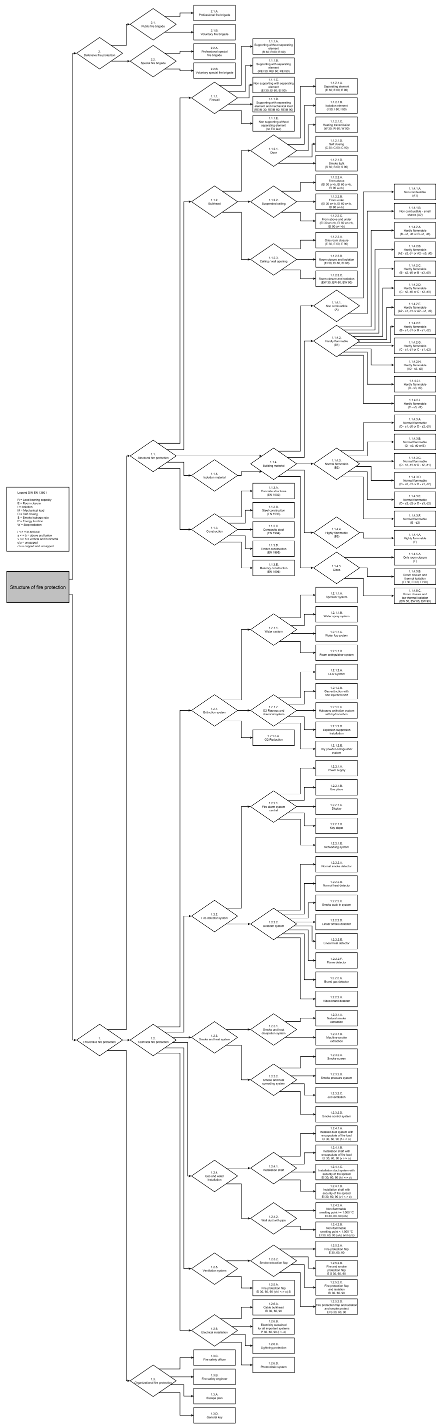


Figure 4.13: The figure shows a new development algorithm for clustering found errors made during a fire inspection. It is based upon the European classification DIN EN 13501 [Deu19] and split accordingly. The main separations in preventive fire protection are organizational, technical and structural requirements. The defensive part is split into public and special fire brigade. A rhombus is a division and a rectangle is an answer. Detailed view of the plot on pages 176 to 178.

Since this research is a methodical work, and it is only presented as a general approach, possible details are given below in the R programming language as an example. Concrete training for a neural network is only possible with the real data. The description is taken from the tutorial by Tensorflow® [Ten20]. The following description is a short introduction to Keras advanced features in programming script *R*. It uses:

1. *tfdatasets* to manage input data.
2. A custom model.
3. *tfautograph* for building a custom training loop.

Before running the quick start you need to have Keras installed. Please refer to the installation instructions before starting the installation:

```
library(keras)
library(tensorflow)
library(tfdatasets)
library(tfautograph)
library(reticulate)
library(purrr)
```

Start by loading and preparing the MNIST dataset. The values of the pixels are integers between 0 and 255, and they are converted into floats between 0 and 1:

```
mnist           <- dataset_mnist()
mnist$train$x   <- mnist$train$x/255
mnist$test$x    <- mnist$test$x/255

dim(mnist$train$x) <- c(dim(mnist$train$x), 1)
dim(mnist$test$x)  <- c(dim(mnist$test$x), 1)
```

Now, tfdatasets are used to batch and shuffle the dataset:

```
train_ds <- mnist$train %>%
  tensor_slices_dataset() %>%
  dataset_take(20000) %>%
  dataset_map(~modify_at(.x, "x", tf$cast, dtype = tf$float32)) %>%
  dataset_map(~modify_at(.x, "y", tf$cast, dtype = tf$int64))   %>%
  dataset_shuffle(10000) %>%
  dataset_batch(32)

test_ds <- mnist$test %>%
  tensor_slices_dataset() %>%
  dataset_take(2000) %>%
  dataset_map(~modify_at(.x, "x", tf$cast, dtype = tf$float32)) %>%
  dataset_map(~modify_at(.x, "y", tf$cast, dtype = tf$int64))   %>%
  dataset_batch(32)
```

Now define a Keras custom model:

```
simple_conv_nn <- function(filters, kernel_size) {
  keras_model_custom(name = "My Model", function(self) {

    self$conv1 <- layer_conv_2d(
      filters = filters,
      kernel_size = rep(kernel_size, 2),
      activation = "relu"
    )

    self$flatten <- layer_flatten()

    self$d1 <- layer_dense(units = 128, activation = "relu")
    self$d2 <- layer_dense(units = 10 , activation = "softmax")


    function(inputs, mask = NULL) {
      inputs %>%
        self$conv1() %>%
        self$flatten() %>%
        self$d1() %>%
        self$d2()
    }
  })
}

model <- simple_conv_nn(filters = 32, kernel_size = 3)
```

Then an optimizer can be chosen and loss function for training:

```
loss <- loss_sparse_categorical_crossentropy
optimizer <- optimizer_adam()
```

Select metrics to measure the loss and the accuracy of the model. These metrics accumulate the values over epochs and then the overall result is output:

```
train_loss <- tf$keras$metrics$Mean(name='train_loss')
train_accuracy <-  tf$keras$metrics$SparseCategoricalAccuracy
(name='train_accuracy')

test_loss <- tf$keras$metrics$Mean(name='test_loss')
test_accuracy <- tf$keras$metrics$SparseCategoricalAccuracy
(name='test_accuracy')
```

We then define a function that is able to make one training step:

```
train_step <- function(images, labels) {
```

```
  with (tf$GradientTape() %as% tape, {
    predictions <- model(images)
    l <- loss(labels, predictions)
  })

  gradients <- tape$gradient(l, model$trainable_variables)
  optimizer$apply_gradients(purrr::transpose(list(
    gradients, model$trainable_variables
  )))

  train_loss(l)
  train_accuracy(labels, predictions)
}
```

We then provide a function that is able to test the model:

```
test_step <- function(images, labels) {
  predictions <- model(images)
  l <- loss(labels, predictions)

  test_loss(l)
  test_accuracy(labels, predictions)
}
```

We can then write our training loop function:

```
training_loop <- tf_function(autograph(function(train_ds, test_ds)
  {

  for (b1 in train_ds) {
    train_step(b1$x, b1$y)
  }

  for (b2 in test_ds) {
    test_step(b2$x, b2$y)
  }

  tf$print("Acc", train_accuracy$result(),
  "Test␣Acc", test_accuracy$result())

  train_loss$reset_states()
  train_accuracy$reset_states()
  test_loss$reset_states()
  test_accuracy$reset_states()
```

```
}))
```

Finally, the training loop is run for 5 epochs:

```
for (epoch in 1:5) {
  cat("Epoch: ", epoch, " -----------\n")
  training_loop(train_ds, test_ds)
}
## Epoch:  1  -----------
Acc 0.93095 Test Acc 0.954
## Epoch:  2  -----------
Acc 0.956525 Test Acc 0.95825
## Epoch:  3  -----------
Acc 0.968066692 Test Acc 0.9575
## Epoch:  4  -----------
Acc 0.9752 Test Acc 0.960125
## Epoch:  5  -----------
Acc 0.9796 Test Acc 0.961
```

This system with the basic tutorial by Tensorflow® is the background. The general way to predict the future with MLtools are:

1. Define
2. Compile
3. Evaluate
4. Predict

A further general way to connect each protection target with the data of the questionnaire from real fire operations is to create a dendrogram with R script. The following R script creates a two sided dendrogram with connections between each fire protection target with an example:

```
# Packages need
library(tidyverse)  # data manipulation
library(cluster)    # clustering algorithms
library(factoextra) # clustering visualization
library(dendextend) # for comparing two dendrograms

# Random data matrix
  data <- matrix( sample(seq(1,2000),200), ncol = 6 )
  rownames(data) <- paste0(seq(1,20))
  colnames(data) <- paste0("variable",seq(1,6))

  df <- data
```

```
# Compute distance matrix
  res.dist <- dist(df, method = "euclidean")

# Compute 2 hierarchical clusterings
  hc1 <- hclust(res.dist, method = "complete")
  hc2 <- hclust(res.dist, method = "ward.D2")

# Create two dendrograms
  dend1 <- as.dendrogram (hc1)
  dend2 <- as.dendrogram (hc2)

# Definition protection targets
plot <- tanglegram(dend1, dend2, main=
  "Double␣dendrogram␣with␣hierarchical␣clustering") +
legend("bottom", legend = c(
    "Protection␣target:␣Building␣fire␣resistance␣class␣and␣time␣management",
    "Protection␣target:␣Hinder␣the␣spread␣of␣smoke␣and␣fire",
    "Protection␣target:␣Effective␣extinguishing␣by␣firefighters",
    "Protection␣target:␣Evacuation␣and␣rescue␣of␣people",
    "Protection␣target:␣Firefighter␣Safety",
    "Protection␣target:␣Environmental␣protection"),
    col = c("red", "blue" , "orange" ,
    "black" , "green" , "yellow"),
    pch = c(20,20,20,20,20,20),
    bty = "y", pt.cex = 1.5, cex = 0.8 ,
    text.col = "black", horiz = FALSE, inset = c(0, 0.1))
```

Figure 4.14 shows a possible outcome of the data analysis with a dendrogram as the result of data analysis.

4.5 Machine Learning application

The following subsection shows a brief application of the ML techniques on a data set to present the methodology. It should demonstrate that it is possible to predict complex relationships. The question of the meaningfulness of good fire protection solutions (best ratio between cost and the increase in safety) cannot be specifically addressed by looking or looking at a purely theoretical consideration. The data from real fires are a direct part of this. The evaluation should reveal to what extent preventive measures were entitled to work, functioning or even content. In order to make a well-founded statement about this, a large number of fire events must be examined and analayzed, especially focussing on the various building classes and their different utilizations.

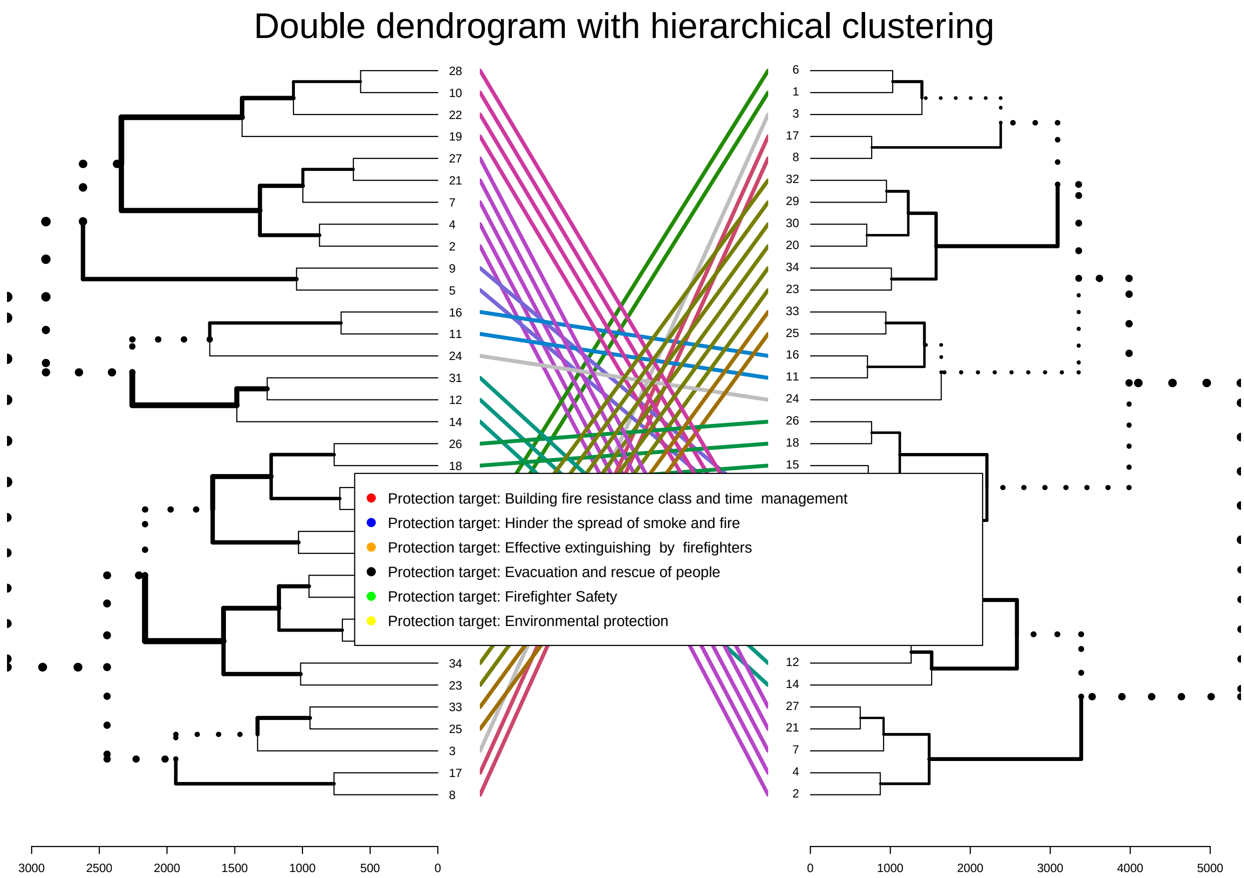


Figure 4.14: Possible figure with a double sided dendrogram to connect the protection targets with real fire operations using R script.

With the help of these results it is hoped that in the future pertinent and affordable fire protection solutions will be made available for certain types of building and structure management. As already described in section 4.3.2, there are various protection goals that can be examined. The following framework is created:

- Prediction by ML methodology
- Integrated first protection target: Smoke spread limited on building level
- Integrated second protection target: Injured people depending on the time of the fire
- Further protection targets are not analyzed, since this is only an application example and otherwise it would exceed the limits of this thesis
- Serving as the basis are real data sets from the evaluation of real fire operations in Germany

The following section with the application of ML methodology in structural fire protection is an brief example. Subsection 4.5.3 and 4.5.3 is based on a co-supervision of a master's thesis by *Moritz Göldner* [Gö21].

4.5.1 Data collection

As already described, various influencing factors must be taken into account in order to quantify the effectiveness of individual measures taken (see figure 4.12). In order to determine the effectiveness of preventive and defensive fire protection measures, only theoretical considerations are insufficient. This is due to the possibility that there can also be influences that are not recorded. For this reason, a good analysis is only possible if real events, in this case fires, are scientifically processed. Normally, real fires have to be scientifically monitored and quantified right from the start. However, this is not possible due to the time. It is impossible to quantify a real room fire under real events right from the start, since qualified personnel are only present when the fire brigade arrives (usually on the scene approximately 10 - 15 minutes after initial alarm). Moreover, in this situation, there are not enough fire fighters present so that a scientific investigation can be carried out in real time. This means that real fires can only be analyzed retrospectively. This represents an enormous effort. Section 4.3 describes which characteristics of these fires are subsequently quantified by a fire protection engineer. Therefore, here is a summary of the data set used for the ML method:

- The data set only includes fires that were at least larger than one room.
- The investigation in Germany to quantify real fires is currently ongoing ($n = 500$, up to February 2021), with 135 single possible influence factors so that new data sets will be added.
- The data set also contains sensitive information about the place of use, time, etc., so that this was anonymized. A merging of the anonymized data set with the real data is only possible by the Association of Professional Fire Brigades in Germany (AGBF) [Bac17].

- As this is still an ongoing study, only sound characteristics for the spread of fire and smoke will be included for the ML method.

- The data collection process is as follows:
  1. The fire starts.
  2. The fire brigade arrives at the scene, saves people and fights the fire.
  3. When the fire is extinguished, the fire prevention department is informed if the fire is larger than a room.
  4. They send a fire protection engineer to the scene of the incident.
  5. The fire protection engineer uses a questionnaire to record the fire data with the characteristics described in section 4.3.
  6. The contents of the questionnaire are then transferred to a database.
  7. This data now serves as the basis for the ML methodology.

- The data set contains data from several different German fire brigades and is collected in a period from 2018 and 2021. The survey is still ongoing.

- The number of data records increases steadily, only when at least 1,000 real assignments have been recorded is this fully published. Until then, the data set is only used for this thesis.

- Until now the ML tools is used for this data set. Up to now it has only been used by master theses at TUM for quantitative counting [Kel19, Fri18, Pau20]. Of course, only at the time of these master's theses.

Since a data set that is as complete as possible is always required for the ML methodology, how well the data set is filled must also be checked. Figure 4.15 shows the overview of the complete data.

4.5.2 Regression method

As already show in section 4.1, there are many different ML methods. The selection of the appropriate methods depends on several factors like scale levels, number of data, type of predictions and type of paradigm [RRC19]. The regression analysis as a sub-item of supervised learning is particularly suitable for this. "*Regression analysis is a predictive modeling technique which investigates the relationship between a dependent (target) and independent variable (predictor). It is an important tool for analyzing and modeling of data. In this method, we try to fit the line/curve to the data points so as to minimize the differences between distances of data points from the curve or line.*" [ANK18]. This description fits very well with the prediction of the data set on the spread of fire and smoke into other rooms.

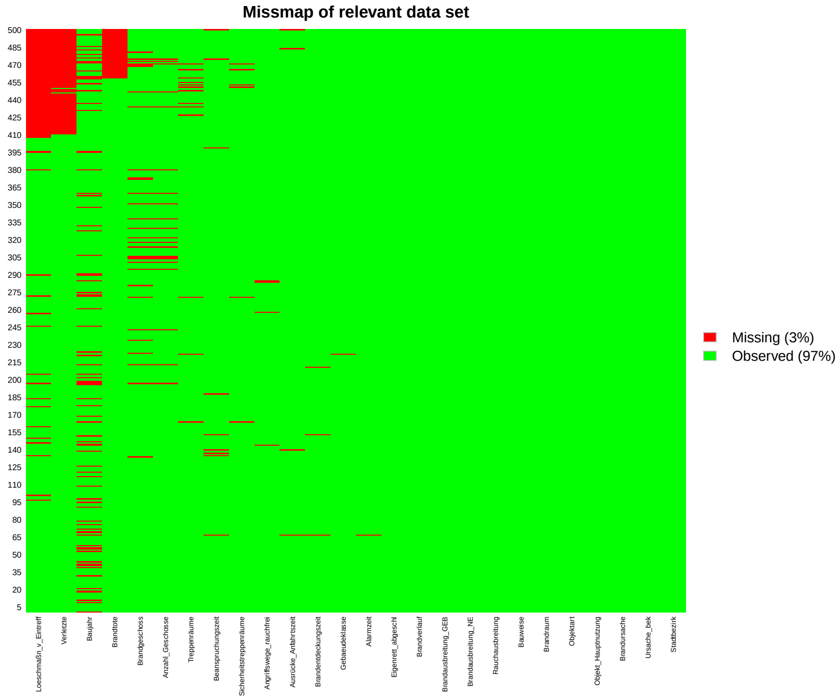


Figure 4.15: The figure shows an overview of the completeness of the data collected with green = data available, red = data not available. The x axis shows the different influencing factors and the y axis the number of real fire operations [Gö21].

4.5.3 Result of Machine Learning

In order to be able to carry out the regression analysis, $\frac{2}{3}$ of the data set ($n = 500$) was randomly defined as a test data set and $\frac{1}{3}$ as a control data set. In this way, a statement about the reliability of the prediction of the data set can then be made. Due to the enormous amount of influences and possible predictions, only brief statements are made below about the spread of smoke and fire.

Smoke spread

Figure 4.16 shows the result of a regression analysis for the probability of smoke spreading outside the fire area, depending on the fire time. To calculate the probability, the number of floors, the course of the fire and the time until the start of the extinguishing measures are included. It is a clear, almost linear pattern to see that the likelihood of smoke spreading decreases linearly with time.

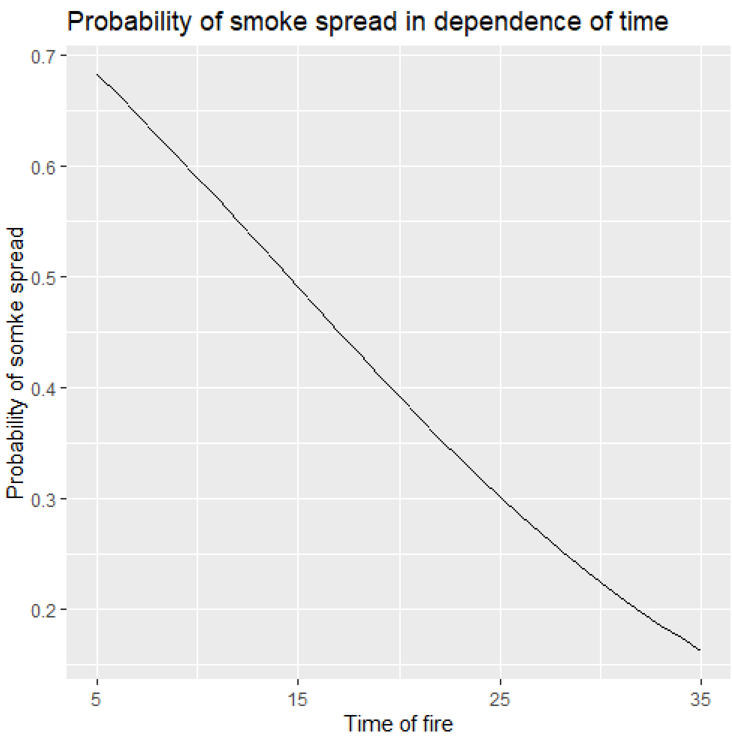


Figure 4.16: Figure shows the probability of spread the smoke to the next room in relation to the time of fire [Gö21].

Injured persons

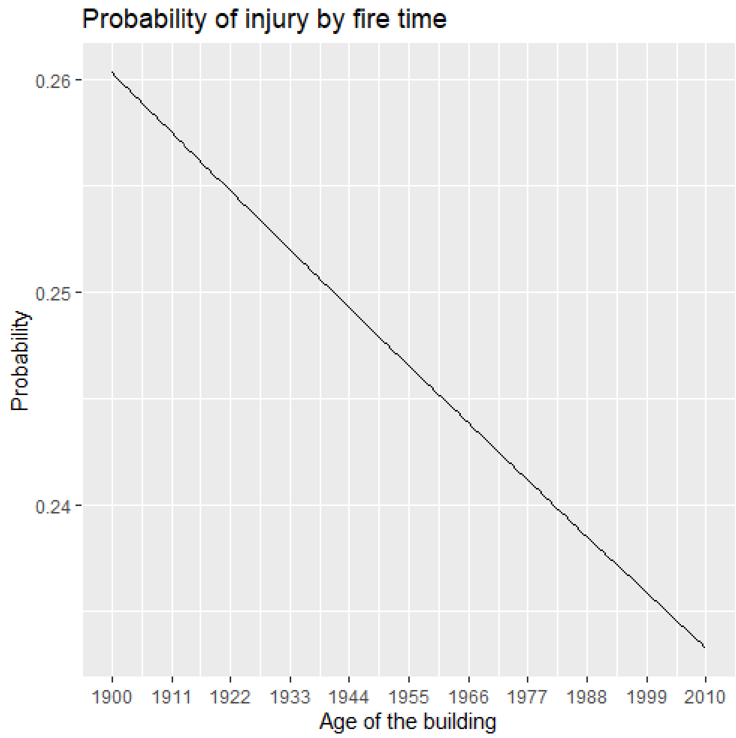


Figure 4.17: Figure shows the probability of possible injury by fire time in relation to the age of building [Gö21].

Figure 4.17 shows the result of a regression analysis for the probability of possible injured, depending on the age of the building. To calculate the probability, the number of injured persons, the course of the fire, the time until the start of the extinguishing and the age of the building measures are included. It is a clear, almost linear pattern to see that the likelihood of people being injured decreases linearly with time.

Prediction fire and smoke spread with classification three

Figure 4.19 and 4.18 show the result of a classification tree with the ML tool. The figures are the result of a combination of possible influencing factors on the spread fire or smoke from one room to the next. Here, the classification model is used and is set at engine range. The aim of the prediction is, to identify possible influencing factors and their number, to generate high quality data regarding fire and smoke spread. The model uses the following influencing factors:

- Fire detection time
- Type of building utilization

- Building classification
- Floor of the building where the fire starts
- Type of building materials

With this brief analysis of the data, the classification tree is limited to a maximum of 6 influences. In addition to the 5 bullet points listed above, the influencing factor of fire or smoke spread is added, so that a total of the 6 influencing factors is analyzed. The number of random forests is 1,000 repetitions. Figure 4.18 shows an overview of three different ways to predict the accuracy independent from the influencing factors / features for smoke spread. The highest quality prediction is a random forest with an accuracy of 0.831 in the model, this is a random forest with 6 features.

Figure 4.18: The figure shows the quality of accuracy assessment to predict smoke spread from one room to the next with three different models. On the left is a forest tree with four features, in the middle, a random forest with 4 features and on the right, a random forest with 6 features. The best combination is that of 6 features in a random forest, which has an accuracy of 0.831.

The same method of prediction that is used to analyze the spread of smoke from one room to the next, is also applied to predict the spread of fire from one room to another. Figure 4.19 shows the result of accuracy with three different models to predict fire spread.

4.6 Outlook for the possible results of machine learning tools

This thesis is the basic work for risk quantification in fire protection. Due to the enormous effort to quantify the probability of the fires in buildings and the probability of death during the fire, future hypotheses will be presented. The proposal for the detection of real fires,

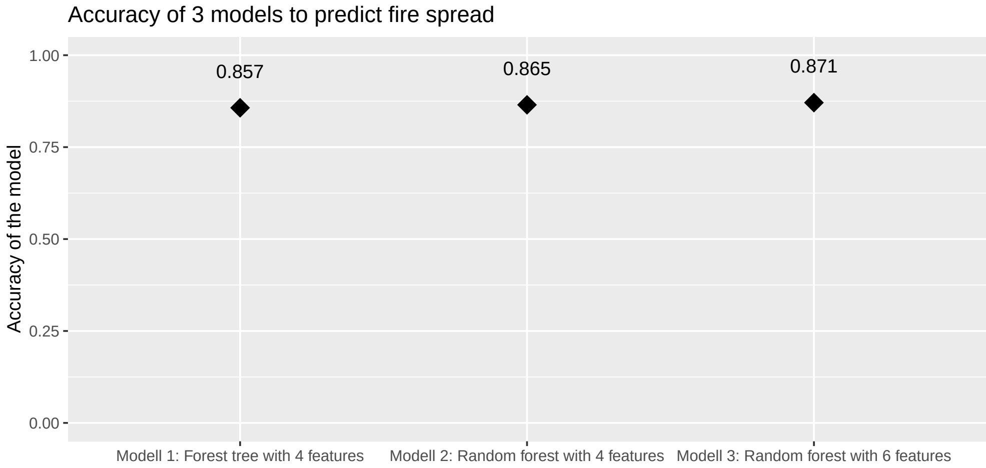


Figure 4.19: The figure shows the quality of accuracy assessment to predict fire spread to the next room with three different models. On the left is a forest tree with four features, in the middle a random forest with 4 features and on the right a random forest with 6 features. There is not a large variation between the models. The best combination is that of 6 features in a random forest, which has an accuracy of 0.871.

the preventive fire inspections, the structure of defensive fire protection and fire protection plans are included in the learning process as input variables. Quantification in structural fire protection is very different when compared with the quantification the failure rates in technical fire protection, however detailed data collection has also been carried out in this context. There is also a lot of research in peer reviews in journals in the event of a fire [BGI16]. The situation is different in the area of the efficiency of the measures for fire protection. For example, the collapse of a house or building is a very, very rare case. There are only isolated cases of such an event happening [AA11, Fer14], this event which is structural failure probably occurred the European codes [Deu10a] were not adhered to. There are still many areas where in terms of fire protection, better data collection methods need to be established, improved and implemented, therefore more reliable predictions concerning the probability of failure or reliability of systems can be made.

Another point in structural fire protection which must be considered and is explained in this thesis is the fire resistance period. Many standards which were set for the respective times of fire resistance duration of 30, 60 or 90 minutes come from almost three decades ago and may not be up to date. Adjustments to these standards must also be made here, so that firefighters can fight fires in buildings effectively and efficiently. A typical example of the outdated regulations are fire walls in Germany with a fire resistance duration of 90 minutes every 40 m [Bau12]. The idea behind this regulation comes from the times during the two world wars, when the fire brigade were unable to attend every emergency and extinguish every fire. The fire wall would then prevent several buildings from burning down in parallel from one emergency situation. This assumption, that the fire brigade can no longer extinguish a fire, is out of date. This regulation should be revised in order to enable more effective fire protection and not cause unnecessary costs. Due to the multitude of influences, the adequate fire resistance duration can only be found out through a neural network. By surveying real fires with the questions presented, this is now possible.

Another important point is the uniform description of requirements for components such as bulkheads, doors, etc. Section 1.3 already describes the requirements of the respective countries, which buildings when constructed have to adhere. However, building regualtions are still the responsibility of the federal states and not the EU. It is therefore very difficult to create uniform requirements here. Scientific research on this topic is urgently needed and not only in specific countries, but also across the EU. Since, there is now also a comparability of components [Deu10a].

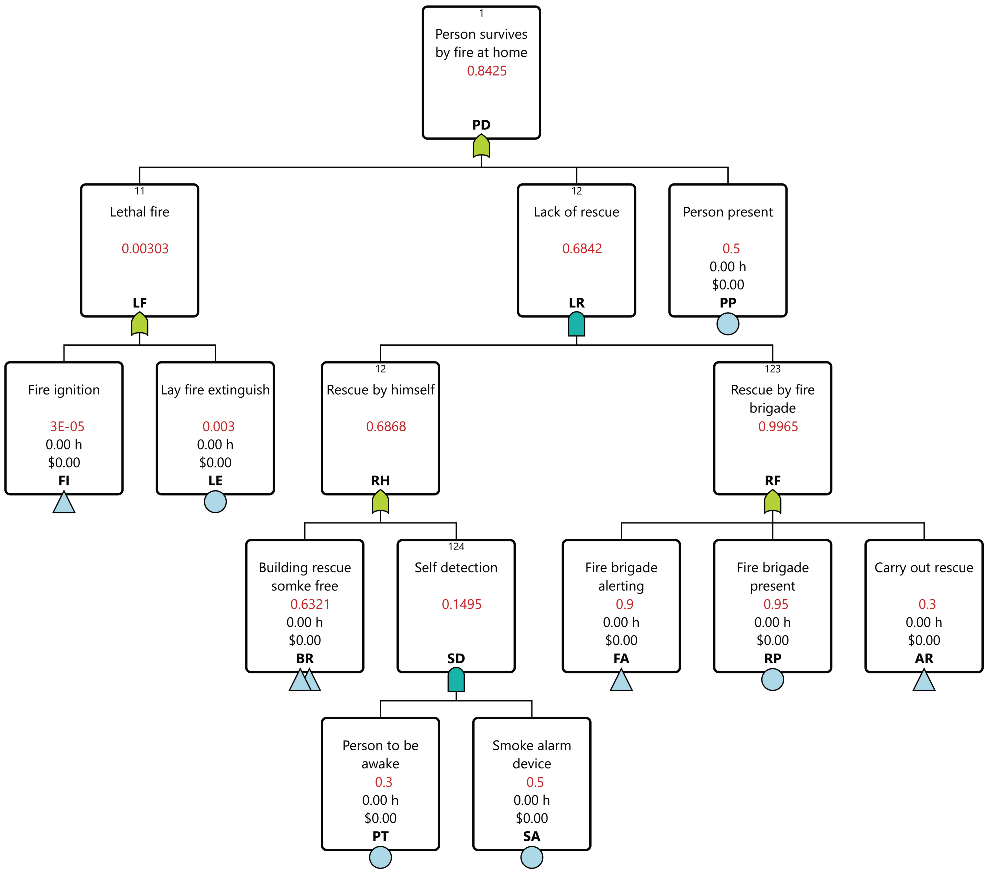


Figure 4.20: Possible risk quantification for a person surviving a fire at home and the two ways of escape from a building and rescue with fire brigade assistance.

Risk quantification using DL methods is a good approach. However, there are also a number of other methods, for example network analysis. Since this combination of network analysis and structural fire protection does not yet exist, the publication of *Klamroth* can be used for the application of network analysis for passenger flow analysis in buildings in the event of fire [KLSS20]. Here, network analysis is used to examine the topic of people flow when there are evacuees in the event of a fire. It offers the possibility to show the connections through a very clear detailed graphic form. Although, it is always necessary to enter the relevant primary events with the appropriate probabilistic data. Therefore, a data set or the probability of failure must always be known for this method. Figure 4.20 shows a simulated example applied to rescue probabilities.

As soon as a corresponding risk of death for a person is quantified and costs for the improvement of the measures lead to an increase in the level of safety, a new question will soon be asked. What is a human life worth [CFSG16]? Of course, a human life can never be broken down into a monetary sum. When considering risk, it should be noted that it is a correct means of comparing measures. According to the As low as reasonably achievable (ALARA) principle, for example, an amount of CHF 6.7 million was defined as the cost per person, when examining preventable deaths by fire in Switzerland. The number can be traced back to the costs of protective fire protection in relation to the total number of deaths caused by fires in Switzerland [Fis20].

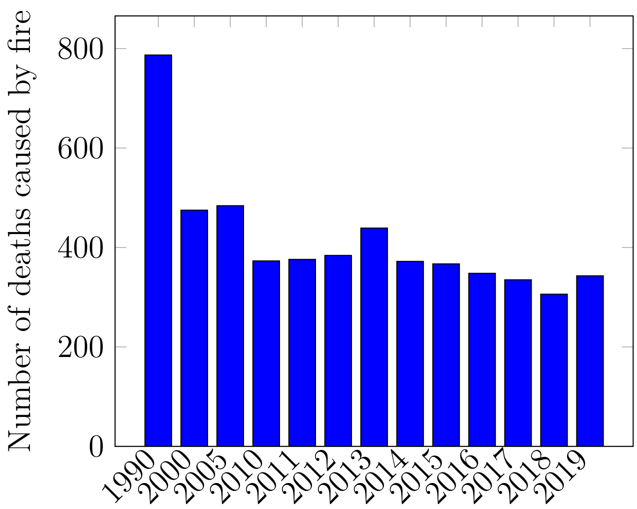


Figure 4.21: Number of deaths caused by fire in Germany between 1990 and 2019 [Sta20].

In general, in the case of structural fire protection, the proportionality between the current number of dead people and cost of the measures taken for this number must also be observed. When the number of deaths caused by fires in Germany is used as an example (see figure 4.21), the number has not increased for over 10 years. There are many reasons for the stagnating number of deaths. For example, the organizational, technical or structural fire protection systems have been improved. In general, however, the thesis can state that approximately 400 fire deaths per year is an acceptable social risk.

Chapter 5

Review and Outlook

The following section is a combination of the classic discussion of the research results and the outlook for further research projects. Since every chapter already critically examines the research results, a general assessment of the risk and an outlook for other fields of study follows. The research question was divided into the three main parts of preventive fire protection (organizational, technical and structural). By dividing the thesis into these sections, a comprehensive assessment of the thesis is carried out and individual new approaches to solutions are presented for each section. The main chapters have specifically drawn on the positive side of the research results. However, good research is particularly characterized by critically examining its own results.

The focus of the thesis is on research into new methods of risk quantification in fire protection and weak point analysis. It can serve as the basis for further research projects and somewhat narrows gap between protective and preventive fire protection. In general, it can be said that the analysis of risk in fire protection is a very complex field. In order to be able to make high quality statements, not only is the classical discipline of technical engineering necessary, but in addition, a diverse range of scientific disciplines also have to be considered. These include mathematics with a focus on statistics, as well as, psychology, ethics and also a certain degree of social development. Whenever risk quantification in fire protection is examined, the ability and viability to the transfer research results to the general public must be considered as an initial question. So that it can improve the overall differences in risk consciousness throughout our entire society. The ever increasing popularity of various risk management systems suggests that society's awareness of risk has been strengthened [Sch14]. This is based on the fact that the structures, causes and effects of industrial and technological processes are analyzed and presented systematically.

An important starting point for a critical assessment of risk is the discrepancy between the real risk values and the mathematical values. All mathematical models are based on the principle that the input variables also match the real probability. In the case of the predictions for a simulated fire or a real fire, however, a completely reliable model for the spread of real smoke and fire is still not available. Simple spatial structures can be analyzed very precisely in relation to a real fire, although only for simple spatial structures without any furniture, objects or cars [YCW+19]. This naturally raises the question of possible influencing factors. Were all influencing factors taken into account or are there any factors that were incorrectly assessed or still unidentified? How far can the simulated result be transferred to reality? Especially in fire protection, this is a large research field with many unknown variables. Trying to describe the influencing factors in a real fire (see page 134 and the following subsections) is the first step. The thesis only provides the basis for precisely answering the research question. The future will show whether all influencing factors were taken into account or whether there are more, which have yet to be discovered. It can also be the case that many influencing factors are quantified that have no effect at all. It is therefore necessary to record and consider the almost 80 influencing factors, which are identified for future studies.

With the definition that the risk is defined as the product of the probability of occurrence and the extent of damage, it is mathematically seen that the extent of the damage is given the same weight as the probability of occurrence. In fire protection, however, the maximum extent of damage, at least the number of people effected, can be limited. Because here, the death of all people in the building defines the maximum extent of damage. Other protection goals must of course also be considered. An essential part of this thesis is the collection of important failure probabilities of components in fire protection (see page 165 and the following pages). When selecting the sources, the focus is on a very high quality data basis. High quality is based on experience with high quality systems, such as reactors, aircraft and safety systems. This inevitably leads to a distortion of the results. Here is a small example: many of the parameters described come from the records of failure probabilities based on nuclear reactors. High quality systems are installed here, and they are also checked on a regular basis. In addition, the personnel in a reactor have a high level of technical understanding and education. So the question can be asked whether the values can also be transferred to a system, which does not meet the high quality standard? In the example of plant technology: Can the failure probability of a fire detection system in a nuclear reactor be transferred to an apartment building? The answer is differentiated:

- When it comes to the real likelihood of a top event occurring in an FTA, the transfer of results from a high quality system to a simple system is not permitted. The reason lies in the different initial conditions such as the quality of the system, the cycle of the inspections and the specialist staff, all of which differ greatly.

- When it comes to calculating the best performance ratio between increased security and the corresponding costs, it is possible to transfer the probability of occurrence. This is due to the type of calculation. If the top event does not reflect the real result, but only serves as a comparative value between the different systems, it is possible. Example: The FTA methodology simulates the best performance ratio between the increase in security and the costs used. The high quality occurrence probabilities of nuclear reactors are very good, however the ratio of gains in safety and costs can still be simulated in simple systems.

The transfer ability of the technical system has now also been discussed. Of course, the acceptable residual risk of the individual person must as well be considered. The current largest test example for risk assessment is the worldwide Covid 19 pandemic. It is clear that not everyone who is infected with Covid 19 dies [Wor20]. So, there is a certain amount of risk that could affect the population and it needs to be analyzed to determine the chances of anyone dying from the disease. There are very different regional assessments of society's willingness to take risks. There is a completely different perception of Covid 19 risk in Germany, compared to Norway [NR20]. The system of the accepted residual risk is also transferable in fire protection. There are also regional disparities within the EU and Germany, as well as differences in their respective protection goals. Normally, in instances where restrictions related to risk are lowered or non existant, the higher the probability that such risks occur, which therefore, results in the outcome that more protective measures have to be taken and implemented in the future after their occurrence and especially when they result in death. A possible classification of the residual risk when planning fire protection measures would be [Sch20]:

- **Necessary**: Minimum fire protection requirements stipulated by legal regulations. It is not legally allowed to fall below the requirements and is also not socially accepted.
- **Nice to have**: The minimum requirements are exceeded. Measures have been taken that have a very good relationship between the costs used and the increase in safety.
- **Luxury**: The minimum requirements are totally exceeded. Measures have been applied here that raise the level of protection to an extraordinarily high level.

This division of the different safety standards enables fire protection safety systems to be adapted depending on the user. In a high performance data center, a different level of protection has to be applied than in a classic residential building, as far as the protection objective is concerned. In this way, the client can define a level of protection necessary in relation to the regional regulations. Every improvement to a system must be evaluated for its economy. This is a normal process. If this is necessary in building fire protection, however, it is very difficult because of the current procedures that are in place. This is particularly due to the fact that construction costs are not listed separately. At the moment, only costs for land, preparatory measures, building structures, technical systems, outdoor facilities and open spaces, equipment and works of art, ancillary construction costs and financing are listed and differentiated by default by [Deu18]. Here, a further approach to extending building fire protection could be considered and should be able to include larger amounts of data.

Until now, mainly technical and mathematical aspects have been discussed. However, a scientific paper must also examine the ethical aspects. The basic principle of ethics is to think about the moral consequences of actions [Nim11]. From this it can now be deduced whether the methodology and the new approaches are also socially responsible?

For this, the benefits must be weighed very objectively in relation to the risks. Risk quantification now makes the residual risk in fire protection measurable, including the technical, structural and organizational resources to minimize the risk. This can lead to a conflict of interest between the state and the respective insurance companies. The state has the task of protecting its population, while insurance companies have to ensure a good relationship between income and expenditure. A small example of how risk quantification is ethically justifiable is shown here: Since there is never 100 % protection in fire protection, there is always a residual risk. If either the availability or the probability of failure of buildings is defined according to their use, the following question must also be asked: Does the same level of protection in structural fire protection have to be sufficient for a school as in a retirement home? Is a death in a retirement home that is caused by fire, perhaps more socially acceptable than the death of a child in a school? In my opinion, this question cannot be solved technically or mathematically, however it must be determined politically. The engineers can only build according to the PBC in order to fulfill this task. In summary, it can be generally stated that in fire protection, ethical aspects must also be taken into account.

At the end of this work, it should be noted that in general there are still large areas of research concerning fire protection waiting to be investigated. The topic of fire protection is, unfortunately, extremely underrepresented in the general scientific world. This thesis lays the foundation for further studies, answered some research questions and made a proposal on how to supplement the general methodology for risk quantification in fire protection.

Chapter 6

Appendix

Input reliability values

Statistic test algorithm

Fire inspection algorithm

NASA-RTLX answers from test persons

RIAAT® manual

Lay fire extinguisher

Time until fighting begins	Fire extinguisher	Beginning and spread phase	Full fire phase	Literature	Quality
1 min	Portable	$5.0 * 10^{-2}$	not possible	[Fac15]	+++
3 min	Portable	$1.0 * 10^{-1}$	not possible	[Fac15]	+++
5 min	Portable	$3.0 * 10^{-1}$	not possible	[Fac15]	+++
10 min	Portable	$8.0 * 10^{-1}$	not possible	[Fac15]	+++
>10 min	Portable	$9.5 * 10^{-1}$	not possible	[Fac15]	+++
not defined	Wall hydrant	$1.9 * 10^{-4}$ to $7.4 * 10^{-3}$		[Fac15]	+++

Table 6.1: The values only refer to development and spread phase. Minutes in the first column describe the time between detection of the fire and when fire fighters begin to start extinguishing the fire. The input values for wall hydrant are the same at the beginning and in the full fire phase.

Non-detection failure rate

Fire detection by	Fire beginning and spread phase	Full fire phase	Literature	Quality
Human: always present	$1.0 * 10^{-1}$	$1.0 * 10^{-3}$	[BM79]	+++
Human: mostly present	$8.0 * 10^{-1}$	$2.0 * 10^{-2}$	[BM79]	+++
Human: 1/3 time present	$9.9 * 10^{-1}$	$2.0 * 10^{-3}$	[BM79]	+++
Human: rarely present	1.0	$5.0 * 10^{-1}$	[BM79]	+++
Automatic*	$2.0 - 10^{-2}$	$2.0 - 10^{-1}$	[Fac15]	+++
Indirectly with errors	not possible	$6.0 * 10^{-2}$	[Fac15]	+++

Table 6.2: The table shows the unavailability per requirement in case of fire for the fire beginning and full fire phase. The human fire detection data is based on US studies. *In case of automatic fire detection, detection is normally made by only one single smoke detector per room. If there are more smoke detectors per room, the total value per room must be calculated.

Fire alarm system reliability

Door type	$5\% - \mathcal{Q}$	$50\% - \mathcal{Q}$	$95\% - \mathcal{Q}$	Mean	σ	Literature	Quality
Central G.II	1.1^{-9}	1.5^{-7}	2.0^{-6}	4.8^{-7}	9.1^{-7}	[FE16]	+++
Central G.III	3.3^{-9}	4.5^{-7}	6.1^{-6}	1.4^{-6}	2.7^{-6}	[FE16]	+++
Sub-system G.II	2.8^{-10}	3.8^{-8}	5.1^{-7}	1.2^{-7}	2.3^{-7}	[FE16]	+++
Sub-system G.II	9.4^{-10}	1.3^{-7}	1.7^{-6}	4.1^{-7}	7.8^{-7}	[FE16]	+++
Insertion G.II	3.5^{-11}	4.8^{-9}	6.5^{-8}	1.5^{-8}	2.9^{-8}	[FE16]	+++
Insertion G.III	2.4^{-10}	3.2^{-8}	4.4^{-7}	1.0^{-7}	2.0^{-7}	[FE16]	+++
Det. line G.II	4.9^{-12}	6.3^{-10}	9.0^{-9}	2.1^{-9}	4.1^{-9}	[FE16]	+++
Det. line G.III	6.4^{-12}	8.8^{-10}	1.2^{-8}	2.8^{-9}	4.3^{-9}	[FE16]	+++
More criteria G.IV A	1.2^{-11}	1.6^{-9}	2.2^{-8}	5.2^{-9}	1.0^{-8}	[FE16]	+++
More criteria G.IV B	4.2^{-11}	5.8^{-9}	7.8^{-8}	1.8^{-8}	3.5^{-8}	[FE16]	+++
Opt. det. G.II A	2.4^{-12}	3.3^{-10}	4.5^{-9}	1.0^{-9}	2.0^{-9}	[FE16]	+++
Opt. det. G.III A	1.3^{-10}	1.8^{-8}	2.4^{-7}	5.6^{-8}	1.1^{-7}	[FE16]	+++
Flam. det. G.III A	3.1^{-9}	3.6^{-8}	2.1^{-7}	6.2^{-8}	7.8^{-8}	[FE16]	+++
Head diff. G. II A	7.2^{-11}	9.8^{-9}	1.3^{-7}	3.1^{-8}	6.0^{-8}	[FE16]	+++
Ion. smoke G. II A	4.3^{-10}	3.4^{-9}	1.6^{-8}	5.2^{-9}	5.7^{-9}	[FE16]	+++
Ion. smoke G. II B	3.1^{-9}	2.5^{-8}	1.2^{-7}	3.8^{-8}	4.1^{-8}	[FE16]	+++
Smoke suck in G. I	7.3^{-8}	6.9^{-7}	2.6^{-6}	1.0^{-6}	1.6^{-6}	[FE16]	+++
Smoke suck in G. II	8.7^{-9}	5.7^{-7}	1.4^{-5}	9.0^{-6}	6.1^{-5}	[FE16]	+++
Push button alarm	2.4^{-10}	1.4^{-7}	3.5^{-6}	7.0^{-7}	1.2^{-6}	[FE16]	+++

Table 6.3: All probabilities are in the unit $1/h$. The data is based on results from nuclear reactors. The types of the fire detectors are split into Type A (technical direct release) and Type B (technical indirect release). Furthermore, there are four different generations of fire alarm systems. Generation I, do not have an address to report to (almost no longer in use), Generation II, have an intelligence report with a trigger detector, Generation III, have an intelligence report with a detector that has more criterion and Generation IV, same as Generation III, with a new software version. Variables in the header are $\mathcal{Q}$ representing quartiles and σ representing the standard deviation.

Stationary extinguishing system

Technical system	Fire beginning and spread phase	Full fire phase	Literature	Quality
Water fire pump	$8.5 * 10^{-4}$ to $3.5 * 10^{-2}$*		[Fac15]	+++
CO_2 gas extinguisher	$9.2 * 10^{-3}$ to $8.1 * 10^{-2}$*		[Ges01a]	+++
Inert gas extinguisher	$5.8 * 10^{-2}$*		[Ges01a]	+++
Water spray system general	$2.0 * 10^{-2}$*		[Fac15]	+++
with remote and total failure	$2.2 * 10^{-4}$ to $3.9 * 10^{-3}$*		[Fac15]	+++
failure remote control	$3.2 * 10^{-4}$*		[Fac15]	+++
with alarm check valve	$3.2 * 10^{-4}$*		[Fac15]	+++

Table 6.4: Technical failure probability for fire fighting systems. The data refers to the whole functionality of the system, if no further information is described. For partial functions, the examples given that data remotely transfered are specified separately. *Same probability for beginning spread phase and full fire phase and development and spread phase.

Occupancy sprinkler reliability

Occupancy	Reliability	Effectiveness of suppression	Probability of success	Literature	Quality
Apartment	98	98	96	[XH13]	++
Health care	96	100	96	[XH13]	++
1 or 2 family dwelling	94	100	94	[XH13]	++
Educational	92	100	92	[XH13]	++
Hotel	97	94	91	[XH13]	++
Stores and offices	92	97	90	[XH13]	++
Manufacturing	93	94	87	[XH13]	++
Public assembly	90	89	81	[XH13]	++
Storage	85	90	77	[XH13]	++

Table 6.5: The table shows the proportion of reliability, effectiveness and probability of sprinkler system performance. All values are in units % of the whole data frame. The data is based on a study from China with over four years of full survey. The statistical mass is 562,235 fires over 4 years. It must be checked whether the results can also be transferred to the EU.

Fire door reliability

Door type	$5\% - \mathcal{Q}$	$50\% - \mathcal{Q}$	$95\% - \mathcal{Q}$	Mean	σ	Literature	Quality
Self closing	2.5^{-7}	1.0^{-6}	2.8^{-6}	1.2^{-6}	7.9^{-7}	[FE16]	+++
Self locking	1.1^{-7}	8.3^{-7}	3.2^{-6}	1.2^{-6}	1.5^{-6}	[FE16]	+++
Closing sequence	9.4^{-7}	2.0^{-6}	4.1^{-6}	2.2^{-6}	6.7^{-7}	[FE16]	+++
Barrier function	2.1^{-7}	4.8^{-8}	4.3^{-7}	1.6^{-7}	6.4^{-7}	[FE16]	+++
Fixed function	3.3^{-7}	8.3^{-7}	5.0^{-6}	1.4^{-6}	1.1^{-6}	[FE16]	+++

Table 6.6: All probabilities are in the unit $1/h$. The data is based on results from nuclear reactors. The doors were checked every three months for several decades and errors recorded. This corresponds to a very high safety standard, since the errors were also corrected during the check. The deliberate stopping by wedges or other objects was not included. There are only technical failure rates. The variables in the header are $\mathcal{Q}$ representing quartiles and σ representing the standard deviation.

Bulkhead failure rate

Bulkhead type	$5\% - \mathcal{Q}$	$50\% - \mathcal{Q}$	$95\% - \mathcal{Q}$	Mean	σ	Literature	Quality
Melting lot trigger system							
Variant 0	4.4^{-9}	9.4^{-8}	4.9^{-7}	2.0^{-7}	5.6^{-7}	[Fac15]	+++
all Bulkhead	1.5^{-9}	2.1^{-7}	2.0^{-6}	4.8^{-7}	5.9^{-7}	[Fac15]	+++
With remote function							
Variant 1	2.9^{-9}	4.8^{-7}	6.1^{-6}	1.7^{-6}	4.8^{-6}	[Fac15]	+++
Variant 2	3.7^{-7}	2.0^{-6}	6.0^{-6}	2.4^{-6}	1.8^{-6}	[Fac15]	+++
Variant 3	3.8^{-8}	5.6^{-7}	2.7^{-6}	8.2^{-7}	5.8^{-7}	[Fac15]	+++
Variant 4	9.1^{-9}	7.5^{-7}	8.0^{-6}	4.8^{-6}	3.0^{-5}	[Fac15]	+++
Closing and barrier function							
Variant 0	7.4^{-10}	2.7^{-7}	5.3^{-6}	1.7^{-6}	7.1^{-6}	[Fac15]	+++
Variant 1	2.5^{-8}	1.9^{-7}	5.9^{-7}	2.5^{-7}	2.8^{-7}	[Fac15]	+++
Variant 2	8.8^{-8}	4.8^{-7}	1.5^{-6}	5.9^{-7}	4.6^{-7}	[Fac15]	+++
Variant 3	9.1^{-8}	2.6^{-7}	6.7^{-7}	3.0^{-7}	1.6^{-7}	[Fac15]	+++
Variant 4	1.4^{-8}	8.7^{-7}	8.5^{-6}	4.3^{-6}	2.4^{-5}	[Fac15]	+++
all Bulkhead	9.1^{-9}	2.1^{-7}	6.1^{-7}	2.5^{-7}	8.9^{-8}	[Fac15]	+++
Smoke and heat discharge bulkhead							
Bypass, smoke	3.9^{-8}	1.2^{-6}	6.6^{-6}	1.9^{-6}	1.4^{-6}	[Fac15]	+++
Light dome	4.0^{-7}	2.4^{-6}	6.4^{-6}	2.8^{-6}	2.4^{-6}	[Fac15]	+++
Flap in-wall	9.5^{-8}	2.0^{-6}	1.5^{-5}	5.2^{-6}	1.6^{-5}	[Fac15]	+++

Table 6.7: Variant 0: only melting lot, no remote function, variant 1: electrical pneumatic trigger, variant 2: electrical magnetic trigger with opening help, variant 3: electrical magnetic trigger without opening help, variant 4: detection magnet. All probabilities are in the unit $1/h$. The data is based on results from nuclear reactors. The bulkheads were checked once a year for several decades and errors recorded. This corresponds to a very high safety standard, since the errors were also corrected during the check. The variables in the header are $\mathcal{Q}$ representing quartiles and σ representing the standard deviation.

Fire fighting technical equipment

Equipment	$5\% - \mathcal{Q}$	$50\% - \mathcal{Q}$	$95\% - \mathcal{Q}$	Mean	σ	Literature	Quality
Extinguish water supply							
Pump begin	5.7^{-8}	1.7^{-6}	1.0^{-5}	2.8^{-6}	2.4^{-6}	[Ges01a]	+++
Pump go on	4.2^{-8}	2.3^{-6}	1.6^{-5}	4.3^{-6}	4.4^{-6}	[Ges01a]	+++
Hydrant outside	6.7^{-9}	4.0^{-7}	3.3^{-6}	8.4^{-7}	9.4^{-7}	[Ges01a]	+++
Hydrant wall	8.3^{-10}	4.5^{-8}	3.9^{-7}	9.9^{-8}	1.2^{-7}	[Ges01a]	+++
Foam mix syst.	2.1^{-7}	2.0^{-6}	8.4^{-6}	2.8^{-6}	2.4^{-6}	[Ges01a]	+++
Deluge water system							
Remote exting.	6.4^{-8}	2.6^{-6}	1.7^{-5}	5.0^{-6}	7.5^{-6}	[Ges01a]	+++
Gas extinguishing system							
CO^2	2.2^{-9}	2.5^{-6}	2.3^{-4}	1.6^{-3}	2.8^{-2}	[Ges01a]	+++
Inert gas	3.3^{-8}	4.5^{-6}	6.1^{-5}	1.4^{-5}	2.7^{-5}	[Ges01a]	+++

Table 6.8: All probabilities are in the unit $1/h$. The data is based on results from nuclear reactors. It is only with the probability of failure of the technical system. Human mistakes are not included. Components are also described as part of an overall system. The variables in the header are $\mathcal{Q}$ representing quartiles and σ representing the standard deviation.

Fire brigade performance

Fire fighting by	Additional Information	Value	Literature	Quality
Public fire brigade	t.t.p. <15 min	0.2	[Deu10b]	+
Public fire brigade	t.t.p. >20 min	0.5	[Deu10b]	+
Factory fire brigade*	t.t.p. >10 min 24 fire fighters	0.02	[Deu10b]	+
Factory fire brigade*	t.t.p. >10 min 12 fire fighters	0.05	[Deu10b]	+

Table 6.9: The values of the probability of failure rate of fire fighting per alarm to performance in the described time. Abbreviation t.t.p. (time to performance) includes the alarm time + support time. Between the t.t.p. it is possible to interpolate linearly between the two times. *In the case of the factory fire brigade, it is assumed that an automatic fire detection alarm is used.

Fire causes in Germany

Fire influence	Causes 2018	Causes 2002 - 2018	Literature	Quality
Electricity	31 %	32 %	[Ins18]	++
Other and unknown	22 %	21 %	[Ins18]	++
Human misconduct	20 %	17 %	[Ins18]	++
Fire arson	9 %	9 %	[Ins18]	++
Overhead	8 %	9 %	[Ins18]	++
Flammable work	3 %	3 %	[Ins18]	++
Explosion	2 %	2 %	[Ins18]	++
Open fire	2 %	3 %	[Ins18]	++
Spontaneous combustion	2 %	2 %	[Ins18]	++
Lightning strike	0.5 %	0.3 %	[Ins18]	++

Table 6.10: The information on the distribution of causes of fire relates exclusively to Germany and is always rounded to the full percent. The basis for the period from 2002 to 2018 there was a total of 1,600 fires, which were recorded by a professional fire investigation agents from insurance companies. The statistics only included fires that were reported to insurance companies.

Fire per unit of use

$O =$ Occupancy	$p_{approx}(O) =$ Housing unit per year (1/a)	$a =$ Basic value per $1/(m^2 * a)^{-1}$	$b =$ Exponent for split units	Literature	Quality
Residential	3.0^{-3}	4.8^{-5}	0.9	[Deu10b]	++
Office	$6,2^{-3}$	5.8^{-5}	0.9	[Deu10b]	++
Hospital, Nursing	3.0^{-1}	7.0^{-4}	0.75	[Deu10b]	++
Hotel	3.7^{-2}	8.0^{-5}	1.0	[Deu10b]	++
School, University	4.0^{-2}	2.0^{-4}	0.75	[Deu10b]	++
Shopping mall	8.4^{-3}	6.6^{-5}	1.0	[Deu10b]	++
Theater, Cinema	2.0^{-2}	9.7^{-5}	0.75	[Deu10b]	++
Discotheque	1.2^{-1}	9.7^{-5}	1.0	[Deu10b]	++

Table 6.11: The probability for a fire starting in an occupied structure $p_{approx}(O)$ see the second column per unit of use. It is possible to calculate the FTA with these values, but its conservative assumption. Alternative calculate exact $p_{exact}(O) = a * A^b$ with $A = m^2 area$. Also $p_{approx}(O) \approx a * A^b$.

Probability of fire spread and of deaths

Occupancy per	p_{st} (year)	p_{de} (fire)	p_{sp} (fire)	$r_f * 10^{-4}$ (year)	$r_{sp} * 10^{-4}$ (year)	Literature	Quality
Resid.-Other	0.067	0.123	0.06	82	40	[HNGT02]	++
Resid.-Institut.	0.021	0.090	0.03	19	6	[HNGT02]	++
Entertainment	0.0038	-	-	-	-	[HNGT02]	++
Industr. & Storage	0.0035	0.078	0.16	3	6	[HNGT02]	++
Assembly.	0.0077	0.042	0.10	3	8	[HNGT02]	++
Shop & Commercial	0.0030	0.077	0.12	2	4	[HNGT02]	++
Office	0.0017	0.063	0.08	1	2	[HNGT02]	++

Table 6.12: The table shows a summary of the probability (p) of a fire occurring and the consequences of a fire in terms of casualty rate per fire and spread rate beyond the room of origin per fire for each of the purpose groups. Entertainment is excluded from analysis because of insufficient data. Index: st = *start*, de = *death*. Data from the London Fire Department (2002).

Number of spread and their spread

Source of ignition	Number of fire	Resc.	Inju.	Death	Casu.	% spread room	Literature	Quality
Naked flames	1,687	449	117	12	0.076	13.3	[HNGT02]	++
Cooking appl.	435	7	27	0	0.062	8.3	[HNGT02]	++
Domestic appl. and equipment	340	6	15	0	0.044	5.0	[HNGT02]	++
Electrical sup.	318	8	15	0	0.047	9.1	[HNGT02]	++
Industrial equi.	316	1	44	0	0.139	7.0	[HNGT02]	++
Water heating equipment	211	0	8	0	0.038	5.2	[HNGT02]	++
Unspecified source	203	26	95	3	0.483	16.3	[HNGT02]	++
Lighting and office equi.	195	3	9	0	0.046	4.6	[HNGT02]	++
Not specified	90	4	15	1	0.178	4.4	[HNGT02]	++
Vehicular source	24	3	4	0	0.167	25.0	[HNGT02]	++

Table 6.13: Table shows the number of fires, rescues, injuries, deaths and percentage of fire spreading beyond the room of origin, for each of the general source of ignition categories for fires occurring in commercial premises. Data from the London Fire Department (2002).

Incident of deaths and numbers

Number of deaths per incident	Number of incidents	Total number of deaths	Literature	Quality
1	244	244	[HNG03]	++
2	12	24	[HNG03]	++
3	2	6	[HNG03]	++
4	-	-	[HNG03]	++
5	1	5	[HNG03]	++

Table 6.14: Table shows the number of deaths per incident and number of incidents (period 1996 to 2000). There were not 4 deaths at the same time in a fire. Data from the London Fire Department.

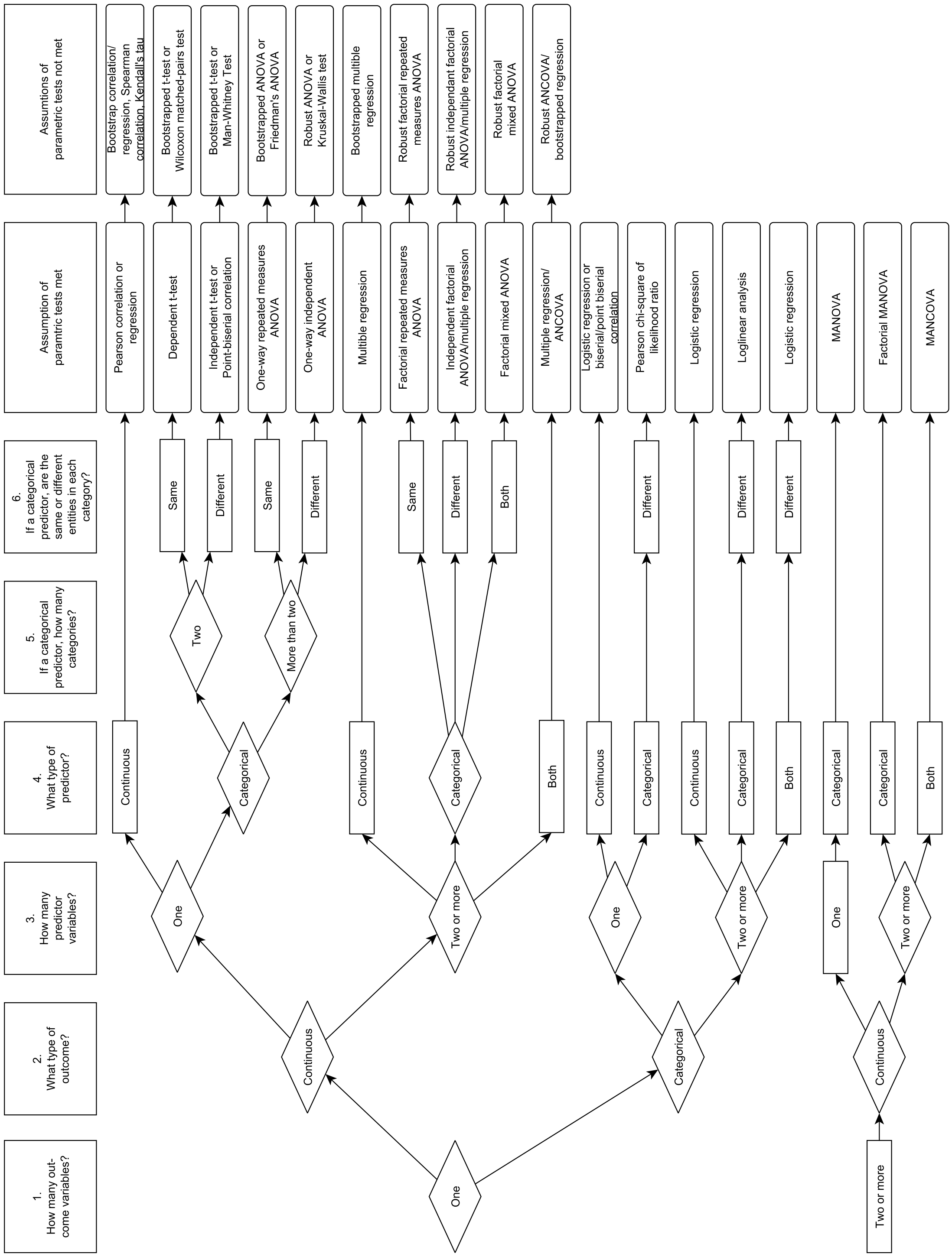


Figure 6.1: Statistical test algorithm to find the parametric test and met [FMF12].

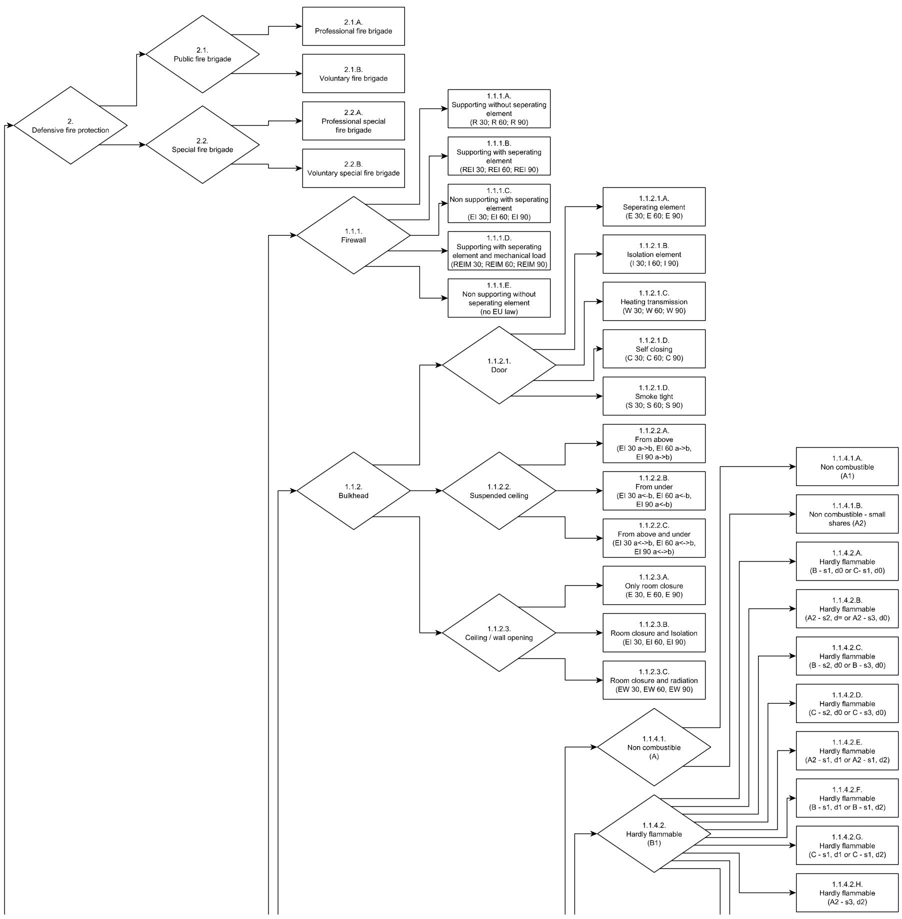


Figure 6.2: The figure shows the algorithm for fire inspection, the upper third.

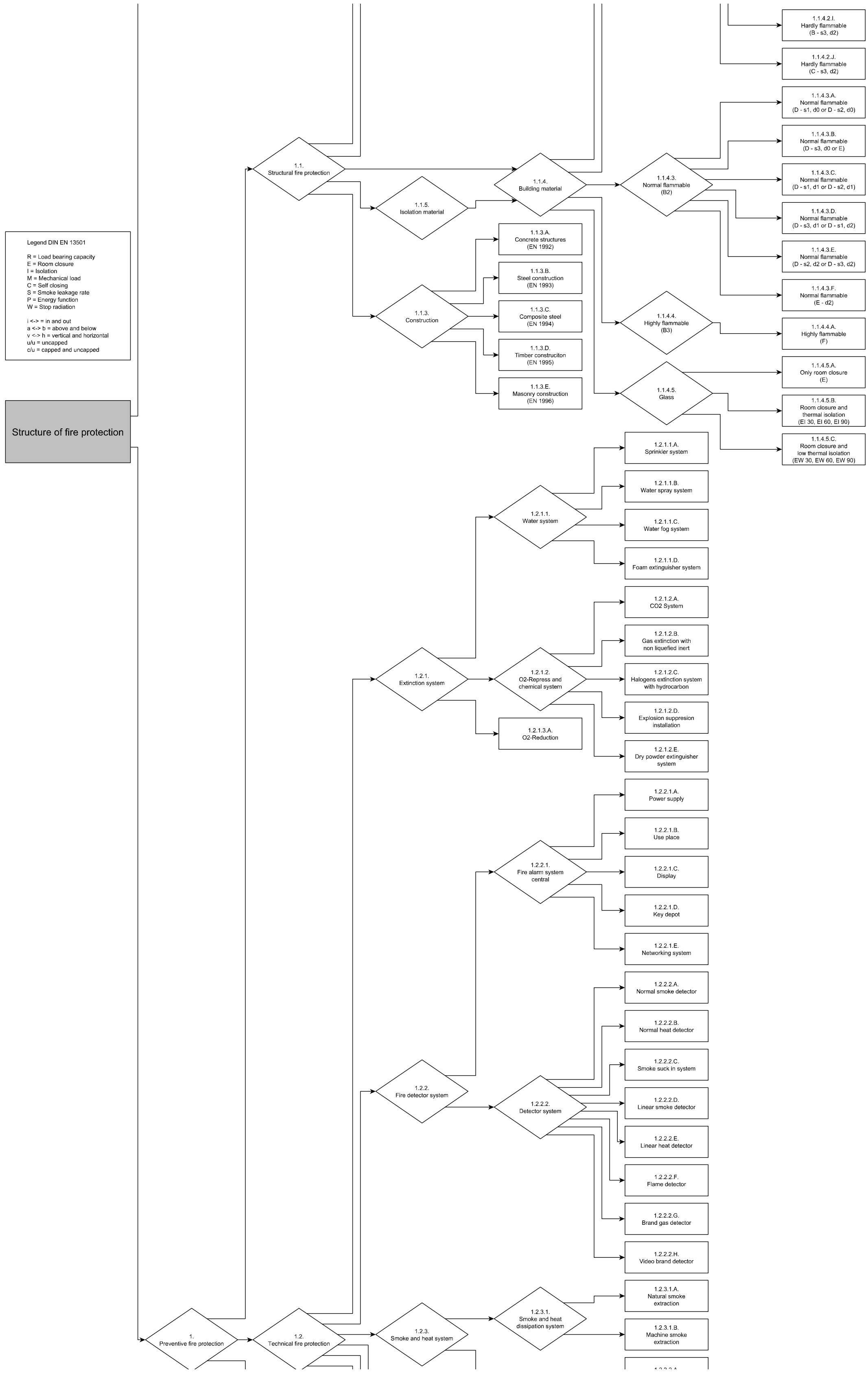


Figure 6.3: The figure shows the algorithm for fire inspection, the middle third.

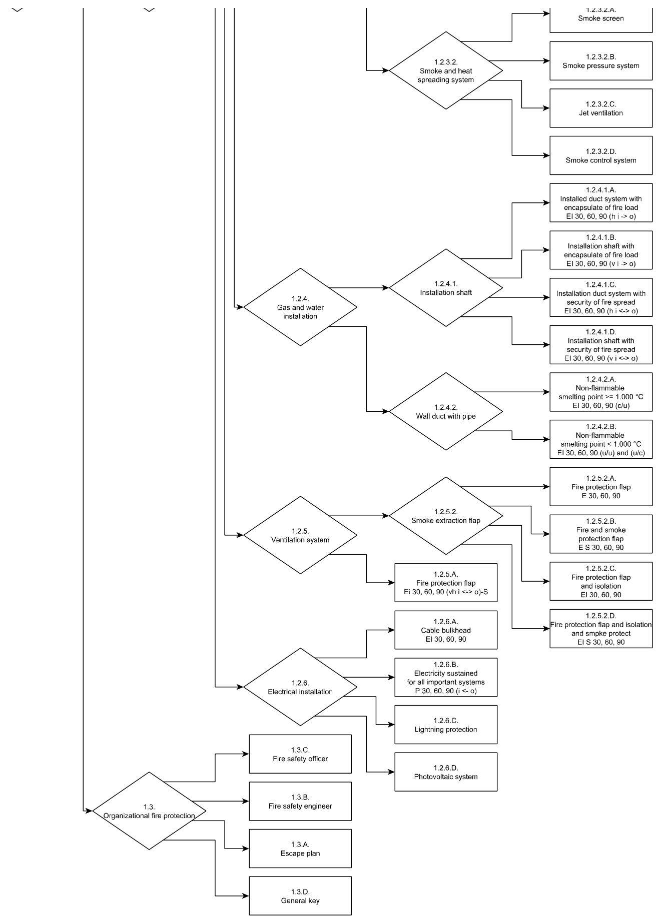


Figure 6.4: The figure shows the algorithm for fire inspection, the lower third.

Test person	Instruction form	Mental requirem.	Physical requirem.	Time requirem.	Performance	Effort	Frustration	Age	Sex	Flight experience	Complex syst. exp.
V001	text	20	2	18	20	18	16	24	f	n	n
V002	algorithm	4	0	13	9	4	7	21	m	y	n
V003	image	17	2	18	4	15	4	24	m	n	n
V004	algorithm	8	5	10	4	11	7	24	m	n	n
V005	image	12	1	10	12	12	11	23	f	n	y
V006	text	6	1	15	1	7	5	25	m	y	n
V007	algorithm	14	2	16	16	15	14	28	m	y	n
V008	image	16	4	17	13	12	16	25	f	n	n
V009	text	9	5	14	5	15	14	24	f	n	n
V010	image	12	4	16	8	12	6	26	m	y	n
V011	text	14	2	10	16	12	14	23	f	n	n
V012	algorithm	16	10	18	16	16	6	24	m	n	n
V013	image	12	5	12	7	10	4	26	f	y	n
V014	text	20	0	20	10	18	14	27	f	y	n
V015	image	16	6	8	4	8	8	23	f	n	n
V016	algorithm	13	1	7	19	5	14	24	m	n	n
V017	algorithm	13	5	15	9	7	3	25	m	y	y
V018	text	16	3	19	14	10	8	38	m	y	y
V019	algorithm	17	12	18	16	14	8	22	m	n	n
V020	image	15	1	8	6	11	2	27	f	n	y
V021	text	12	6	14	13	13	8	22	f	n	n
V022	algorithm	14	2	14	4	14	5	24	m	n	n
V023	image	17	3	17	6	16	8	26	m	n	n
V024	text	14	0	16	4	14	12	32	m	n	y
V025	image	13	4	12	3	8	2	26	m	n	n
V026	text	18	1	18	3	13	14	26	f	n	n
V027	text	18	2	17	16	16	14	27	m	n	n
V028	text	14	4	12	4	10	4	23	m	n	n
V029	text	15	2	16	6	11	10	24	m	n	n
V030	algorithm	11	4	12	13	10	7	25	m	n	n
V031	algorithm	16	2	18	10	16	10	29	m	y	n
V032	image	14	5	13	10	5	13	48	m	n	n
V033	image	12	8	14	4	14	6	23	m	n	y
V034	text	10	6	9	2	10	8	20	f	n	n
V035	algorithm	2	3	14	6	2	0	20	m	y	n
V036	algorithm	12	4	10	4	14	8	22	m	y	n
V037	text	7	1	15	17	5	1	41	m	n	y
V038	image	10	2	10	4	4	0	22	m	y	n
V039	image	15	4	16	7	16	14	54	f	n	n
V040	text	18	2	14	10	4	14	18	f	n	n
V041	text	9	5	13	8	12	12	25	m	n	n
V042	algorithm	8	3	6	10	12	5	30	m	n	n
V043	text	5	4	8	2	4	1	21	m	n	n
V044	image	6	8	10	6	7	2	24	m	y	y
V045	algorithm	12	0	18	15	12	13	26	m	n	n
V046	text	7	2	12	12	10	8	21	m	n	n
V047	algorithm	7	1	10	5	3	10	22	m	n	n
V048	text	13	6	12	8	6	4	25	m	y	y
V049	text	9	5	15	15	11	7	25	m	y	y
V050	image	12	4	10	0	14	4	26	m	y	n
V051	text	16	10	14	8	16	14	25	m	n	y
V052	algorithm	12	2	14	14	6	10	28	m	n	y
V053	text	17	3	19	7	11	13	31	m	n	n
V054	image	5	2	13	4	13	5	27	m	n	n
V055	algorithm	10	4	10	3	4	0	19	m	y	n
V056	text	14	4	6	3	5	6	26	m	n	n
V057	image	6	4	10	0	6	0	24	m	y	y
V058	algorithm	18	1	16	1	16	0	22	m	n	n
V059	image	15	1	17	1	13	3	34	m	y	y
V060	image	13	1	13	1	7	1	27	m	n	n

Table 6.15: Answers from the questionnaire completed by the test persons regarding workload, age, flight experience and experience in complex systems, part 1 [HKF20a].

Test person	Instruction form	Mental requirem.	Physical requirem.	Time requirem.	Performance	Effort	Frustration	Age	Sex	Flight experience	Complex syst. exp.
V061	algorithm	6	6	6	6	4	4	25	m	n	y
V062	image	8	3	14	4	10	2	23	m	y	n
V063	algorithm	12	3	12	7	16	12	22	m	n	n
V064	image	11	6	14	16	8	2	30	m	n	y
V065	algorithm	14	2	13	1	8	4	26	m	y	n
V066	image	16	2	19	18	10	18	25	f	n	y
V067	algorithm	5	2	14	14	6	10	40	m	n	n
V068	image	5	1	10	2	2	1	35	m	n	y
V069	algorithm	16	4	17	15	14	8	24	m	n	n
V070	text	18	4	11	16	16	8	28	m	n	n
V071	algorithm	11	1	1	3	3	1	37	m	n	n
V072	image	11	3	11	9	7	3	47	m	n	y
V073	image	4	0	12	2	4	4	31	m	n	y
V074	algorithm	18	2	19	14	11	12	35	m	n	n
V075	text	15	3	15	9	15	11	43	m	n	y
V077	algorithm	8	4	10	12	6	6	31	m	n	n
V078	image	0	3	3	2	1	1	53	m	n	y
V079	image	12	6	14	6	8	14	21	m	y	n
V080	image	6	2	5	12	3	3	42	m	n	y
V081	algorithm	13	7	15	18	10	14	31	m	n	y
V082	text	14	2	16	0	14	0	31	f	n	n
V083	text	17	15	15	7	13	9	26	m	n	y
V084	algorithm	12	2	8	4	8	9	59	m	n	y
V085	algorithm	9	5	16	11	12	3	24	f	n	n
V086	text	11	3	17	9	5	13	39	m	y	y
V087	image	14	0	0	8	2	3	61	m	n	y
V088	image	15	6	14	7	12	10	58	f	n	n
V089	image	5	3	13	2	2	2	29	m	n	n
V090	text	14	4	15	13	14	1	15	m	n	n
V091	algorithm	14	4	14	2	14	0	26	f	y	n
VP92	algorithm	18	2	15	9	1	1	43	f	n	n
VP93	text	9	2	7	8	19	2	28	m	n	n

Table 6.16: Answers from the questionnaire completed by the test persons regarding workload, age, flight experience and experience in complex systems, part 2 [HKF20a].

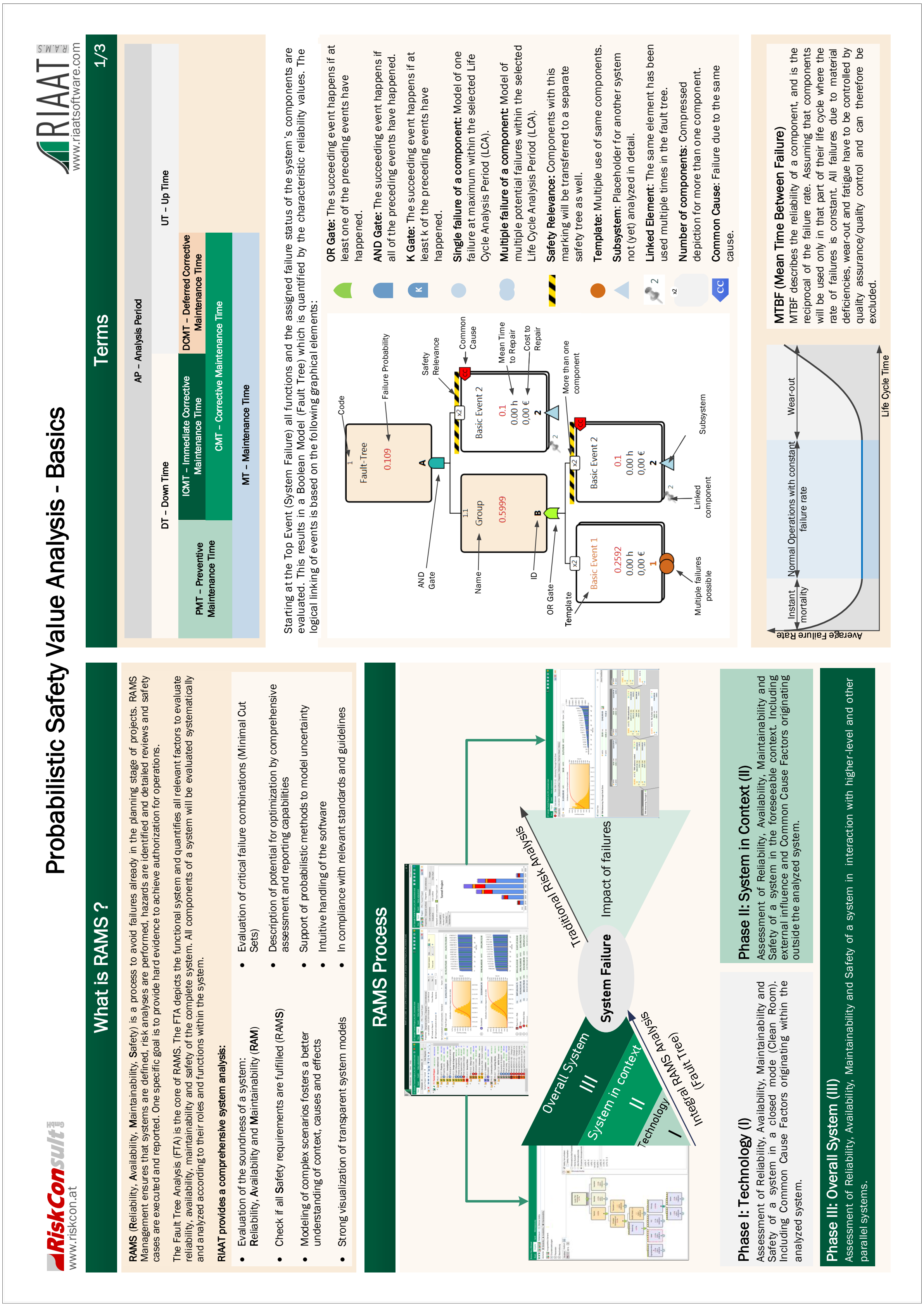


Figure 6.5: Page 1 of 3 in RIAAT® manual package FTA.

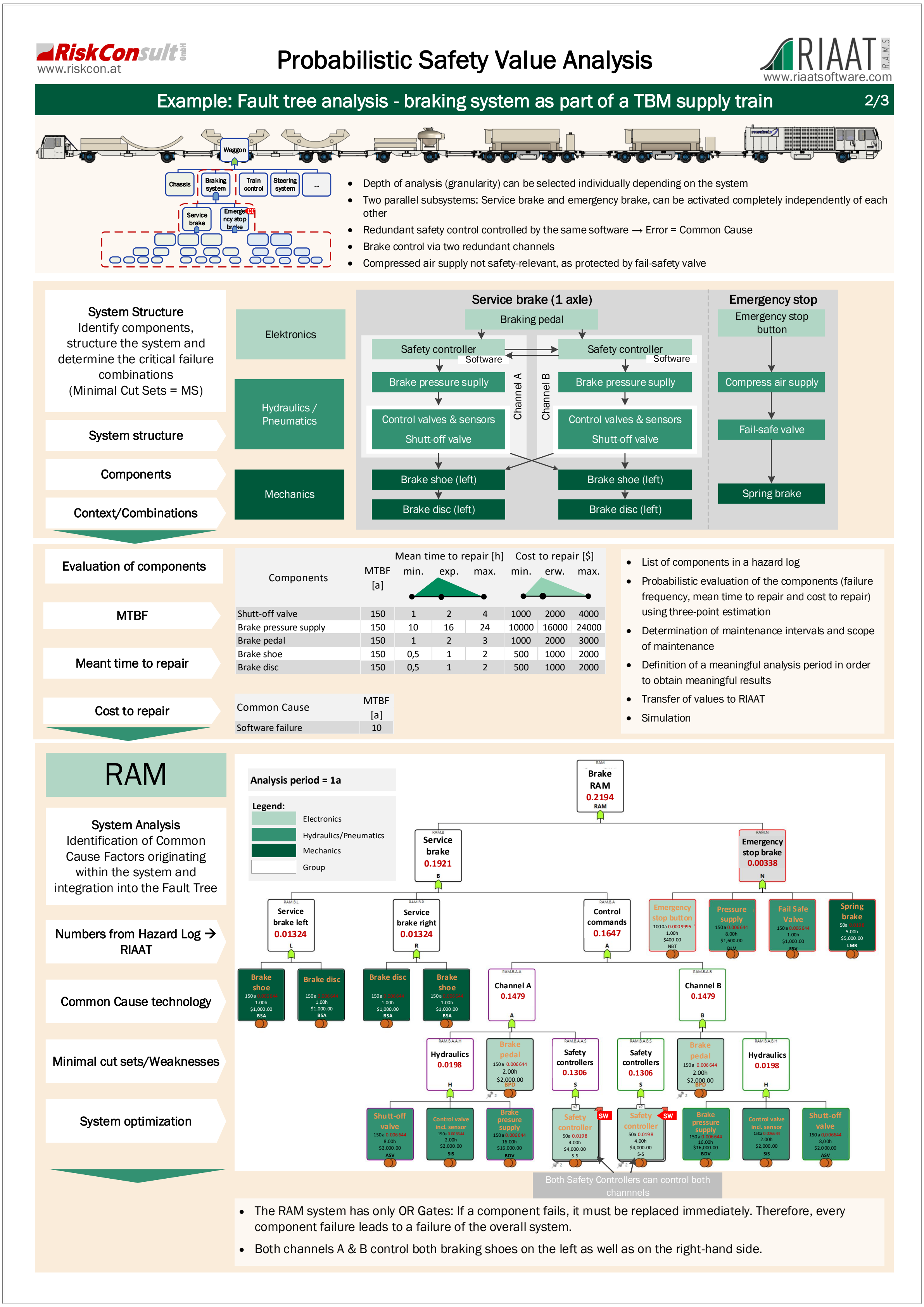


Figure 6.6: Page 2 of 3 in RIAAT® manual package FTA.

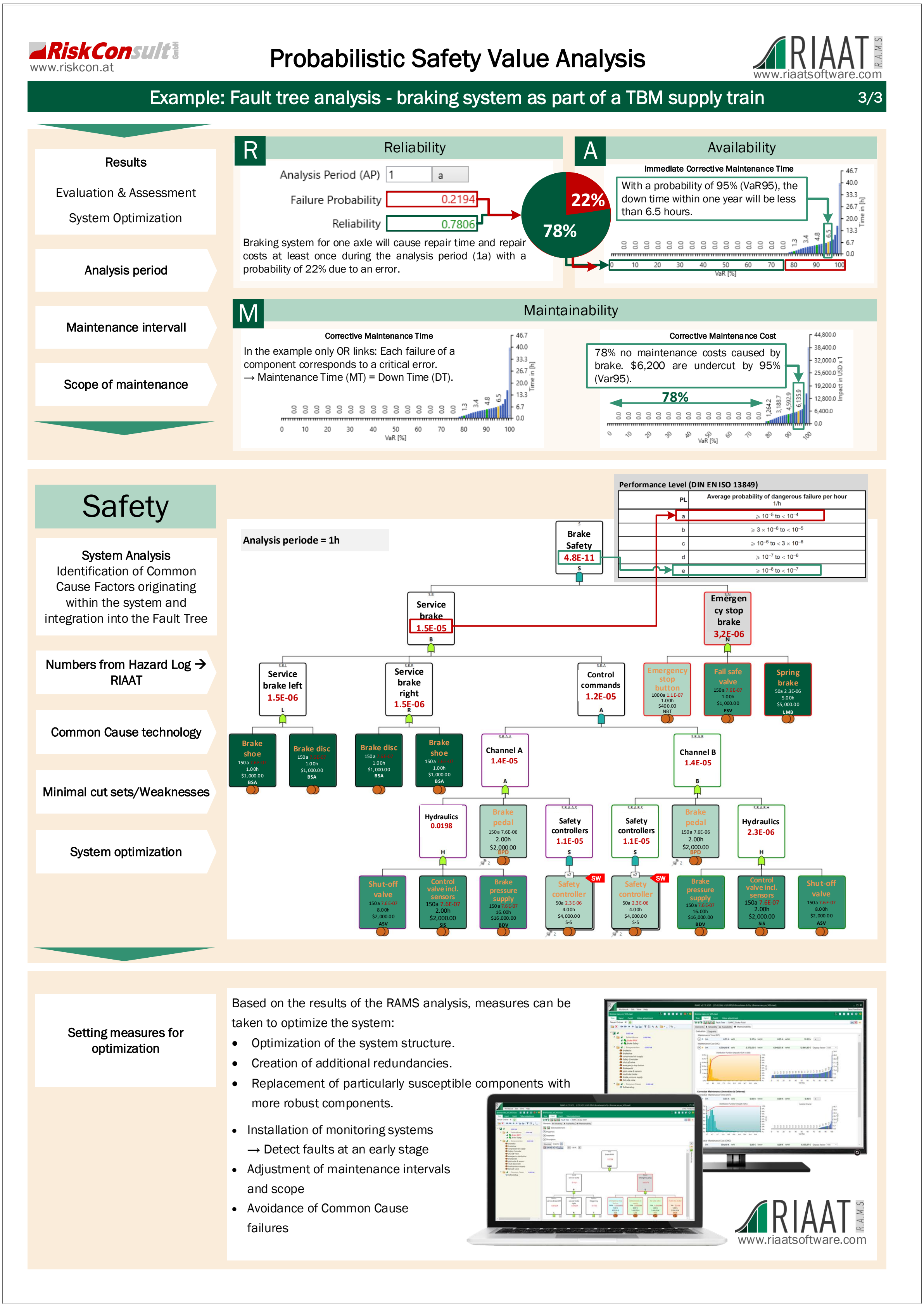


Figure 6.7: Page 3 of 3 in RIAAT® manual package FTA.

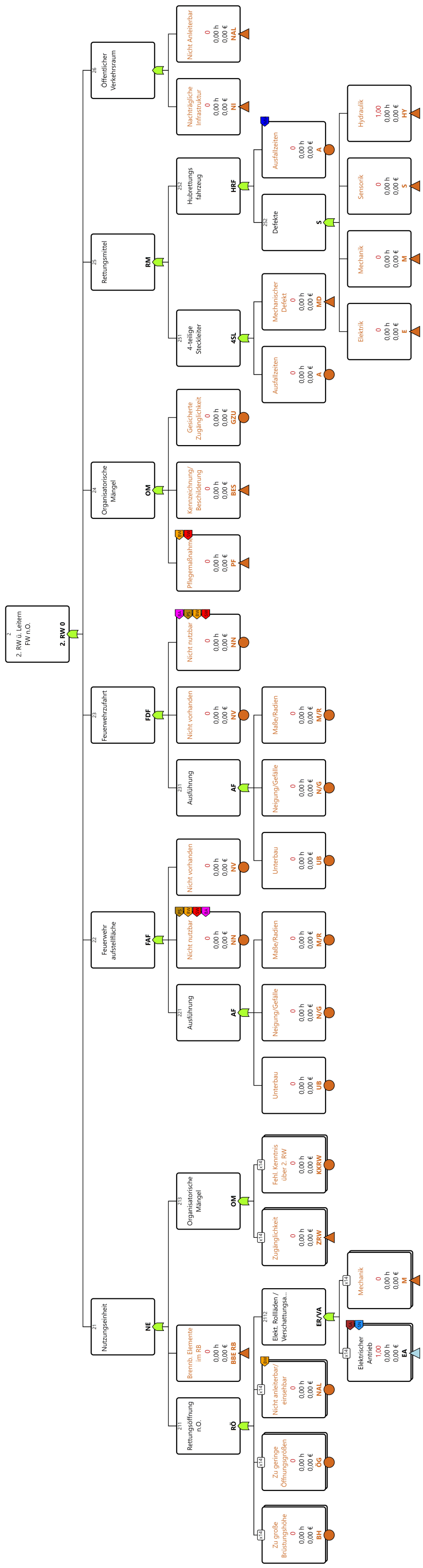


Figure 6.8: The Event Tree with the influencing factors related to rescuing a building resident with an automatic fire ladder at time t_0 [Hoo20].

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