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Solution Approach for a Coherent Probabilistic Assessment of Explosion and Fire Safety for Facilities at the Chemical Process Industries

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Abstract

In the field of explosion and fire protection, the assessment of individual risks often bases on qualitative or indexing methods because a full-scale probabilistic approach is infeasible in many cases for chemical enterprises. This established procedure undermines efforts of quantitative risk assessment to assess frequencies of undesired events and their consequences as accurately as possible.

Though classical risk assessment techniques are still actively applied and are reasonable for an assessment of hazards and risks of separate technological processes, they are generally labor-consuming and do not always give an overall or semi-quantitative assessment estimate. With the foundation of the European Union a new concept for harmonizing the legal regulations was developed taking a standardized European internal market into consideration. This new concept called “new approach” only uses fundamental requirements as a set target. Therefore, such an approach has certain disadvantages one of them being the qualitative assessment and thus calls for considerable knowledge while carrying out the audits.

The dissertation at hand seeks to give an overview concerning the current situation available for semi-quantitative and indexing approaches and application programs which leads to the conclusion that there is no universal method of fire and especially explosion risk assessment which would be accepted as obligatory in the standard documentation regulating questions of explosion and fire protection.

The result of the dissertation consists of two developed solution approaches for a coherent probabilistic assessment of explosion and fire safety at the chemical process industries.

The first method is a combination of the semi-quantitative and indexing approaches and allows to carry out an assessment which is based on weighting procedures utilizable for risk rating and benchmarking for individual risk quantification. The main focus of this method is the development of an equation which calculates the risk considering hazards and protection measures. This allows a more exact calculation of all possible worst case and best case scenarios and parallel to the quantitative risk value, the common class of hazard. The consideration of the deviations while calculating is important because due to a probability of an error which comes from the conditional values, involved in the risk calculation.

The complexity of the dependencies and interrelations between the hazards and safety measures asks for an additional transfer of the extended semi-quantitative approach for individual risk assessment into a MS Excel prototype tool. A practical application of the developed method for the chemical industries serves as a further step in its development. The extended semi-quantitative approach evaluates the individual risk from the side of the acceptance.

After preceding semi-quantitative approach for individual risk assessment it is advisable to follow the causes-effect chain, because the calculated probability value of the individual risk does not give a statement about the consequence of a possible worst case scenario(s).

The second developed quantitative method for consequence assessment gives the option to calculate the physical effects of hazardous substances based on an approach from the Russian ordinances. This is recommended after a comparison with one of in the European Union leading approaches which is based on the Dutch CPR-guidelines used in fields of labor safety, transport safety and fire safety. A developed MS Excel prototype tool, which is based on the Russian approach, is also applied for its future application.

The provided methods, semi-quantitative approach for individual risk assessment and quantitative approach for consequence assessment give the opportunity for a coherent probabilistic assessment of explosion and fire safety for facilities at the chemical process industries.

Contents

1 Introduction

The chemical process industries (CPI) are a significant sector with a good position in economic and, of course, mainly in political terms closely to the nuclear industry. The nuclear industry and CPI are examples of safety critical industries. The CPI have undergone considerable changes in the process conditions. Plants have grown in size and contain large items of equipment; the high technological processes are more interconnected with each other.

CPI are subject to manifold risks. There are different chemical-specific risks at the German national regulations and standards level, as well as at the European level (fig. 1). Some examples of the chemical-specific risks at the German national level are use-specific risks, risks from plants and facility, natural risks, organizational and other risks, explosion and fire risks etc.

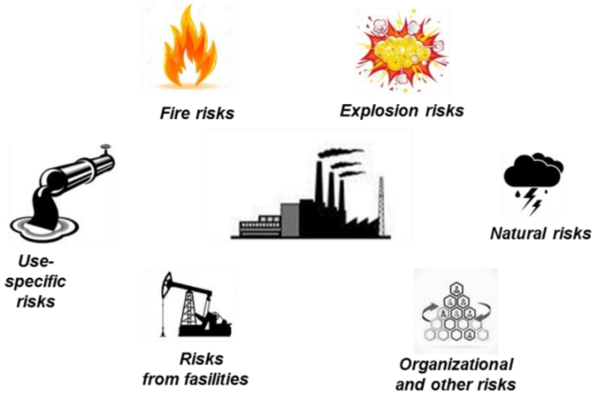


Figure 1. Example of the chemical-specific risks in CPI.

These risks can be divided into hazards and exposures in which the explosion, fire and risks from hazardous substances are explicitly stressed, e.g. in the METRIK-Method for risk classification (Schönbucher 2002). In the field of risk assessment explosions and fires are depended on properties of substances and therefore have the same cause (fig. 2):

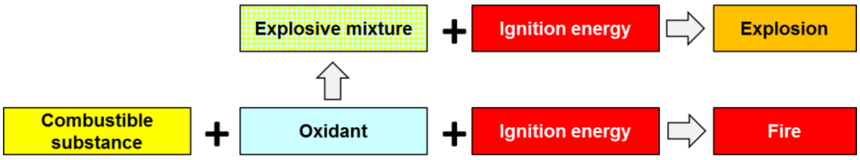


Figure 2. Comparison of the event determining factors in case of fire and explosion.

From the literature research and own personal experience these two chemical-specific risks have a great potential for loss both in economic and in human terms therefore they have to be considered as equivalent from the perspective of explosion and fire protection (EFP). Thus, one of the most important reasons of these risks have the potential to cause big damages, e.g. for the environment, financial aspects, losses of company approvals, political as well as public perception. Historical loss statistics show that fires have a bigger probability as explosions, but fires can be a subsequent event of an explosion or vice versa.

In practice the assessment of the chemically-specific risks in CPI could be divided into: common unspecific risks regarding the type of risk and especially fire risks (fig. 3):

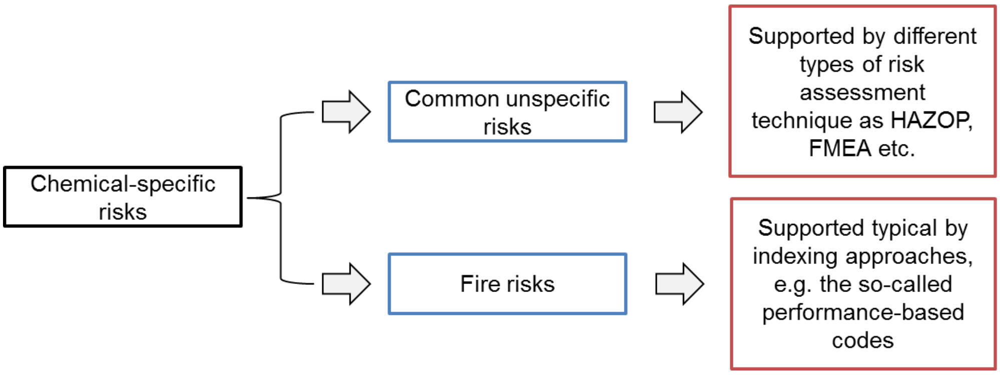


Figure 3. Assessment of the chemical-specific risks in CPI.

In the last decades the European countries initiated a change from strict standardized safety regulations to a more flexible normalization (Hasofer et al. 2007, Meacham 2008, Rasbash et al. 2004, Yung 2008). In the area fire safety this recently introduced “new approach” therefore calls for basic requirements as aims concerning risk assessment in the European Union. Thus, there is a lot of flexibility regarding the qualitative process of risk assessment whereas support is no longer supplied from the methodological side in the area of fire protection. The essence of such approach concentrates more on the individual demands and consists of the so-called performance-based codes. These codes are based on the actual performance of a task. Performance-based codes concentrate on the purposes (aims) of the fire safety system of an object and need to be in accordance with it. However design decisions for their achievement are not regulated. Therefore, restrictions in the object device are minimized. The use of such new approaches to ensure fire safety is stimulated and finally, higher economic efficiency of design decisions (Молчанов et al. 2001) is provided. Considering that the established approach of the rigid application of norms is now replaced with more flexible ones allowing alternative design decisions there is clearly a need for the development of new methods. The use of practicable methods for the assessment of the fire risk of an object needs to be refined. Hence these new flexible approaches base on qualitative risk assessment methods which are admittedly disadvantageous in comparison to their quantitative counterparts.

However it is not said that this method has only benefits; besides, the approaches which concentrate on performance-based codes depend on the enclosed calculation method. Unfortunately this method is not expedient for a risk assessment of CPI which are concerned with dangerous and hazardous substances either transported, stored or processed and which are capable to oxidizing reactions (explosions, fires, etc.) with each other or with air oxygen. The literature research shows that there is no universal method of fire and especially explosion risk assessment which would be accepted as obligatory in the standard documentation regulating questions of explosion and fire safety (Hall 2006, Hall 2008). Moreover there is also no general or standardized method of explosion risk assessment for CPI. In the majority of the European countries the risk analysis (e.g. FMEA, HAZOP, Markov models, fault and event trees etc.) described in (IEC/FDIS 31010 2009), and concrete methods and approaches of its assessment are legally established solely for the objects representing the increased danger — nuclear power plants, storages and terminals of the liquefied natural gas, productions of explosives substances etc.. However all these methods are rather labor-intensive and taking up the author’s preliminary studies (Leksin et al. 2013, Mock et al. 2012).

Moreover a risk analysis, respectively a probabilistic analysis, has to give answers to the three main questions:

1) That can happen?
2) What are the potential consequences of these scenarios?
3) What are the probabilities of such scenarios?

and as an inference from above-mentioned three questions:

Are the calculated risks acceptable?

However the implementation of this kind of analysis needs a detailed and extensive data input, suitable mathematical approaches and last but not least an adequately qualified auditor.

The first question:

1) "That can happen?" comprises the system analysis of the considered object.

The second question:

2) "What are the potential consequences of these scenarios?" comprises the identification of safety measures and hazards.

The third question:

3) "What are the probabilities of such scenarios?" comprises the calculation of the risk.

The result of such risk assessment process in the end phase is the risk evaluation, in other words the comparison of the calculated risk value with an acceptable risk criterion.

The required knowledge and skills when using various approaches can differ fundamentally as well as the answers to each of the three questions regarding the needs of the object they were answered for. These general statements are also applicable to explosion and fire risks as to a special case of technological hazards (SFPE 2002). Therefore, it is important to have a clear idea of what scope, advantages and disadvantages of the available approaches involved are. The disadvantages of existing approaches will be considered in the next chapters.

This dissertation seeks to contribute to the support and the development of explosion and fire risk and consequence assessments based on a semi-quantitative method. With regard to explosion and fire hazards it is important to note that they have to be assessed and estimated alike (Lottermann 2012). Thus, the developed coherent method closes a gap in the field of explosion risk analysis and optimizes the fire risk assessment. The requirements of the developed method for CPI are:

- applicability for both chemical-specific risks: explosion and fire
- supporting with semi-quantitative approach
- substantiation of the values used by the evaluation and assessment
- consideration of the deviations by the risk calculation
- calculation of the individual risk
- risk evaluation with an acceptable risk criterion

- definition of the common class of hazard
- consequence assessment for the worst case scenarios

Before a detailed description of the developed method is given some definitions concerning terminology have to be considered. One of these will comprise the topic of acceptable criteria for understanding and classifying the overall aim of this dissertation. The level of knowledge of available explosion and fire risk assessment applications are discussed. The aim of this survey is to examine the conformity of existing methods regarding requirements as well as additional specification criteria especially focusing on the comprehensibility, effort, level of detail, application range, objectivity and quality of the outcome. As a result of the examination the gap in knowledge becomes obvious.

Subsequently the objective target will be formulated with the detailed structure of the developed method. It is the aim of the author to increase the transparency of the methodological procedure and thus facilitate the readers' comprehension.

After that the presentation, explanation and critical reflection of the extended semi-quantitative approach for individual risk assessment follows. The reader will be led through the single development steps of the semi-quantitative method in combination with the indexing approach under consideration of the deviation values of the calculation resulting in the actual risk calculation.

The conclusion summarises the significant findings and gives an outlook concerning the benefits of the extended method.

Following the extended quantitative approach for consequence assessment is developed in order to assess the worst case scenarios. This is necessary because the calculated risk in the presented semi-quantitative method only considers acceptance but does not refer to the time frame of a possible incident. Therefore, the comparison of the Russian and Dutch approaches concerning the range of applicability, objectivity and quality of the calculated consequence value show that the Russian approach needs to be stressed for the consequence assessment.

The results discuss the benefits and drawbacks and give an outlook regarding the development of explosion and fire risk and consequence assessments based on semi-quantitative and quantitative methods.

2 Terms and definitions

The dissertation at hand aims to improve the basic knowledge concerning risk analysis. An intensive preoccupation with risk management in general and risk analysis in particular therefore becomes an obligatory part of conceptual and methodological basics.

When talking about risk assessment it is of core importance to use unambiguous terminology. Therefore, this chapter seeks to determine as well as explain these terms.

Based on experiences and R & D-project (Mock et al. 2012) a problem occurs among engineers regarding the understanding of the risk term. A classical characterisation of risk according to (ISO 31000 2009) is the combination of the frequency F of an (undesired) event and its (negative) consequence C:

$$R = F \cdot C \tag{1}$$

It remains to be said that the well-used equation is much reduced and a technical risk assessment concept becomes:

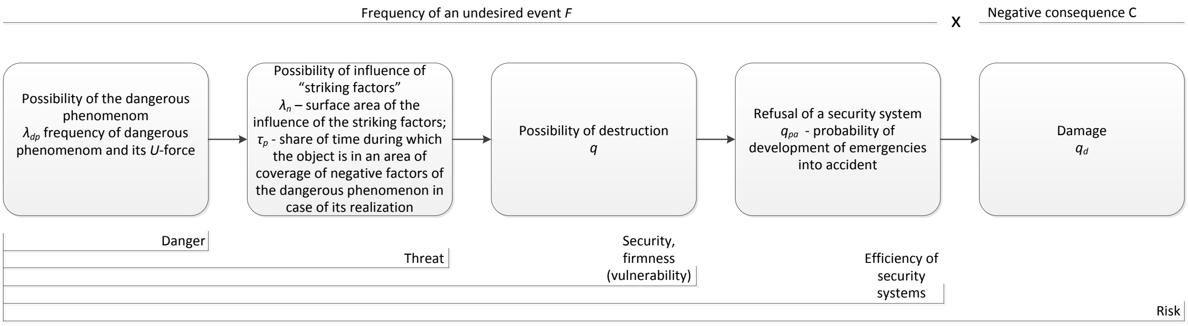


Figure 4. Probabilistic model of risk assessment.

where:

1. the dangerous phenomenon on the considered area characterized by frequency λ_{dp} or an expected value $E_{dp}(\Delta t) = \lambda_{dp} \cdot \Delta t$ (2) for time interval Δt
2. hits in an area of coverage of negative factors of the dangerous phenomenon which for stationary objects is as a first approximation characterized by a part α_n the surface area, which is affected by the striking factors (thus, using as basic data of frequency of the dangerous phenomena in concrete point,

$\alpha_n = 1$). For the moving objects (e.g. persons) it is necessary to consider a time factor k_t - part of time during which the object is in an area of coverage of negative factors of the dangerous phenomenon in case of its realization

3. destruction of objects as a result of action of the striking factors of the dangerous phenomenon characterized by conditional probability q their destructions
4. refusal of a security system because of various combinations of insufficiency of reliability, the human factor and other reasons, characterized by probability q_{pa} of development of emergencies into accident (it is estimated by means of the probabilistic analysis of safety for various scenarios of development of accident)
5. damnification (causing damage) q_d

As described in (Ridder 2015), the classical risk equation (1) cannot be specified a priori depending on the nature of the connection of the probability of occurrence and the severity of the damage. Thus, the risk is considered as the complex event occurring at a joint approach of a number of casual events and, as a result, a negative scenario.
(Kaplan et al. 1980) prefer the definition:

Risk: probability and consequence.

In order to emphasise the significance of scenario analyses in EFP, the extended definition of risk according to The National Fire Protection Association can be also used:

Risk: the set of probabilities and consequences for all possible accident scenarios associated with a given plant or process (NFPA 2003).

The NFPA definition of risk fits well to the use of (generic) event trees as suggested in chapters 7.1 and 7.2. Other terms in use are:

Hazard: source of potential harm (ISO-GUIDE 73 2009).

Also the synopsis of scientific literature and normative documents in the field of explosion and fire shows an inconsistent terminology in quantitative risk assessment (QRA). The dissertation follows the definition of (DIN EN ISO 13943 2010):

Fire hazard: physical object or condition with a potential for an undesirable consequence from fire, whereas

Fire risk: probability of a fire combined with a quantified measure of its consequence (it is often calculated as the product of probability and consequence).

Other definitions can be found, e.g. in the British (PAS 79 2011) or in the Russian (GOST 12.1.033-81 1982).

The definitions of explosion hazard and explosion risk are limited even more on account of the specificity of this topic. The dissertation follows (Dic. Academic 2013):

Explosion hazard: set of the factors causing possibility of formation of the explosive atmosphere in volume, exceeding 5% of room volume, and its ignition. Such factors are: combustible substance, oxidizer and an ignition source (translated from Russian by the author).

A definition of ***explosion risk*** was not found in international standards. For this *explosion risk* is defined by analogy to *fire risk.*

By the discussion of a risk criteria for third parties at major hazard establishments there are various relevant ways to express risks. The most common terms are individual risk and societal risk.
Because the presented and developed semi-quantitative method in this dissertation is concentrated on the “Individuals”, the understanding of “***Individual risk***” is expressed by (I.Chem.E 1992):

as the frequency at which an individual may be expected to sustain a given level of harm from the realization of specific hazards. It is usually taken to be the risk of death, and normally expressed as risk per year.

That is why it is important to note that individual risk is the risk experienced by a single individual in a given time period. It reflects the severity of hazards and the amount of time the individual is in proximity to them. There are typically three different types of individual risks which are described in (I.Chem.E 1992):

“· Location-Specific Individual Risk (LSIR)

Risk for an individual who is present at a particular location 24 hours a day, and 365 days a year. LSIR is not a realistic risk measure because an individual does not usually remain at the same location and is not exposed to the same risk all the time.

· *Individual-Specific Individual Risk (ISIR)*

Risk for an individual who is present at different locations during different periods.
ISIR is more realistic than LSIR.

· *Average Individual Risk (ASR)*

AIR is calculated from historical data, the number of fatalities per year is divided by the number of people at risk.”

The newly developed method of this dissertation takes the time factor and the personnel presence into consideration. Thus, the *Individual-Specific Individual Risk* (further: individual risk) is considered and will be calculated in the developed approach.

Other terms and definitions follow (ISO 31000 2009).

3 Individual risk. Acceptable criteria

For an evaluation of the individual risk it is important to understand that there are acceptable criteria for an individual. For the most common situations the accepted risk values are not given. The requirements for acceptance criteria are either kept very general (e.g. in a qualitative form) or absent in a regulatory context (especially for a quantitative form/analysis). Basically there are only qualitative definitions of the risk acceptability limit.

Organizations establish their risk decision basing criteria on a multitude of benchmarks including industry standards, local and foreign government regulations, practices of industrial partners and qualitative assessment of what is fair and reasonable. Though, most EU-Countries do not have an available risk acceptance criteria, e.g. on how safety distance should be determined using the available qualitative risk analysis methods (IRGC 2005).

This chapter attempts to provide information on existing acceptance criteria and what value could be chosen / suggested as the acceptable criteria in the presented method.

3.1 Terminology and conception

Before accepting the plausible risk criterion its definition should be formulated. The definition is based on (UN/ISDR 2009):

***Acceptable risk**:* the level of potential losses that a society or community considers acceptable giving existing social, economic, political, cultural, technical and environmental conditions.

Based on the definition, risk acceptable criteria have to protect human life and health, as well as environmental resources and natural areas. In other words, acceptable risk criteria is a criterion ensuring the safety measures in place are reasonable in proportion to the risk of accident.

Socially acceptable risk estimates not only and not so much absolute values of risk considering many aspects of activity, but the existing tendencies of growth or decrease in risks of various conservative and new kinds of activity assumed by society. It is pertinent to define the acceptable risk at various levels - from the organization of a branch of economy to the state.

Need of formation of the concept of the acceptable risk is caused by the impossibility of the creation of an absolutely safe activity (e.g. technological process). The acceptable risk combines technical, economic, social and political aspects. In practice it is always a compromise between the safety level reached in society (proceeding from indicators of mortality, incidence, traumatism, disability) and opportunities of its increase by economic, technological, organizational and other methods. Economic opportunities of increase of safety and the socio-technical of systems are not boundless. So, concerning production, spending excessive funds for increase of safety of technical systems, it is possible to weaken financing of social programs of production (reduction of costs of acquisition of overalls, medical care, sanatorium treatment, etc.).

The example of a definition for the acceptable risk is presented in (fig. 5) by increasing the costs of improvement of the equipment, the technical risk decreases, but the social risk grows. The total risk has a minimum at a certain ratio between investments into the technical and social sphere. This circumstance should be considered as a choice of the acceptable risk. Approaches to an assessment of the acceptable risk are very broad. So, accept the schedule presented in (fig. 5) is accepted both for necessary state regulations as well as for the concrete organization. The main thing there is in the first case a choice of the acceptable risk for society, in the second - for staff of the organization.

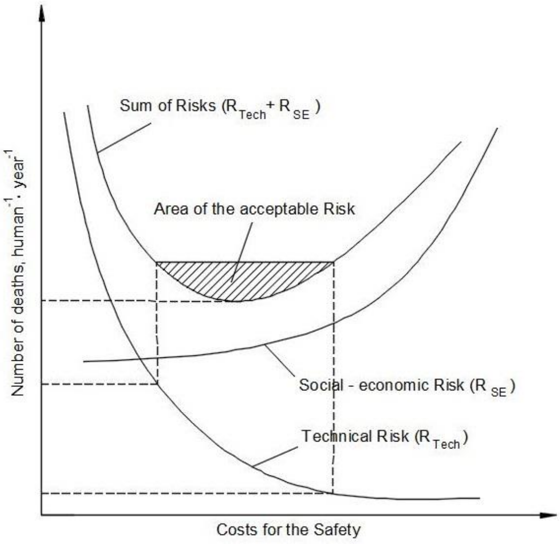


Figure 5. Definition of the acceptable risk of the organization.

The typical well-known acceptance value which can be found in different literatures and numerous regulations worldwide in the field of fire risk (in general) is $1 \cdot 10^{-6}$ per year and per person. This value is internationally comparable and was determined via a socio-political consensus for example in the Netherlands. Whereby this value corresponds to the average life risk (Duijm 2009, Trebojevic 2005, CPR 18E 2005). But this value is to general and must be defined for every country and their enterprises in detail. Based on a literature research further chapter presents some examples of acceptable risk criteria's for different countries.

3.2 Acceptable criteria in different countries

As mentioned earlier "organizations have moral, legal and financial responsibilities to limit risk. Whether the potential receptors are employees or members of the public, they cannot be exposed to a level of risk that is bigger than what is morally tolerable. In addition to the risk for people, the risk given to environment […] should be considered. [By setting] a good risk management program, with [strictly] selected risk tolerance criteria, will balance between these three responsibilities (fig. 6)" (Marszal 2001):

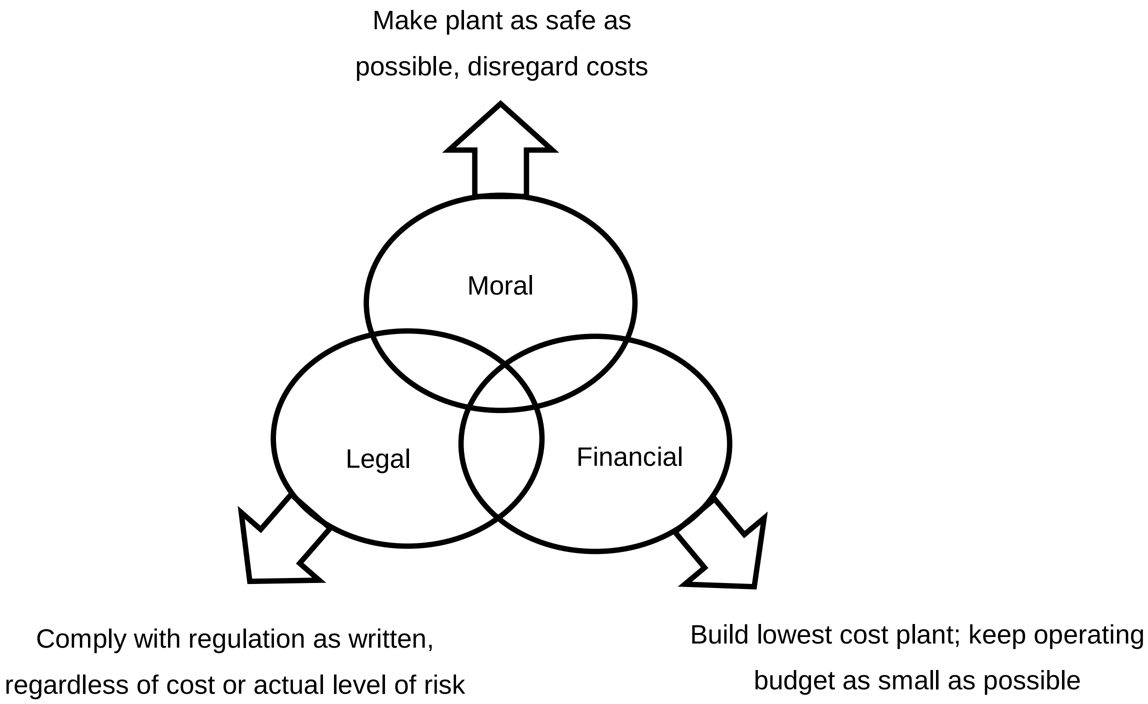


Figure 6. Risk management responsibilities (Marszal 2001).

The easiest way to approach a definition of risk criteria is by determining a single risk level, which separates the acceptable from the unacceptable risk. Considering this, only a few countries have accepted and endorsed specific numerical values for this risk level (Kauer et al. 2002). Table 1 reviews some qualitative and quantitative criteria's that has been used by governments and industries of various countries, based on (SFK-GS-41 2004, Kauer et al. 2002, CPR18E 2005, Trebojevic 2005, Duijm 2009, HSE 1989, HSE 2004, Salvi et al. 2004).

Table 1. Comparison of individual risk criteria and methods.

Country	Qualitative evaluation	Quantitative evaluation [1/a]	Additional information
Netherlands	X	10^{-5}	Existing process/structure
		10^{-6}	New process/situations
Switzerland	√	10^{-5} - 10^{-6}	Cantonal regulations
UK	X	10^{-6}	Broadly acceptable level of risk
		10^{-5}	Risk has to be reduced to the level As Low As Reasonably Practicable (ALARP)
USA	√	$4 \cdot 10^{-4}$	"de manifestus risks" from regulatory (supervisory) authority or defined by enterprises for itself (have an by influence on insurance)
Denmark	√	10^{-6}	exceeding approx.
France	√	10^{-5} - 10^{-6}	… in almost the same way as in the Netherlands
Belgium	√	10^{-5}	Flanders (region of Belgium) commercial activities permitted outside the establishment's boundary line
Germany	√	X	The unofficial value is 10^{-5} - 10^{-6} [1/a] which is not part of the national legislation (SFK-GS-41 2004)
Finland	√	X	3 zones qualitative catergories (safety Technologys Authority TUKES)
Hungary	√	10^{-5} - 10^{-6}	… in almost the same way as in the Netherlands
Czech Republic	√	10^{-5} - 10^{-6}	… in almost the same way as in the Netherlands
Russia	X	10^{-6}	required in National level by orders

3.3 Summary

"[…] it is strictly necessary to properly understand which risks have to be measured and the acceptance criteria that should be used to get external (authorities, public, etc.) and internal (management, operation department, inspection, department, financial department, etc.) acceptance. This should be decided at the earliest stage of the risk-based decision-making process […]. Any actions taken and the results which follow must be based on these criteria. It should be clear that there is a difference in using risk assessment to minimize the expenditure on maintenance and in using it to reduce overall safety, health and environmental risks for the personnel and the public, without overspending" (Kauer et al. 2002).

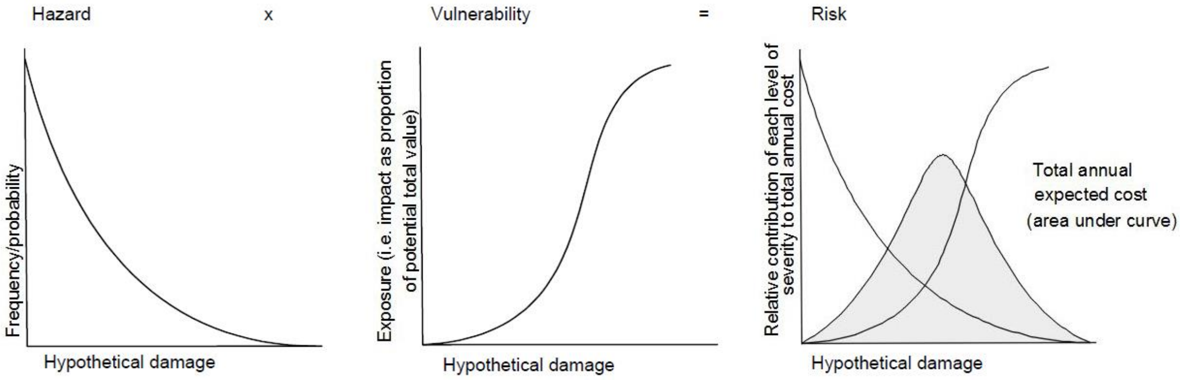


Figure 7. Dependences between hazard, vulnerability, damage, risk and as a result the possible total annual expected costs. Adapted from (Coburn et.al. 1992).

To review the qualitative criteria which can be evaluated to determine what amount of risk can reasonably be tolerated some recommendations are made. These criteria can fulfil requirements regarding:

- Analysis and statistics of accidents
- Consistency, proportionality and transparency
- All accident possibilities
- Specific safety measures of the establishment.

Every country has to determine its own value of acceptable risk criteria according to the national regulations. As a first step the real figures of the accidents have to be considered and they must be adapted and optimized after a certain time. This should be applied individually. Based on (table 1) this dissertation uses as an acceptable risk criterion value of $1 \cdot 10^{-6}$ per year.

4 Risk analyses in explosion and fire protection

In the area of CPI the objectives of risk analyses studies can be different. There are numerous qualitative, semi-quantitative and quantitative methods, subjacent the deterministic, heuristic (indexing) and probabilistic methods, which are used in CPI, e.g. in the field of fire protection these three methods are distinguished and classified according to (NFPA 551 2007). In last decades different methods have been developed for risk assessment. They can be divided in applications to support the risk assessment for buildings and applications for chemical facilities. In most cases these applications evaluate the risk only for fire protection. Risk from a possible explosion scenario is evaluated only for chemical facilities. Further presented literature research gives an overview about the findings of comprehensive survey of methods and applications.

4.1 Survey of applications for explosion and fire risk assessment in buildings

4.1.1 Quantitative methods

The surveys of (Leksin et al. 2014, Leksin et al. 2013, Mock et al. 2012), give a first impression of risk related application programs and services in fire protection as already offered by, e.g. engineering companies. The findings of this survey shrink to a manageable amount of applications following a certain method, when concentrating solely on risk assessing approaches:

- CRISP (UK) "… is a Monte-Carlo model of entire fire scenarios. The sub-models, representing physical 'objects', include[ing] rooms, doors, windows, detectors and alarms, items of furniture •...•, hot smoke layers and people. The stochastic aspects include starting conditions, such as windows and doors open or closed, the number, type and location of people within the building, the location of the fire and type of burning item" (Fraser-Mitchell et al. 1993). The fire and smoke spread are simulated by a two layer zone model. The simulation uses a variable time step in order to achieve maximum efficiency while still maintaining a numerically stable solution.

  And CRISP2 (UK) … fire zone model in which people are represented as individuals. "The list of object classes in CRISP2 includes: items of furniture, hot gas layers, cold air layers, vents between rooms and leading to the outside, walls, rooms, smoke detectors and occupants. It is based on object oriented programming techniques. It means that a system can be treated as a collection of objects. The objects usually correspond to a physical component of a real-world system. A section of the program, which defines the object's behaviour in response to input data, represents each object. The objects may interact in many ways, depending on the mutual exchange of information. Thus, the system is complex due to the large number of interactions occurring simultaneously" (Björkmann et al. 2011).

- FIERAsystem (Canada) "…is a computer model for evaluating fire protection systems in industrial buildings. The model has been developed as a tool to assist fire protection engineers, building officials, fire service personnel and researchers in performing fire safety engineering calculations. It can be used to conduct hazard and risk analyses, as well as to evaluate whether a selected design satisfies established fire safety objectives. … is primarily designed for appliance in warehouses and aircraft hangars, it can be modified for application to other industrial buildings" (Benichou et al. 2005).
- FiRECAM (Fire Risk Evaluation and Cost Assessment Model) (Canada) developed by The National Research Council of Canada (NRCC) in collaboration with Public Works and Government Services Canada (Dutcher et al. 1996) "…calculates the expected number of deaths and fire losses. These values are then combined with the probabilities of occurrence for the fire scenarios to obtain the following two decision-making parameters: expected risk to life (ERL) … and fire cost expectation (FCE)" (Hadjisophocleous et al. 2004).
- AssessNET. Fire Risk Assessment Module: "… allows to split the workplace into different zones […]. Generic questions allow to answer in a yes / no format and AssessNET finally identifies the corrective remedial actions that need to be taken." (AssesNET).
- COSSH Assessment Software: This "Risk Assessment Software is used to help companies to manage Health and Safety and fire safety. It can also be used to help remain compliant and to manage environmental health and safety and assess fire risks. Apart from the obvious safety implications this can also be important for insurance purposes" (COSSH 2013).
- TAM: "… is a web-based, flexible and scalable Health and Safety management system …". The company offers templates, e.g. in the areas of

“Health and Safety Risk Assessment” namely “Fire Risk Assessment Template, Fire Safety Policy Template, Fire Precautions and Maintenance”. (TAM Software Ltd. 2007).

- Synergi Life Risk Management “…provides a scenario-based evaluation of risk level as a function of likelihood of occurrence and potential severity of impact towards the organisations objectives.” (DNV 2012).

These methods seemingly show the current practice in the area of quantitative risk assessment in fire protection as all of them use the risk term. However when looking at details, the approaches are restricted to hazard evaluation purposes. Enterprises often apply the risk terminology in a market-oriented manner whereas a clear definition of a risk remains rather fuzzy especially to the public. In this respect, Synergi Life Risk Management stays a risk assessment approach without a doubt. Another application program with reference to risk is:

- FRAME (Fire Risk Assessment Method for Engineering). The application program is used to define a “…fire safety concept for new or existing buildings”. “…one can calculate the fire risk in buildings for the property and the content, for the occupants and for the activities in it.” “ … The Fire Risk for the building and its content is defined as the quotient of the Potential Risk P by the Acceptance Level A and the Protection Level D”. (FRAME 2013).

Hence, the FRAME approach is not in concordance with the common risk definition. The survey also yields a tool basing on Bayesian approaches:

- AgenaRisk is a “Bayesian network and simulation software for risk analysis and decision support” It “… supports both diagnostic and predictive reasoning about uncertainty using risk maps, otherwise known as Bayesian networks” (AGENA 2012).

An additional comprehensive survey of computer models for fire and smoke can be found in (Stephen et al. 2003). But they cannot be used in the field of CPI. Moreover for the majority of the presented methods the auditor needs an appropriate training in the use of this application program.

In the end it is difficult to come to a final conclusion about possibilities of fire protection risk assessment applications. The understanding of risk terms as well as fields of operation vary significantly and, hence, comparable results cannot be taken for granted. One of the best examples is FIERAsystem and FiRECAM which provide several calculation options, which allow the user to conduct a risk analysis. As described in (Benichou et al. 2005) “if information on the probabilities of different fire scenarios occurring is available and the reliabilities of fire protection systems are known, then a full risk assessment can be conducted using information from the hazard analyses of all of the possible fire scenarios.” If it is not possible, the computer model uses only the “Life Hazard Model” for the calculation of the time-dependent probability of death, based on the probit function.

4.1.2 Indexing methods

Where the strict quantitative analysis of risk by probabilistic methods is difficult or impossible, analysts appreciate fast heuristics. Such methods are fire risk indexing, performance-based codes and scoring methods (Hall et al. 2008, Watts 2002). However it should be noted that these methods are only practical when carrying out a fast analysis at the level of fire protection equipment, as well as to determine the necessity of additional fire prevention measures.

The literature survey also shows the current practice in the area of indexing point scheme audits:

- Dow Chemical Method – developed by The Dow Chemical Company (USA) “… provides a simple method of rating the relative acute health hazard potential to people in neighboring plants or communities from possible chemical release incidents. Absolute measures of risk are very difficult to determine, but the CEI system will provide a method of ranking one hazard relative to another. It is not intended to define a particular design as safe or unsafe.

  The CEI is used:
    - For conducting an initial Process Hazard Analysis (PHA).
    - As a screening tool for further study
    - In Emergency Response Planning

It is a simple method for predicting dispersion of vapors/gases from process leaks, and the Index is used as part of Dow Risk Assessment” (Dow Chemical Method 2013). For a detailed description see (Chemical exposure index 2006).

- FRIM (Fire Risk Indexing Method) for Multistory Apartment Buildings. This method adjusts fire-prevention systems of wooden houses by comparison of an index of fire risk with a similar index for buildings with nonflammable bearing designs. This method is in fact a method of hazard assessment as no likelihoods are considered (Karlsson 2002).
- FSES (Fire Safety Evaluation System) evaluates the overall level of the fire safety of buildings. It provides means of comparing the effectiveness of proposed improvements by producing a comparative baseline and shows the relative gain in fire safety for proposed improvements (NFPA 101A).
- SIA 81 or Gretener method and its modifications “… is used to evaluate and compare the level of fire risk of alternative concepts by grading the elements of a building and their performance. The grading factors are claimed to be based on expert knowledge, a large statistical survey and tested by a wide practical application. The calculated risk is compared to the accepted risk, where the latter is a function of the number and the mobility of the persons involved and of the location of the relevant fire compartments within the building” (Larsson 2000). Methods like, ERIC - Evaluation du Incendie par le Calcul (Cluzel et al. 1979), Fire Risk Assessment Method for Engineering (FRAME 2013) etc. are modifications of SIA 81.

The literature survey testifies that probabilistic and indexing methods are beneficial applications, which take their own place in the range of approaches to a problem with regard to QRA. However when carrying out the application the auditor needs a profound expert knowledge about the individual requirements of the industrial branch in question. The advantages and disadvantages of the presented methods are summarized in the next table 2:

Table 2. Comparison of risk assessment applications for buildings.

Methods	Consider the risks	Consider the hazards	Regard to fire risk	Regard to explosion risk	Potential applicable in CPI	Semi-quantitative (SQ) or heuristic (Indexing) (HI)
CRISP+CRISP2	±	+	+	-	±	SQ
FIERAsystem	+	+	+	-	+	SQ
FIRECAM	±	+	+	-	+	SQ
AssessNET	-	+	+	-	-	SQ
COSSHAssessment Software	±	+	+	-	±	SQ
TAM	±	±	+	-	±	SQ
Synergi Life Risk Management	+	+	+	±	+	SQ
FRAME	-	+	+	-		SQ
Agena Risk	±	+	+	-	+	SQ
Dom Chemical Methods	±	+	+	+	+	HI
FRIM	-	+	+	-	-	HI
FSES	-	+	+	-	±	HI
SIA81	±	+	+	-	+	HI

The summary shows that these methods are only applicable to fire risks and do not consider explosions risks. Next chapter gives an overview about the survey of applications for chemical facilities, where the explosion and fire risks are considered.

4.2 Survey of QRA applications for chemical facilities

If the risk analyses for chemical facilities are considered, QRA is only one of several inputs to the decision-making process. It depends on the questions which aims are pursued the enterprise and how they should be balanced with the engineering judgement and company values. There is a range of different well known methods in the qualitative approach, such as the check lists (Giannini et al. 2006), the Hazard and Operability analysis (HAZOP) (Lawley 1974), Failure Mode and Effect Analysis (FMEA) (NUREG/CR-2815 1983) and more overs described in (ISO/IEC 31010 2009, Lewis 2005). Approaches concerning the consequence and frequency assessments are commonly used without a full QRA study to guide engineering solutions, hazard identification and control, safety system design, emergency planning etc. However CPI consider also the use of QRA to attempt and specify the estimation of absolute risk level of a system, plant or the effects on the facilities or processes, which could have an impact on the environment, business markets or other areas of interest. In order to continuously improve safety engineering in general, it is a major task of industry, insurance and academia to build up a sound knowledge base about the potential accident scenarios. In order to be able to do this, a number of approaches exist, which support an enterprise (auditors) in the QRA for chemical facilities. The advantage is that the QRA for CPI, as a risk assessment method, enhances systematic identification and evaluation of possible accidental events, e.g. physical effects of accidental releases of hazardous materials, including their causes and consequences. ”QRA has over the years established itself as a standard component of the risk management programme for offshore” (DNV GL 2016) and onshore facilities and in the field of CPI.

The summary of the available application programs is based partially on the paper (Lewis 2005), which “presents the findings of a comprehensive survey of [application programs] currently available for undertaking QRA for onshore and offshore oil and gas facilities” (Lewis 2005). As (Leksin et al. 2013) have already stated, the number of commercial QRA assisting application programs is surprisingly small and from an initial list of applications (over 80 application programs) in the field of CPI, only a handful of application program products could undertake full QRA, what is confirmed auxiliary with the specified paper (Lewis 2005).

“From this list, a subset of ‘leading‘ software providers was selected based on criteria including: user base, validation of the software model, ease of use and resources required, quality of product support, and continuous improvement” (Lewis 2005). From the methodological point of view, three approaches adopted for risk assessment can be distinguished. A total of 19 consequence, 19 frequency and 8 QRA leading applications were selected and presented in table 3 from (Lewis 2005) with addition of some Russian approaches:

Table 3. Leading application programs.

Methods	Consider the risks	Consider the hazards	Regard to fire risk	Regard to explosion risk	Potential applicable in CPI	Semi-quantitative (SQ) or heuristic (Indexing) (HI)
AERMOD/ISC PRO (C)	+	+	+	+	+	SQ
AUTOREAGAS (C)	+	+	+	+	+	SQ
BLOWFAM (F)	±	+	+	+	+	SQ
CAMEO (ALOHA) (Q)	+	+	+	+	+	SQ
CAFTA (F)	±	+	+	+	+	SQ
CANARY (C)	+	+	+	+	+	SQ
CAPTREE (F)	±	+	+	+	+	SQ
CARA (F)	±	+	+	+	+	SQ
CEBAM (C)	+	+	+	+	+	SQ
CIRRUS (C)	+	+	+	+	+	SQ
COLLIDE (F)	±	+	+	+	+	SQ
CRASH (F)	±	+	+	+	+	SQ
DAMAGE (C)	+	+	+	+	+	SQ
DDMT (F)	±	+	+	+	+	SQ
EFFECTS (C)	+	+	+	+	+	SQ
FAULT & EVENT TREE (F)	±	+	+	+	+	SQ
FAULT TREE+ (F)	±	+	+	+	+	SQ
FAULTREASE (F)	±	+	+	+	+	SQ
FIREX (C)	+	+	+	+	+	SQ
FLACS (C)	+	+	+	+	+	SQ
FRED (C)	+	+	+	+	+	SQ
FT PROFESSIONAL (F)	±	+	+	+	+	SQ
HAZ FIRE/EXPLOSION (C)	+	+	+	+	+	SQ
HAZ PROFESSIONAL (C)	+	+	+	+	+	SQ
KAMELEON FIREX (C)	+	+	+	+	+	SQ
LEAK (F)	±	+	+	+	+	SQ
LOGAN F&ETA (F)	±	+	+	+	+	SQ
NEPTUNE (Q)	+	+	+	+	+	SQ
OILMAP (C)	+	+	+	+	+	SQ
OSIS (C)	+	+	+	+	+	SQ
PHAST (C)	+	+	+	+	+	SQ
PLATO (Q)	+	+	+	+	+	SQ
PSA PROFESSIONAL (F)	±	+	+	+	+	SQ
RISKCURVES (Q)	+	+	+	+	+	SQ
RISKMAN (F)	±	+	+	+	+	SQ
RISKPLOT GRAPHIC (Q)	+	+	+	+	+	SQ
RISKSPECTRUM (F)	±	+	+	+	+	SQ
SAFETI (Q)	+	+	+	+	+	SQ
SAPHIRE (F)	±	+	+	+	+	SQ
SCOPE (C)	+	+	+	+	+	SQ
SHEPHERD (F)	±	+	+	+	+	SQ
TOXI+Hazop (F)	±	+	+	+	+	SQ
TOXI+Risk (Q)	+	+	+	+	+	SQ
TRACE (C)	+	+	+	+	+	SQ
СИТИС: Блок+ 3.00 (C)	+	+	+	+	+	SQ
СИТИС: Спринт 1.50 (Q)	+	+	+	+	+	SQ

C = Consequence modelling; F = Frequency assessment; Q = Quantitative risk assessment

The consequence approaches (table 4) can be used in the first step and shows the consequence area for lethal effects and serious injuries resulting from the scenarios assessed (hazard identification and probability calculation of the injury based on the probit function).

Table 4. Leading Consequence approaches (Lewis 2005).

Empirical models
FRED
PHAST
TRACE
CIRRUS
EFFECTS
CANARY
HAZ PROF
Release, fire, explosion and gas dispersion

The analyses of frequency are not often used in the CPI due to absence of frequency and/or probabilities data of several system components.

QRA approaches tend to concentrate on determining risk for facilities and plants. In the last years the majority of countries are starting to use active QRA based methods to quantify risk. The problem of the resulting risk criteria is that they are often not even transparent or traceable. The technical leaders of the QRA approaches are presented in the table 5:

Table 5. Leading QRA approaches (Lewis 2005).

Onshore QRA
RISKCURVES
EFFECTS
DAMAGE
RISKPLOT GRAPHIC
SAFETI

Although, EFFECTS (TNO 2015) is a one of the leading consequence and QRA approaches, advantages and disadvantages are even discussed by (TNO 2015) itself in (Boot 2013):

“TNO has been working on a complete revision of its QRA tool, and much effort has been put in the usage of a standardized method to obtain transparent, traceable results in terms of the resulting quantified risk values itself. Unfortunately, while comparing the results with other [application programs], it appeared that substantial differences could be associated with several steps of the calculation, due to differences in the consequence models used, the damage (lethality) relations applied, the typical governing parameters used in the models, and last but not least, the risk calculation method itself."

It should be noted that due to the absence of the description of the Russian approaches in English, their comparisons with other worldwide application programs was not found in the English literature survey, as SITIS (SITIS 2015) based on (GOST 12.1.004-91 1992) and TOXI+ (TOXI 2015) based on (RD-03-26-2007 2008).

4.3 Potential of the available QRA applications

The synopsis of the literature survey is that the applications, which support the risk assessment for buildings, only consider fire scenarios. This means that the process, which allows the possibility of an explosion scenario in a building, cannot be evaluated by applications mentioned in the previous chapters. The possibility of using these applications for the evaluation of the fire risk of buildings in CPI is not excluded. Explosion risk is not considered by such application programs. Additionally the findings show that only a few of the presented applications for chemical facilities are suitable for a qualified risk assessment. A combination of approaches, which could evaluate the individual risk and consequences, does not exist. Therefore, a methodological gap in the field of explosion and fire risk assessment for CPI will be covered by the developed semi-quantitative approach, presented in this dissertation.

5 Objective target

The primary aim of this dissertation consists in the development of a new method, which will be based on the combination of semi-quantitative and indexing procedures, for the calculation of the individual risk in CPI in the field of EFP. The method will evaluate the explosion and fire risks. Also the method should be simple to use for the auditor, should not demand special training courses and be fast in respect of calculations. Such a semi-quantitative approach gives a quantitative numerical value as a calculated result, which can be used for different aims. One of them could be, e.g. comparison with the acceptable risk criteria for the concrete audited enterprise or an audited area of the enterprise to define the acceptability or non-acceptability of the individual risk.

Chapter 4 describes the existing methods and application programs as well as their benefits and drawbacks. Thus, the gaps in the calculation of the individual risk in CPI in the field of EFP were identified.

The results of this research lead to the conclusion that the method developed in this dissertation has to focus on two areas: on a semi-quantitative approach for individual risk assessment and a quantitative approach for consequence assessment. However these areas have to be considered separately, that means that the developed method has to carry out the assessment of the risk in two phases. This is summed up in the following table 6:

Table 6. Structure of the developed method.

Results	Semi-quantitative approach for individual risk assessment	Quantitative approach for consequence assessment
Calculated individual risks	The “actual” individually risk is calculated based on a new developed risk equation	Does not consider (in the right sense) the classical terminology of risk, but rather the evaluation of dangerous phenomenon from a fire, explosion, fireball or tourch fire: this according to a probit function
Assessment of scenarios	Due to the assessed “actual” risk, a worst case and also best case scenarios are considered in the calculation	Due to the evaluation restriction of the proportions, or respectively based of the result from an event, e.g. an explosion which already accrued, those data will be considered in the consequence according the calculation of the probit function. This is viewed as the worst case scenario (if-when…)
Aspects which are considered in the calculation	• time factor • safety index • safety coefficient • frequencies of a fire for different enterprises • weighting factors (for safety measures & hazards)	• material characteristic • process characteristic • based on an existing Russian approach which is then implemented in MS Excel prototype tool • comparison with the one of the world leading tools “TNO Effects” to proof (argument) the advantages of the new developed MS Excel prototype tool • calculation of the consequences based on probit function with the consideration of the impacts/effects parameters of the scenario

Such an extended method contributes to enhance the scientific knowledge concerning significant phenomena in terms of risk. It serves the development of concepts as well as principles for the assessment and the assessment of risks.

In the end of the developed method, two MS Excel prototype tools are additionally developed. This leads to a better visualization of the risk calculation process and a simpler and at the same time automatic calculation of the individual risk and consequences as well as of hazard and safety factors.

With other words the concept of the procedure of the individual risk and consequence assessment can be introduced with the following (fig. 8):

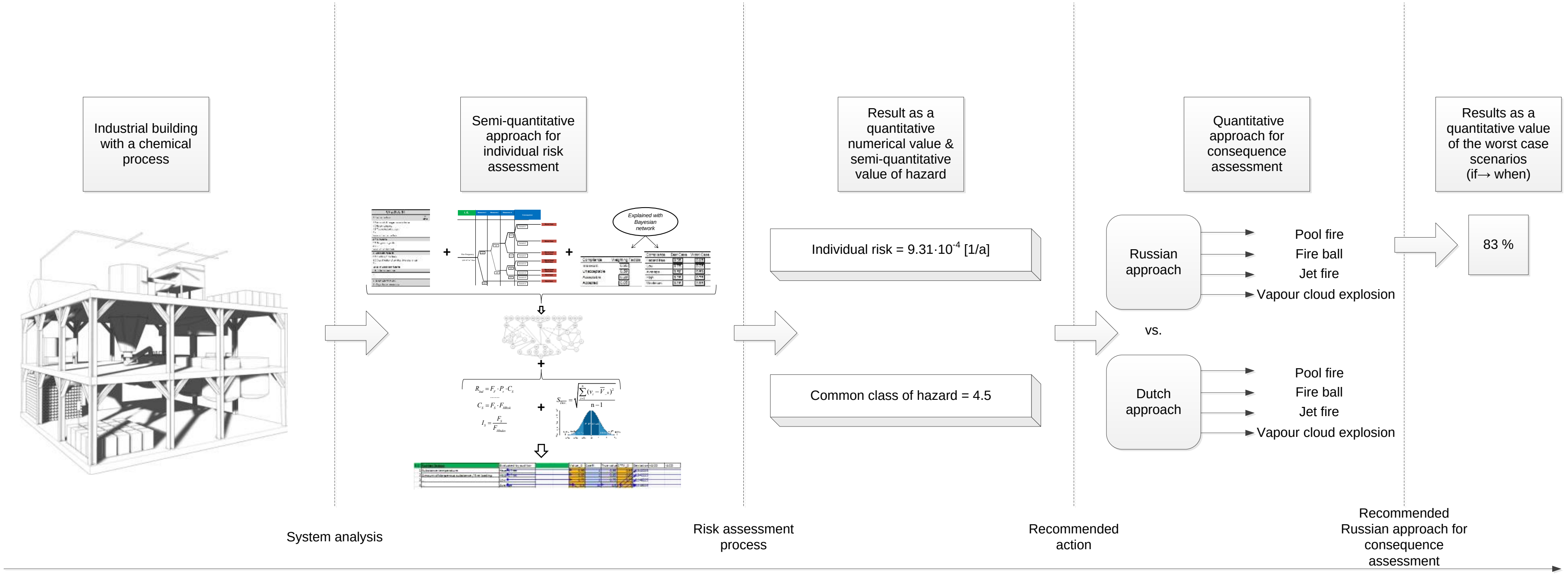


Figure 8. Procedure of individual risk and consequence assessment of the developed method.

6 Principle of risk assessment processes in the extended semi-quantitative approach

The academia and the practitioners follow approaches of their own. The academia problem-solving approach pursues universality of (risk analysis) methods in the first instance while the practitioners' approaches concentrate on practical convenience. However the academia and the practitioners pursue also the same aim in the risk assessment process:

"... [an] application-oriented interpretation considers risk as probability of coincidence (i.e. areal, temporal) or completion of a functional chain: occurrence of danger → causing hazard → effecting impairment → resulting harm. It also takes into account the effectiveness and availability of both types of essential risk reducing measures. Measures to safeguard antagonise the hazard, whereas measures to protect work against the vulnerable subject (i.e. person, building, facility and environment). This context is outlined in (fig. 9)" (Mock et al. 2012):

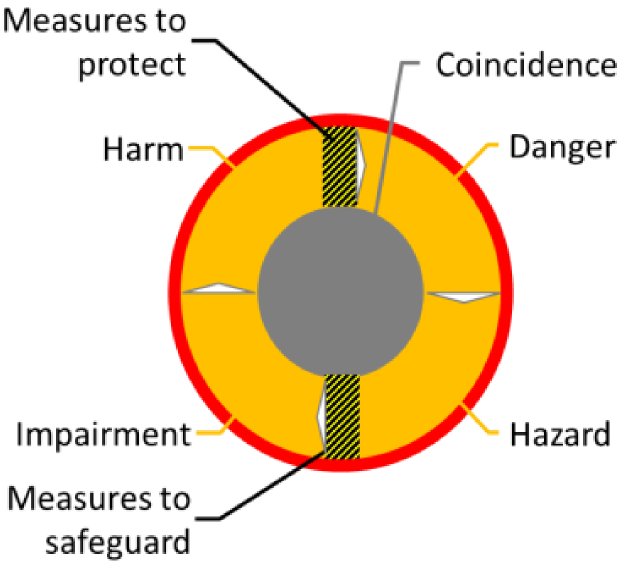


Figure 9. Interaction of functional risk chains and risk reducing measures.

Thus, the developed method follows the risk management process of (ISO 31000 2009) with some adjustments concerning the risk assessment process (fig. 11):

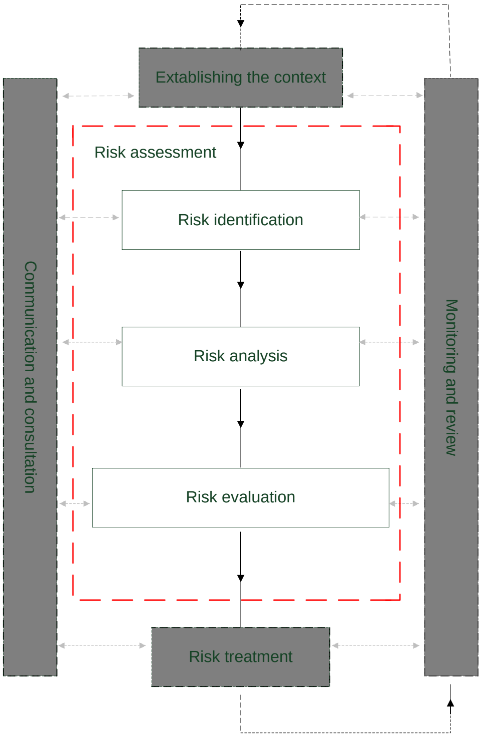


Figure 10. Risk management process (ISO 31000 2009).

The points “communication & consultation” and “monitoring & review” are not the object of this work and are not discussed. The risk assessment area (fig.11) is considered in the developed method and support the reader step-by-step through the descriptions in the following chapters.

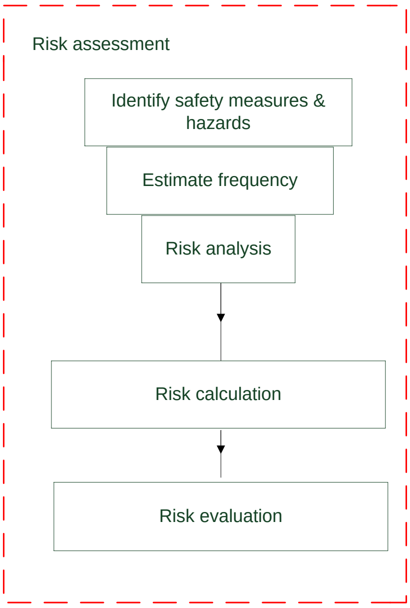


Figure 11. Risk assessment process.

7 Extended semi-quantitative approach for individual risk assessment

By consideration of an individual risk assessment in the CPI with regard to the EFP the auditor faces an industrial building with different plants and devices, pipelines, reactors with unit processes and protection facilities (fig. 12). Hazards are primarily posed by hazardous substances which are able to change their substantial properties depending on the processes and the conditions of the respective unit processes.

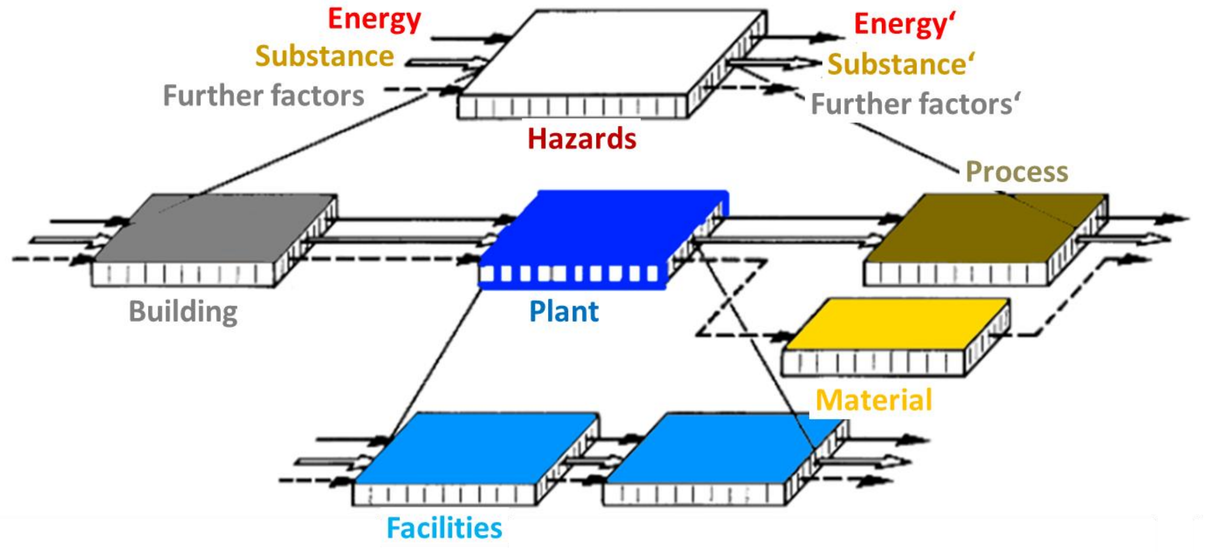


Figure 12. Forming of a functional structure by splitting up a whole function in part functions modified by Leksin-Barth (Pahl 2007)

To ensure a better traceability of the issue to be presented, the next (fig. 13) illustrates an example of a paint manufacturer who has to carry out a risk analysis.

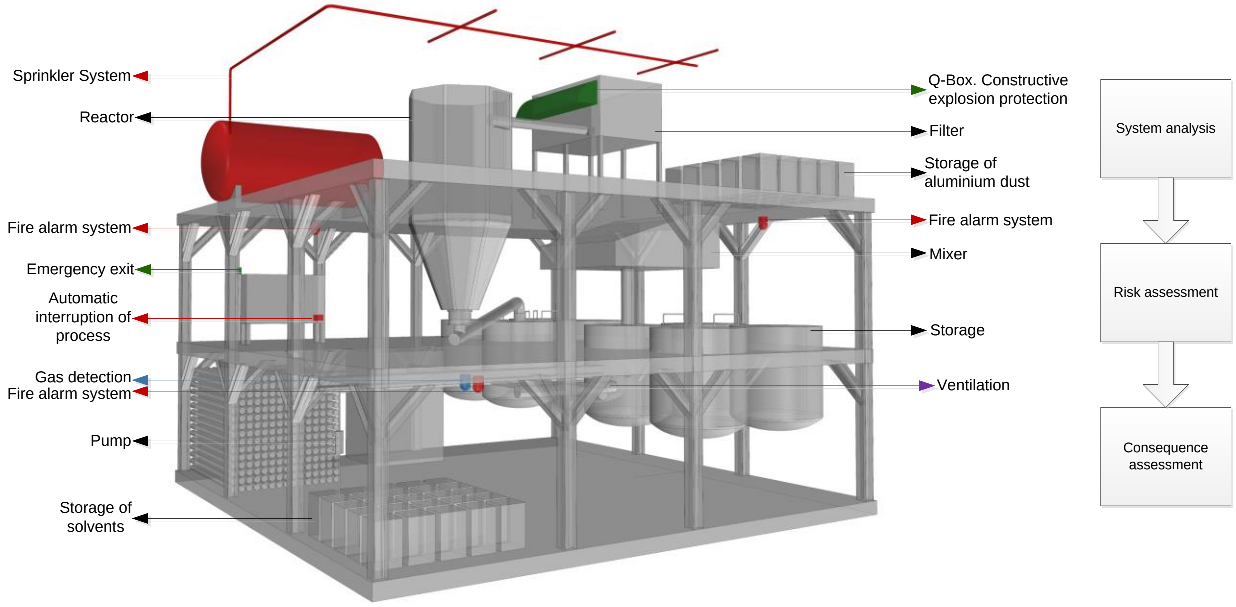


Figure 13. Example of a risk analysis by a paint manufacturer

The building, processes, plants etc. are components of a system which have to be considered during the risk assessment. They are the most important elements concerning risk analysis. It is the aim to carry out the risk and hazard assessment of the paint manufacture production as a first step, and secondly apply a consequence assessment of the separate parts of the whole system.

This chapter describes the developed method which is based on the mixing of semi-quantitative and indexing approaches for the calculation of an individual risk in the field of EFP. The concept is structured in the following steps:

- short introduction of the problem identification in the field of the usage of the Event Tree Analysis (ETA) in risk assessment, advantages and disadvantages of the involvement
- development of the semi-quantitative approach in the extended method
- development of the indexing approach in the extended method
- connection of both approaches and development of the extended method
- gradual description of the risk calculation steps
- summary of the developed semi-quantitative method for individual risk assessment

7.1 Problem identification

“As mentioned […], EFP audits are often compliance checks in order to judge the condition of fire protection equipment on the base of (e.g. national) fire regulations. However QRA approaches are also needed to prioritise safety optimisation measurements.

The simultaneous consideration of operating and non-operating safety barriers within a single diagram finally gives a pronounced risk characterisation beyond pure hazard evaluation. This comprehension also shifts the audit from a pure expert judgment to proven probabilistic risk assessment approaches. Hence the ETA enriches the audit process.

However pure ETA method is not a [risk assessment] approach and has to be adjusted to the risk [assessment] principles. The way out is to define generic scenarios as typical in EFP. Figure 14 shows a simplified generic event tree” (Leksin et al. 2013):

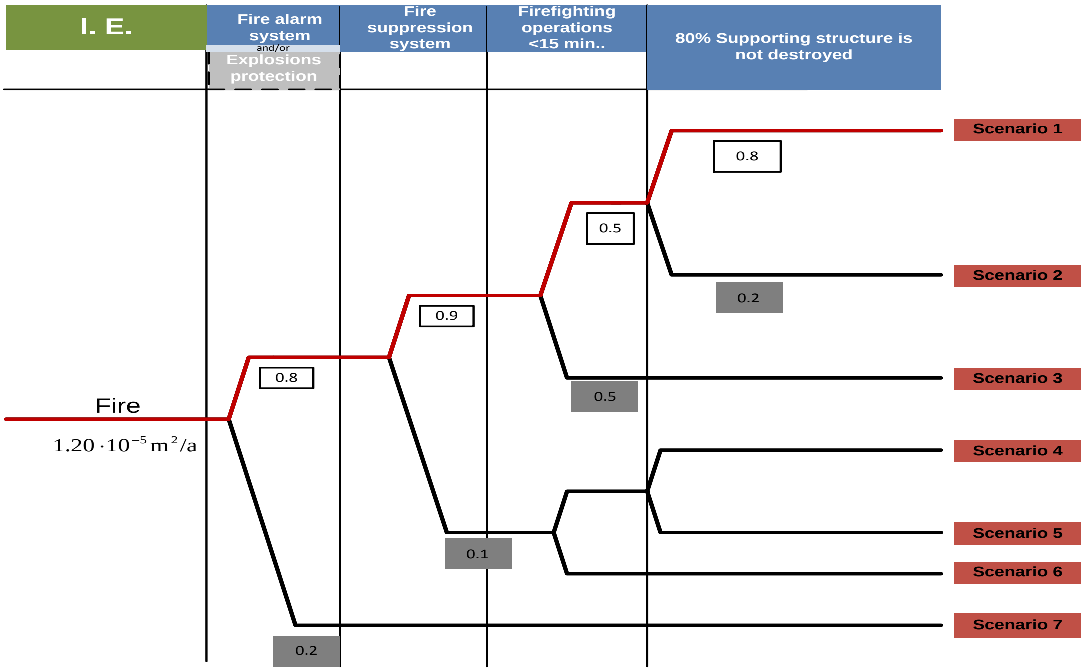


Figure 14: Simplified ETA (I.E.: initiating event) (Leksin et al. 2013).

The use of this knowledge base as well as the introduction of pre-defined criteria (e.g. weighing factors) to generic event trees allows to optimize the risk evaluation toward of a semi-quantitative field.

7.2 Semi-quantitative approach

In practice, the common QRA approaches are unable to cope with individual risks on a level of needful, e.g. for business and insurance purposes. Taking up the authors' preliminary studies (Leksin et al. 2013, Mock et al. 2012) a semi-quantitative approach is used and integrated within a common check list approach. Hazards and safety measures are considered and developed in form of an alternative check list. Attachment "Example of a check list survey" gives an example of how such a check list can look like and discusses the problem of its formulation.

The check list contains indicators of hazards: explosion hazards, fire hazards and factors (designated as: further factors) which have influences on the explosion and fire hazards or are interconnected with these, designated as macro parameters. Every macro parameter has a number of micro parameters, which are evaluated by an auditor. The same applies for the safety measures. This context is outlined in table 7.

Table 7. Check list of parameters.

1. Further factors
1.1 Amount of dangerous substance
1.2 Room category
1.3 Technological process
1.x …
Value of Further factors
2.Fire hazards
2.1 Dangerous goods
2.y …
Value of Fire hazards
3. Explosion hazards
3.1 Instability/Reactivity
3.2 Classification of combustible substances
3.z …
Value of Explosion hazards
I. Architects measures
I.I
I.II
II. Technical measures
III. Organization measures

This kind of check list characterizes all scenarios of an event tree, which enriches the risk assessment process and takes into account the worst and best case paths of this ETA, as shown in (fig. 15):

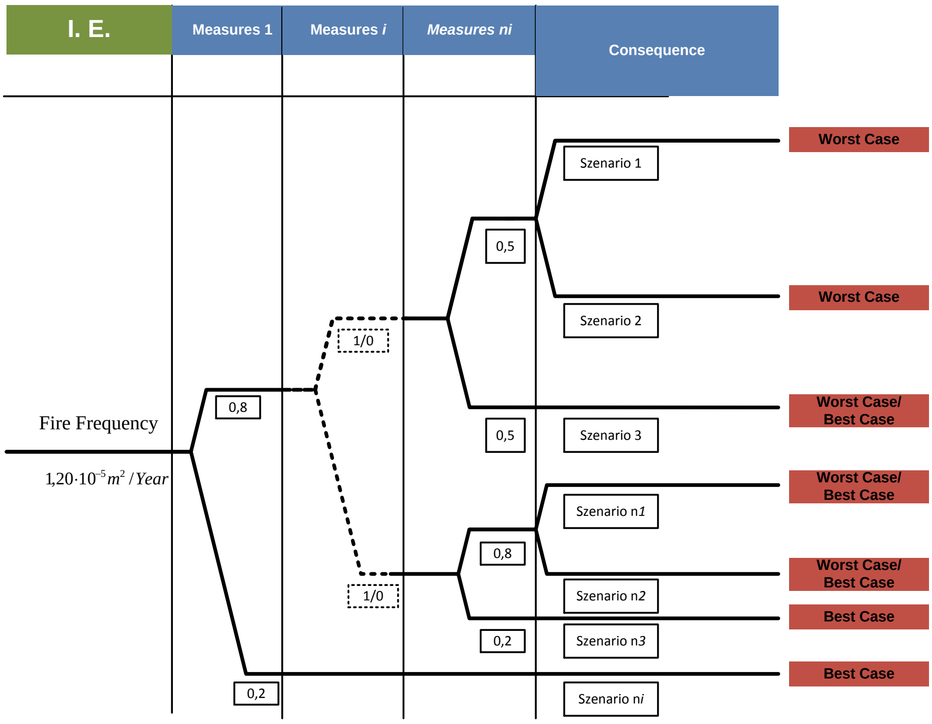


Figure 15. ETA in the audit process (I.E.: initiating event).

The next step in the semi-quantitative approach is the evaluation of the macro and micro parameters (hazards and safety measures). For this, determined weighting factors are used. The weighting factors of table 8 are used for safety parameters:

Table 8. Weighting factors for safety parameters.

Compliance	Weighting Factors
Irrelevant	0.95
Unacceptable	0.50
Acceptable	0.20
Accepted	0.05

Every micro parameter is assigned a compliance level by the auditor. However the weighting factors are not mentioned explicitly. Furthermore the weighting factors are defined and fixed, thus the auditor cannot change the features. The given values of the weightings factors mirror their respective percentage figure (e.g. if the auditor evaluates one of the micro parameter as “Acceptable”, it means that this micro parameter is secure up to 80%).

For hazard parameters (e.g. amount of dangerous substances), there are weighting factors for both, worst case and best case.

Table 9. Weighting factors for best and worst case scenarios.

Compliance	Best Case	Worst Case
Hazard free	0.95	0.05
Low	0.75	0.25
Average	0.50	0.50
High	0.25	0.75
Maximum	0.05	0.95

The weighting factors represent an important step for an objective evaluation of the calculated risk as the auditors cannot manipulate the factors.

Procedures, which give information about the risk spectrum of estimates as well as the standard deviation, are taken into account and are described in chapters 7.4.2.2 and 7.4.2.3. Due to the complexity of equations and the dependency among the factorial indicators, the mathematical context is presented in chapter 7.3 “Indexing approach”.

In addition to the weighting factors, which are used by the auditor, there are suggested correction factors (e.g. emergency exit - escape route - 0.8 and 0.2) to get more exact statements about the risk.

The dependency of hazard factors and safety measures is taken into consideration in the same way. By these mathematical combinations between factorial indicators and weighting factors of the evaluated scenario, more exact statements about the calculated risk values are possible.

In this case, the developed check list actually takes a position about the scenario and thereby about the complete event tree, which can only be visualized in form of a complex graph. Figure 16 shows, how such a graph might look like.

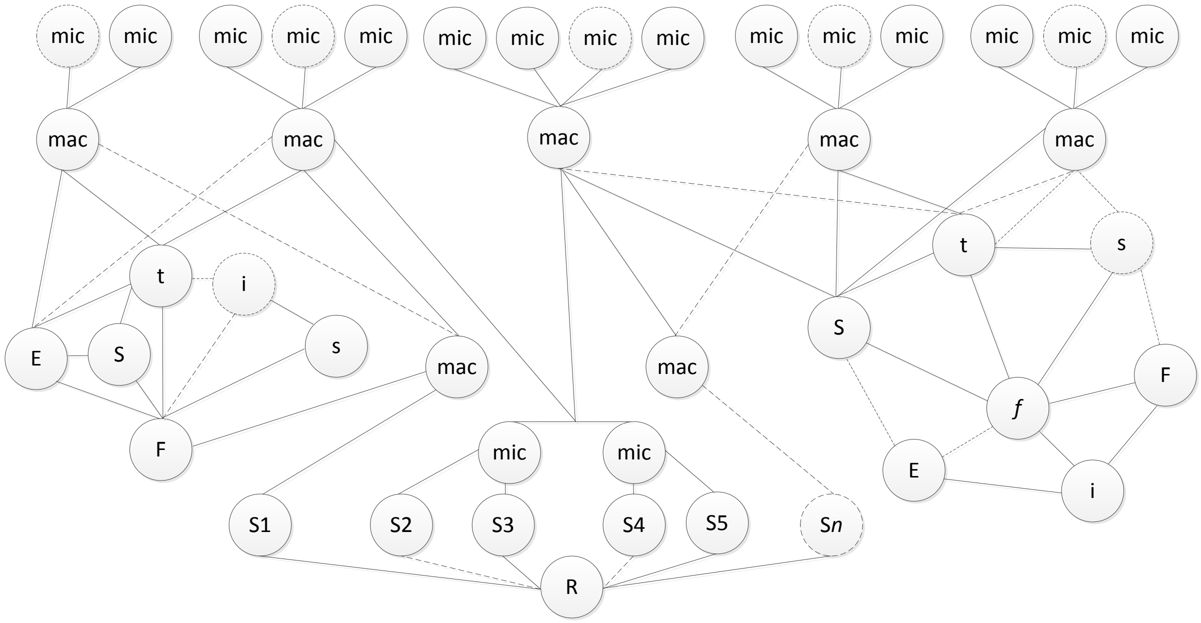


Figure 16. Schematic diagram of a risk analysis (explanation see text).

Figure 16 use the following notation: mic/mac = micro and macro parameters of hazard and safety measures; F = fire, e.g. for an I.E.; E = existing violations; t = presence of personnel; i = fire frequency of industry branch; s = substance/material (dust, liquefied gas, etc.); S = area of testing zone; S1-Sn = scenarios; R = risk.

Although, such ETA approach in a form of a complex “dynaxity” graph as well as the use of apriority knowledge gives “promising figures”, the audit still bases on ad-hoc estimates (tables 8 and 9). The components of a technical system or technological processes are interconnected. These are internally including control systems and devices linked with each other as well. Consequently, the system becomes even more complex. By means of (fig. 16), the risk assessment process must consider different possibilities, as from the side of hazards as well as from the side of actual measures. It means that the dependency of hazard factors and measures must be taken into consideration in the same way. By this combination the developed scenario can only be visualized in form of a complex graph.

Quantitative risk analysis in general lacks sufficient statistical database. In case of the offered semi-quantitative approach, which is integrated in form of a check list and evaluated by the fixed weighting factors presented in (tables 8 and 9), the lack of proof of expediency and applicability of these, has to be explained. For this the Bayesian network approach to objectivise the result evaluation of the weighting factors – as conditional probabilities – which are determined in the presented method can be used.

An example of how the expediency of the submitted weighting factors can be proved is to be found in Attachment “Possible role of the Bayesian network in the determined weighting factors” of this dissertation.

Thus, the presented combination of the approaches (check list, ETA, weighting factors) is the first step in the development of the extended semi-quantitative method (fig. 17):

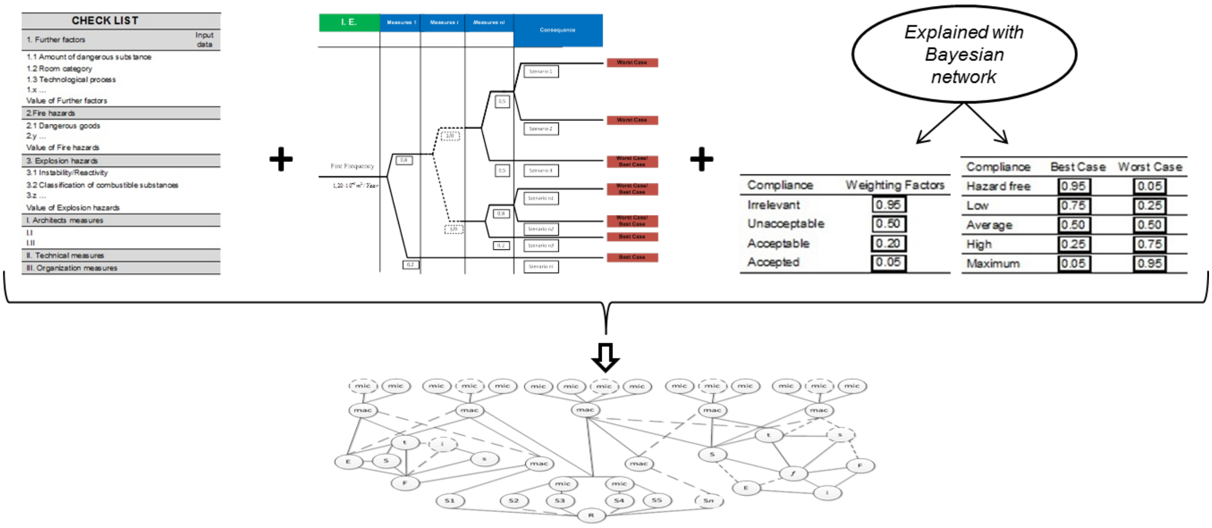


Figure 17. Stepwise development of the extended semi-quantitative method.

7.3 Indexing approach

The set of hazards and protection measures are considered as factorial indicators which define an indexing equation.

To each factorial indicator of the system, a specified number of points are attributed by rules, i.e. the assessment of a condition of the system is made from various points of view.

The common indexing method is developed to assess explosion hazards supported by factorial indicators which consider aspects causing explosions (e.g. maximum explosion pressure, upper explosive limit etc.) as well as measures to mitigate explosion hazards (e.g. gas detection system, lightning protection etc.). The calculated index of explosion risk expresses a level of explosion hazards. A level of fire hazards is calculated identically and is supported by factorial indicators which consider aspects causing fires (fire loading, ignition sources etc.) as well as measures to mitigate fire hazards (availability of fire extinguishing systems, fire resistance of design, existence of an alarm system and evacuation ways, etc.). The formal goal of the suggested method is to comprise index calculations into QRA.

By combining the risk equation $R = F \cdot C$ (i.e. risk R is a function of frequency F and consequence C of an undesired event (ISO-Guide-73 2009)) with the indexing model, the resulting equation of individual risk becomes:

$$R_{Ind} = F_F \cdot P_\tau \cdot C_S \tag{3}$$

where R_{Ind} = individual risk [1/a]; F_F = frequency of a fire at the enterprise [m^2/a]; P_τ = probability of presence of the personnel; C_S = safety coefficient.

7.3.1 Influence of the fire frequency

As mentioned in (Leksin et al. 2013), risk values are industry specific. The frequency F_F of a fire at the enterprise is derived from statistical data for the analyzed enterprise. Average values can be obtained from international statistical data and standards like (CPR18E 2005, FZ 1994). Table 10 exemplifies branches and frequencies in use.

Table 10. Fire frequencies of branches (Leksin et al. 2013).

Industry	Frequency 10^{-5} [m^2/a]	Literature
Power generation	1.20	1,14-16,19
Storage (chemical production)	1.38	1-3,4,7-12,14-16,19
Storage	9.99	1,14-16,19
Manufacturing companies	7.30	1-3,8,10,14-16,19
Chemical enterprises (synth. rubber, fiber)	2.65	14-16,19
Smelting & casting enterprises	1.70	1-3,8,10,14-16,19
Food industry	1.89	1-3,8,10,14-16,19
Metal industry	1.78	1,8,10,14-16,19

([1] CPR 18E 2005; [2] Covo 1981; [3] Lees 1986; [4] OREDA 2002; [5] 1nd Guidelines 1989; [6] 2nd Guidelines 2000; [7] Hauptmann 2003; [8] Offshore hydrocarbon 2001; [9] Spouge 2006; [10] TAA-GS-03 1994; [11] HSE-REPORT 1978; [12] Beernes et al. 2006; [13] Руководство по оценке пожарного риска для промышленных предприятий 2006; [14] GOST 12.3.047-2012 2012; [15] GOST 12.1.004-91 1992; [16] РД 03-418-01 2001; [17] FZ 1994; [18] Федеральный закон № 184 2002; [19] ППБ 01-03 2003)

7.3.1.1 Using accident databases to enhance probabilistic risk assessment

Frequency data are generally assigned using historical-statistical criteria. There is a range of different accident databases which can be used to estimate the fire frequencies of branches. Possibly in combination with expert judgment these data must be updated and adapted for every country individually.

There are some examples of different databases:

- MHIDAS (Major Hazard Incident Data Service) - is no longer updated and is no longer hosted by HSE-Health and Safety Executive (United Kingdom) (http://www.hse.gov.uk/)
- "HSE Public Register of Notice History" - complementary information at UK Health and Safety Executive, especially about major accident hazard (http://www.hse.gov.uk/pipelines/hseandpipelines.htm)
- CSB - U.S. Chemical Safety Board - Completed Investigations (http://www.csb.gov/)
- European Commission / MHAB - Major Accident Hazards Bureau (https://minerva.jrc.ec.europa.eu/en/content/f4cffe8e-6c6c-4c96-b483-217fe3cbf289/chemical_accident_analysis)
- FACTS - Failure and Accidents Technical information System (http://www.factsonline.nl/)
- ZEMA - Database Germany (http://www.infosis.uba.de/)

These databases contain information on incidents involving hazardous materials, explosions and fires in the area of CPI and so-called (in Germany) “Industry 4.0”. Each incident includes: date and place; hazards (e.g. explosion, fire etc.); material name and united nations code; incident type (e.g. fire, fireball, vapour cloud explosion); origin (e.g. process plant, store, rail tanker); general and specific causes; number of people killed, injured or evacuated and other information.

Therefore, the auditor can differentiate between industry specific frequencies or also use some data for specific plants, e.g. for storage tanks, as described in (Risk assessment data directory 2010) in combination with experiment judgments of his country.

7.3.2 Influence of the personnel presence

The calculation of individual risk needs to consider the probability of personnel presence at an endangered zone:

$$P_\tau = \frac{\tau}{24} \tag{4}$$

where τ = working time of a person [h]

7.3.3 Influence of the safety coefficient

Risk to a single person depends on a number of hazards and safety measures. The set of hazards and protection measures is considered as a variety of factorial indicators which define a function based on the indexing method. These factorial indicators are considered by the calculation of the safety coefficient:

$$C_S = F_S \cdot F_{HRisk} \tag{5}$$

where F_S = factorial indicator of safety, which depends on the safety measures; F_{Hrisk} = factorial indicator of hazard, which is dependent on the worst case path of an event tree (relative to indexing factor, which is dependent on the hazards).

Because risk considers the frequency *F* of an event and its consequence *C*, we have a scale from the best case to the worst case scenario which is also considered in ETA.

In order to consider all scenarios of the event tree and to achieve a more exact calculation of the individual risk, factorial indicators of hazards for the worst case and best case scenarios are developed. Figure 15 had shown this approach (chapter 7.2).

7.3.4 Influence of the safety factorial indicator

The influence of the safety factorial indicator F_S is

$$F_S = \overline{M}_{arch} \cdot \overline{M}_{tech} \cdot \overline{M}_{org} = \frac{1}{n}\sum_{i=1}^{n} M_{i,arch} \cdot \frac{1}{m}\sum_{i=1}^{m} M_{i,tech} \cdot \frac{1}{k}\sum_{i=1}^{k} M_{i,org} \tag{6}$$

where $\overline{M}_{arch}$ = arithmetic mean of safety architectural measures; $\overline{M}_{tech}$ = arithmetic mean of safety technical measures; $\overline{M}_{org}$ = arithmetic mean of safety organizational measures; n,m,k = number of micro parameters of architectural, technical and organizational measures respectively; i = index of summation.

7.3.5 Influence of the hazard factorial indicator

The influence of the hazard factorial indicator F_{HRisk} is

$$F_{HRisk} = \overline{H}_{fut} \cdot \overline{H}_{f} \cdot \overline{H}_{ex} = \frac{1}{x}\sum_{i=1}^{x} H_{i,fut} \cdot \frac{1}{y}\sum_{i=1}^{y} H_{i,f} \cdot \frac{1}{z}\sum_{i=1}^{z} H_{i,ex} \tag{7}$$

where $\overline{H}_{fut}$ = arithmetic mean of further factors which have an influence on explosion and fire hazards (e.g. amount of dangerous substance, room category, technological process etc.); $\overline{H}_{f}$ = arithmetic mean of fire hazards; $\overline{H}_{ex}$ = arithmetic mean of explosion hazards; x,y,z = number of micro parameters of further factors, explosion and fire hazards respectively.

As the proposed method bases on the classical risk equation, the risk decreases automatically by simple multiplication of the measure factors. Therefore, it is important to use the arithmetic mean of all micro parameters, which form the macro parameter.

7.3.6 Influence of the safety index

Parallel to the individual risk estimation the safety index I_S is calculated. Its function is to additionally assess and evaluate the calculated risk adequately:

$$I_S = \frac{F_S}{F_{HIndex}} \tag{8}$$

where F_S = factorial indicator of safety, which depends on the safety measures; F_{HIndex} = factorial indicator of hazard, which is dependent on the best case path of ETA (relative to indexing factor, which is dependent on the hazards).

The safety index is based on the classical indexing method – weighting the hazards and safety measures (which are dependent on the best case path of an event tree). As consider the spent time of the personal in the endangered area, the calculated risk can be acceptable if the probability of the presence of personnel is very small. On the other hand, the frequency of a fire at the enterprise is also small but safety measures can be unacceptable. This gives a signal to the auditor that safety measures have to be raised.

Thus, the indexing approach described above presents the next step in the development of the extended semi-quantitative method (fig. 18):

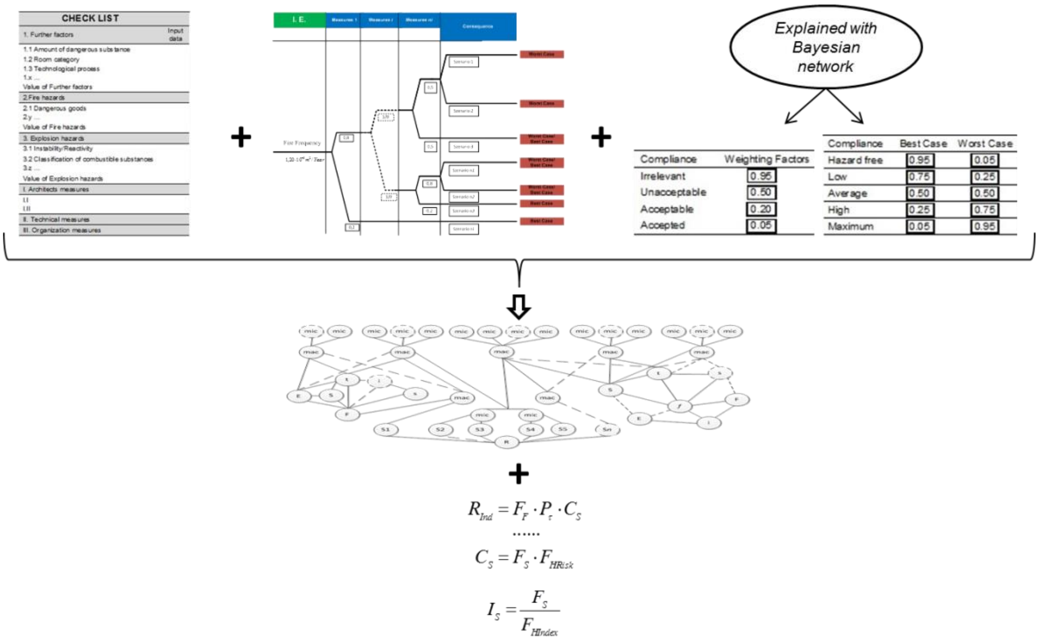


Figure 18. Stepwise development of the extended semi-quantitative method.

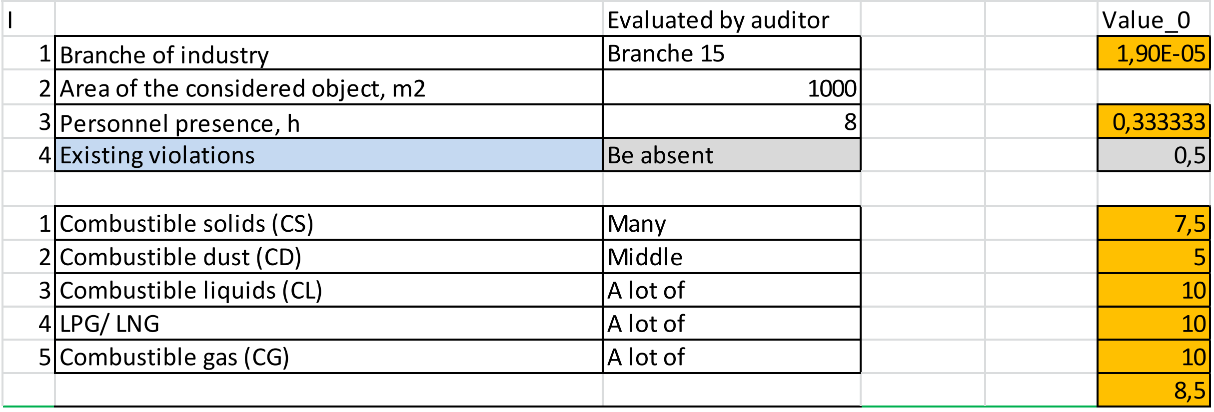
7.4 Operational application

The combination of semi-quantitative and indexing methods results in a probabilistic approach, which bases on weighting procedures. The auditor uses an input mask. First, a parameters check has to be carried out and some audit specific data are entered.

The mathematical equations that serve as the basis of risk calculation and are described in chapter 7.3 are simple, but the relationships between input and output values are not always immediately apparent. Thus, the purely textual description of the method gets complex rather rapidly.

The following chapters present the calculation example for the assessment of individual risk functions serves as an example for procedure in form of extract tables from the MS Excel prototype tool and describes the calculation step-by-step.

7.4.1 I step. Input of specific data



I		Evaluated by auditor			Value_0
1	Branche of industry	Branche 15			1,90E-05
2	Area of the considered object, m2	1000			
3	Personnel presence, h	8			0,333333
4	Existing violations	Be absent			0,5
1	Combustible solids (CS)	Many			7,5
2	Combustible dust (CD)	Middle			5
3	Combustible liquids (CL)	A lot of			10
4	LPG/ LNG	A lot of			10
5	Combustible gas (CG)	A lot of			10
					8,5

Figure 19. I step of the risk assessment.

In the first step the auditor has to enter some audit specific data:

- branch of industry by using the statistical data of the fire frequency, e.g. from (table 10) $[m^2/a]$
- area of the considered object $[m^2]$
- personnel presence [h]

Equally, the auditor has to evaluate the existing violations and amount of dangerous substances. Behind the actual check list with the count “Evaluated by auditor”, are the specified values “Value_0”.

7.4.1.1 Evaluation of the weighting factors for "Existing violations"

For the evaluation of the "existing violations" V_E fixed weighting factors are used:

Table 11. Weighting factors for evaluation of the existing violations.

Compliance	Weighting Factors
Be absent	0.5
Are insignificant	1
Are present	2
In large volume	3

These weighting factors are considered for the calculation of the common class of hazard H_{CC} (chapter 7.4.7):

$$H_{CC} = V_E + \sum \begin{cases} R_{Ind} > R_{AC} \rightarrow 1 \\ R_{Ind} < R_{AC} \rightarrow 0 \end{cases} + \sum \begin{cases} I_S > AC \rightarrow 1.0 \\ I_S = AC \rightarrow 1.5 \\ I_S < AC \rightarrow 0.0 \end{cases} \tag{9}$$

where V_E = existing violations; R_{Ind} = individual risk; R_{AC} = risk acceptance criteria; AC = acceptance criteria for the safety index (..); I_S = safety index. If there were no existing violations, the *Safety measures* are "accepted" and all *Hazards* are evaluated as "hazard free", the common class of hazard is 0.5. By calculated values < 1 (as in this example) the value for the common class of hazard = 1.

If there were some existing violations (weighting factors 1, 2 or 3), the common class of hazard would rise respectively of this factor. If in the past the violations existed and were not eliminated, the auditor would have the possibility to evaluate the risk relying on experience of previous audits, violations and the estimated risk.

7.4.1.2 Evaluation of the weighting factors for “dangerous substances”

The auditor also estimates the amount of dangerous substances with the help of fixed values in a scale from 1 to 10 (table 12).

Table 12. Weighting factors for evaluation of the dangerous substances.

Compliance	Weighting factors
A lot of	10
Many	7.5
Middle	5
Few	3
Very few	1

Values of the evaluated dangerous substances on the basis of given weighting factors in (table 9) can be used for the technical measures (chapter 7.2).

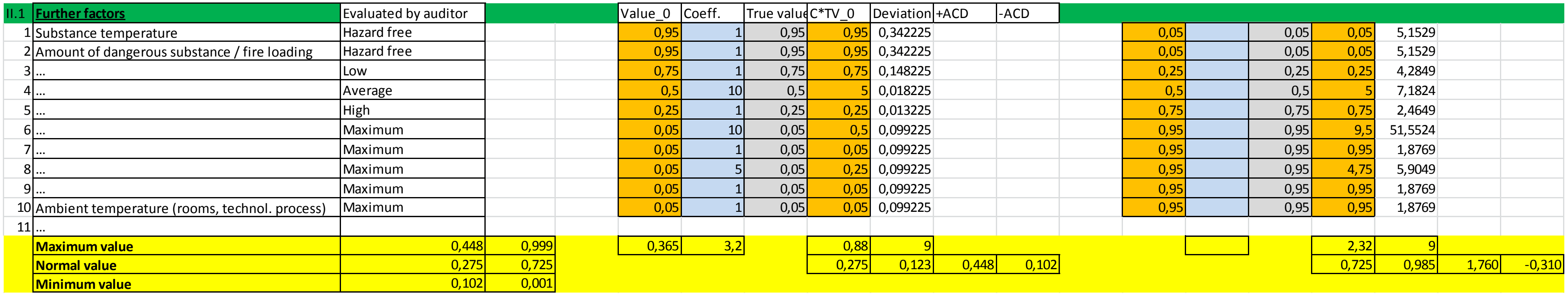
Potential risks and threats which are coming from the dangerous substances on the audited places are dependent on the technical measures. These technical measures can be observed or not observed, or as the other option, they can be observed, but do not correspond to the existing substance.

Some technical measures are very effective for one substance and are ineffective for other substances. There can be different substances at an enterprise; one substance can be bigger in quantity and others in smaller quantity. The existing technical measures can be effective for the substance which is smaller in quantity and ineffective for the substance which is bigger in quantity. This means that the technical measures are not laid out well.

Practical example: if the enterprise works with a gas, so there is no present special sense to have a good sprinkler fire system; a special air-technical system and gas detection system are of greater importance. Thus, the technical measures have to be estimated based on the area of minimization of potential threats of the dangerous substances.

7.4.2 II step. Evaluation of hazards

As described in chapter 7.2, the auditor has also to do the compliance check of hazard parameters:



II.1	**Further factors**	Evaluated by auditor			Value_0	Coeff.	True value	C*TV_0	Deviation	+ACD	-ACD								
1	Substance temperature	Hazard free			0,95	1	0,95	0,95	0,342225				0,05		0,05	0,05	5,1529		
2	Amount of dangerous substance / fire loading	Hazard free			0,95	1	0,95	0,95	0,342225				0,05		0,05	0,05	5,1529		
3	...	Low			0,75	1	0,75	0,75	0,148225				0,25		0,25	0,25	4,2849		
4	...	Average			0,5	10	0,5	5	0,018225				0,5		0,5	5	7,1824		
5	...	High			0,25	1	0,25	0,25	0,013225				0,75		0,75	0,75	2,4649		
6	...	Maximum			0,05	10	0,05	0,5	0,099225				0,95		0,95	9,5	51,5524		
7	...	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
8	...	Maximum			0,05	5	0,05	0,25	0,099225				0,95		0,95	4,75	5,9049		
9	...	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
10	Ambient temperature (rooms, technol. process)	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
11	...																		
	Maximum value	0,448	0,999		0,365	3,2		0,88	9							2,32	9		
	Normal value	0,275	0,725					0,275	0,123	0,448	0,102					0,725	0,985	1,760	-0,310
	Minimum value	0,102	0,001																

Figure 20. II step of the risk assessment (II.1 Further factors).

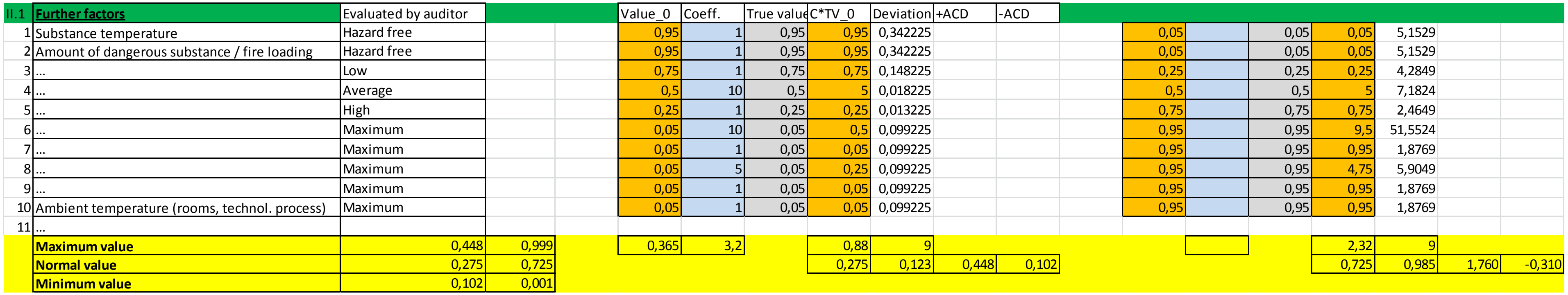
The auditor estimates the hazards with the compliances (table 9). The prototype tool evaluates automatically the worst case and best case scenarios with the weighting factors, which are behind the evaluation check list. Further in the dissertation the worst and best case scenarios are designated as "*hazard factorial indicator*" respectively *"For Index"* and *"For Risk"*. For the calculation of the *"hazard factorial indicator"* (chapter 7.3.5), the calculating values, e.g. in this II step, *Normal value* are used:

- *For Index* = 0.275
- *For Risk* = 0.725

Table 9. Weighting factors for best and worst case scenarios.

Compliance	Best Case	Worst Case
Hazard free	0.95	0.05
Low	0.75	0.25
Average	0.50	0.50
High	0.25	0.75
Maximum	0.05	0.95

For a better overview about the correlations between the Excel cells for this step see in Attachment "Correlations between the Excel cells for II step"



II.1	**Further factors**	Evaluated by auditor			Value_0	Coeff.	True value	C*TV_0	Deviation	+ACD	-ACD								
1	Substance temperature	Hazard free			0,95	1	0,95	0,95	0,342225				0,05		0,05	0,05	5,1529		
2	Amount of dangerous substance / fire loading	Hazard free			0,95	1	0,95	0,95	0,342225				0,05		0,05	0,05	5,1529		
3	…	Low			0,75	1	0,75	0,75	0,148225				0,25		0,25	0,25	4,2849		
4	…	Average			0,5	10	0,5	5	0,018225				0,5		0,5	5	7,1824		
5	…	High			0,25	1	0,25	0,25	0,013225				0,75		0,75	0,75	2,4649		
6	…	Maximum			0,05	10	0,05	0,5	0,099225				0,95		0,95	9,5	51,5524		
7	…	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
8	…	Maximum			0,05	5	0,05	0,25	0,099225				0,95		0,95	4,75	5,9049		
9	…	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
10	Ambient temperature (rooms, technol. process)	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
11	…																		
	Maximum value	0,448	0,999		0,365	3,2		0,88	9							2,32	9		
	Normal value	0,275	0,725					0,275	0,123	0,448	0,102					0,725	0,985	1,760	-0,310
	Minimum value	0,102	0,001																

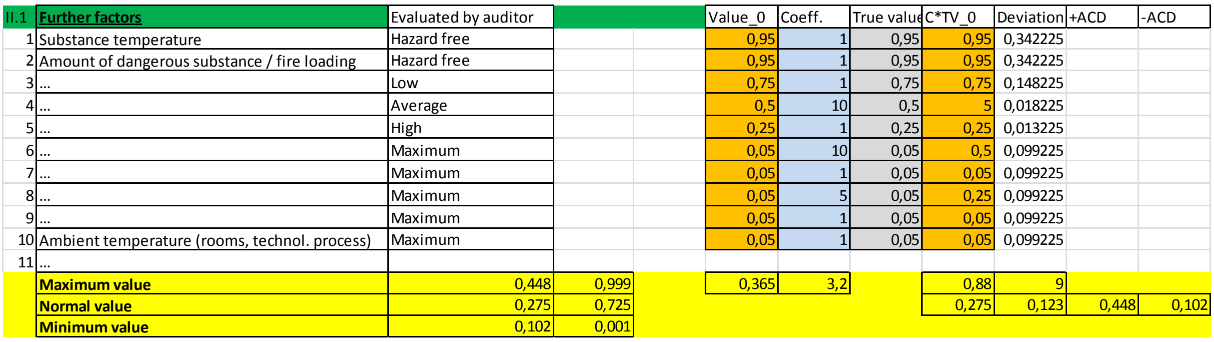
Figure 21. II step of the risk assessment (Value_0).

Behind the check list, *Value_0* (v_i) has the weighting factor of each evaluated by the auditor micro parameter (table 9). Further the arithmetical mean of the *Values_0* is calculated:

$$\overline{V}_{\_0} = \frac{1}{x}\sum_{i=1}^{x} v_i = \frac{1}{10}\cdot\left(0.95+0.95+0.75+0.5+0.25+0.05+0.05+0.05+0.05+0.05\right) = 0.365 \qquad (10)$$

7.4.2.1 Correction coefficient in combination with weighting factors

Correction coefficient $C_{Coeff.}$ has a scale from 1 to 10. Such scale can be used in the tool calculations because these numerical values are transferred into parts.



II.1	Further factors	Evaluated by auditor			Value_0	Coeff.	True valu	C*TV_0	Deviation	+ACD	-ACD
1	Substance temperature	Hazard free			0,95	1	0,95	0,95	0,342225		
2	Amount of dangerous substance / fire loading	Hazard free			0,95	1	0,95	0,95	0,342225		
3	...	Low			0,75	1	0,75	0,75	0,148225		
4	...	Average			0,5	10	0,5	5	0,018225		
5	...	High			0,25	1	0,25	0,25	0,013225		
6	...	Maximum			0,05	10	0,05	0,5	0,099225		
7	...	Maximum			0,05	1	0,05	0,05	0,099225		
8	...	Maximum			0,05	5	0,05	0,25	0,099225		
9	...	Maximum			0,05	1	0,05	0,05	0,099225		
10	Ambient temperature (rooms, technol. process)	Maximum			0,05	1	0,05	0,05	0,099225		
11	...										
	Maximum value	0,448	0,999		0,365	3,2		0,88	9		
	Normal value	0,275	0,725					0,275	0,123	0,448	0,102
	Minimum value	0,102	0,001								

Figure 22. II step of the risk assessment (Coeff. & New Values).

While assessing the check list the auditor has the possibility to evaluate the hazard parameters with the help of a so-called correction coefficient (designated in fig. 22: Coeff.)

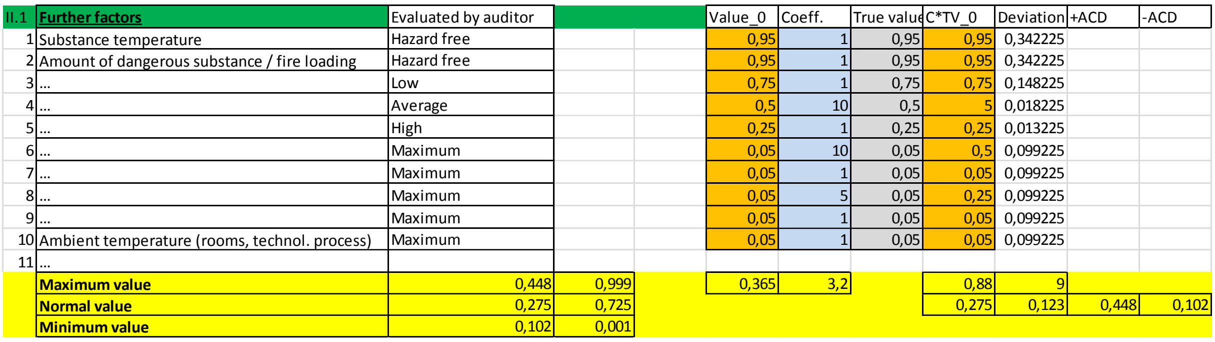
If one or the other micro parameter has a large impact on the individual risk, it can be enlarged with a correction number.

If there is no special influence of the one or other micro parameters to the individual risk, then the correction coefficient remains as "1". If the correction coefficient changes, designated as "C * TV_0" in (fig. 22) from "1" to "10", the "Value_0" (also designated as "True Value" in fig. 22) is multiplied by the correction coefficient.

The arithmetical mean of the correction coefficient $C_{Coeff.}$ is calculated too:

$$\overline{C}_{Coeff.} = \frac{1}{x}\sum_{i=1}^{x} C_{Coeff.i} = 3.2 \tag{11}$$

This arithmetical mean of the correction coefficient will be also considered by the calculation of maximum and minimum values of the “hazard factorial indicator” - “For Risk”.



II.1	**Further factors**	Evaluated by auditor			Value_0	Coeff.	True valu	C*TV_0	Deviation	+ACD	-ACD
1	Substance temperature	Hazard free			0,95	1	0,95	0,95	0,342225		
2	Amount of dangerous substance / fire loading	Hazard free			0,95	1	0,95	0,95	0,342225		
3	...	Low			0,75	1	0,75	0,75	0,148225		
4	...	Average			0,5	10	0,5	5	0,018225		
5	...	High			0,25	1	0,25	0,25	0,013225		
6	...	Maximum			0,05	10	0,05	0,5	0,099225		
7	...	Maximum			0,05	1	0,05	0,05	0,099225		
8	...	Maximum			0,05	5	0,05	0,25	0,099225		
9	...	Maximum			0,05	1	0,05	0,05	0,099225		
10	Ambient temperature (rooms, technol. process)	Maximum			0,05	1	0,05	0,05	0,099225		
11	...										
	Maximum value	0,448	0,999		0,365	3,2		0,88	9		
	Normal value	0,275	0,725					0,275	0,123	0,448	0,102
	Minimum value	0,102	0,001								

Figure 23. II step of the risk assessment (Coeff. & New Values).

Further step is the multiplication of the *Values_0* with the correction coefficient $C_{Coeff.}$ [1]:

$$C \cdot TV\_0_i = C_{Coeff.i} \cdot v_i \tag{12}$$

After the arithmetical mean the “new” Value_0 is calculated by:

$$\overline{C \cdot TV\_0} = \frac{1}{x} \sum_{i=1}^{x} C \cdot TV\_0_i \tag{13}$$

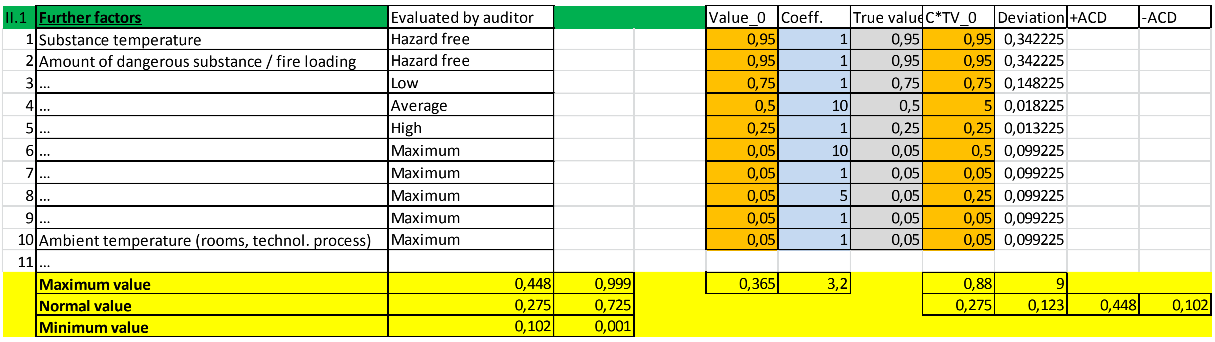
$$\overline{C \cdot TV\_0} = \frac{1}{10} \cdot (0.95 + 0.95 + 0.75 + 5 + 0.25 + 0.5 + 0.05 + 0.25 + 0.05 + 0.05) = 0.88$$

---

[1] Note: the multiplication symbol in MS Excel is designated as * (i.e. C*TV_0)

7.4.2.2 Calculation of the „Normal value” and consideration of the deviation

The calculation of the *„Normal value”* and other parameters is described as follows.



II.1	**Further factors**	Evaluated by auditor				Value_0	Coeff.	True valu	C*TV_0	Deviation	+ACD	-ACD
1	Substance temperature	Hazard free				0,95	1	0,95	0,95	0,342225		
2	Amount of dangerous substance / fire loading	Hazard free				0,95	1	0,95	0,95	0,342225		
3	...	Low				0,75	1	0,75	0,75	0,148225		
4	...	Average				0,5	10	0,5	5	0,018225		
5	...	High				0,25	1	0,25	0,25	0,013225		
6	...	Maximum				0,05	10	0,05	0,5	0,099225		
7	...	Maximum				0,05	1	0,05	0,05	0,099225		
8	...	Maximum				0,05	5	0,05	0,25	0,099225		
9	...	Maximum				0,05	1	0,05	0,05	0,099225		
10	Ambient temperature (rooms, technol. process)	Maximum				0,05	1	0,05	0,05	0,099225		
11	...											
	Maximum value		0,448	0,999		0,365	3,2		0,88	9		
	Normal value		0,275	0,725					0,275	0,123	0,448	0,102
	Minimum value		0,102	0,001								

Figure 24. II step of the risk assessment (calculating of Normal Value).

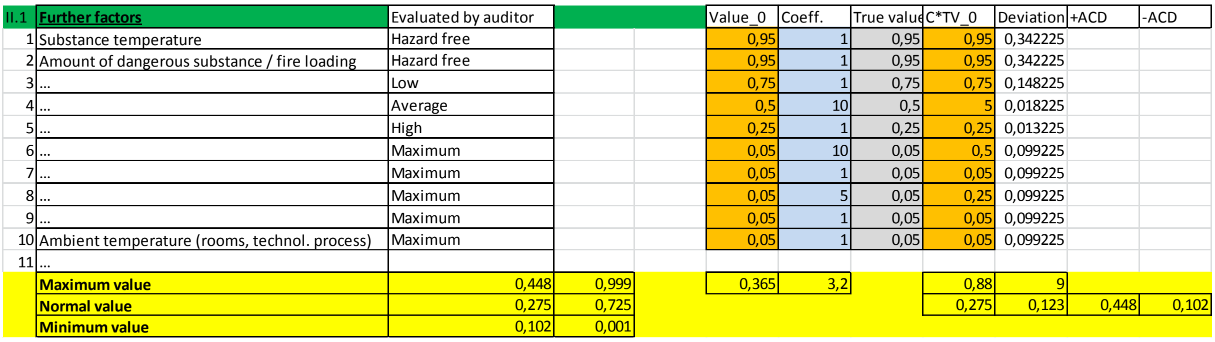
The *„Normal value”* is:

$$NV = \frac{\overline{C \cdot TV\_0}}{C_{Coeff.}} = \frac{0.88}{3.2} = 0.275 \qquad (14)$$

Further this *“Normal value”* will be participate in the calculation of the hazard factorial indicator F_{HRisk} which is:

$$F_{HRisk} = \overline{H}_{fut} \cdot \overline{H}_{f} \cdot \overline{H}_{ex} = \frac{1}{x}\sum_{i=1}^{x} H_{i,\,fut} \cdot \frac{1}{y}\sum_{i=1}^{y} H_{i,\,f} \cdot \frac{1}{z}\sum_{i=1}^{z} H_{i,\,ex} \qquad (7)$$

where $\overline{H}_{fut}$ = arithmetic mean of further factors which have an influence on explosion and fire hazards (e.g. amount of dangerous substance, room category, technological process etc.); $\overline{H}_{f}$ = arithmetic mean of fire hazards; $\overline{H}_{ex}$ = arithmetic mean of explosion hazards; x, y, z = number of micro parameters of further factors, explosion and fire hazards respectively.



II.1	**Further factors**	Evaluated by auditor			Value_0	Coeff.	True valu	C*TV_0	Deviation	+ACD	-ACD
1	Substance temperature	Hazard free			0,95	1	0,95	0,95	0,342225		
2	Amount of dangerous substance / fire loading	Hazard free			0,95	1	0,95	0,95	0,342225		
3	...	Low			0,75	1	0,75	0,75	0,148225		
4	...	Average			0,5	10	0,5	5	0,018225		
5	...	High			0,25	1	0,25	0,25	0,013225		
6	...	Maximum			0,05	10	0,05	0,5	0,099225		
7	...	Maximum			0,05	1	0,05	0,05	0,099225		
8	...	Maximum			0,05	5	0,05	0,25	0,099225		
9	...	Maximum			0,05	1	0,05	0,05	0,099225		
10	Ambient temperature (rooms, technol. process)	Maximum			0,05	1	0,05	0,05	0,099225		
11	...										
	Maximum value	0,448	0,999		0,365	3,2		0,88	9		
	Normal value	0,275	0,725					0,275	0,123	0,448	0,102
	Minimum value	0,102	0,001								

Figure 25. II step of the risk assessment (consideration of the deviation error by the calculation).

Due to the determined scale of the weighting factors (table 9) for the best and worst case scenarios $v_{scenarios} = \{0.05,\ 0.25,\ 0.50,\ 0.75,\ 0.95\}$ and for the evaluation of the safety parameters (table 8) $v_{safetypar.} = \{0.05,\ 0.20,\ 0.50,\ 0.95\}$ exists a probability of an error in the calculation of the *"Normal value"* and, as a consequence, of the individual risk.

To avoid these errors in the calculation, deviations of each calculated value C*TV_0 were considered. In the first step every deviation is calculated by arithmetical mean:

$$Dev_i = \left(v_i - \frac{1}{x} \sum_{i=1}^{x} v_i \right)^2 = \left(v_i - \overline{V}_{\_0} \right)^2 \tag{15}$$

An example of the calculation:

$$Dev_1 = \left(v_1 - \frac{1}{10} \sum_{i=1}^{10} v_i \right)^2 = (0.95 - 0.365)^2 = 0.342225$$

Further the so-called experimental standard deviation of the mean or, also known as the uncorrected sample standard deviation, or sometimes called as the standard deviation of the sample, is defined as follows:

$$S_{\bar{x}} = \frac{S}{\sqrt{\mathrm{n}}} = \sqrt{\frac{\sum_{i=1}^{\mathrm{n}} (\mathrm{X}_i - \overline{\mathrm{X}})^2}{\mathrm{n}}} \tag{16}$$

where the $\{X_1,\ X_2, ...,\ X_n\}$ are the observed values of the sample items and $\overline{\mathrm{X}}$ is the mean value of these observations, while the denominator n stands for the size of the sample: this is the square root of the sample variance, which is the average of the squared deviations about the sample mean.

In this case the corrected sample standard deviation must be used, denoted by $S_{\overline{Dev.}}$, because $n \leq 30$, thus “taking square roots reintroduces bias (because the square root is a nonlinear function, which does not commute with the expectation), yielding the corrected sample standard deviation, denoted by”:

$$S_{\overline{Dev.}} = \sqrt{\frac{\sum_{i=1}^{\mathrm{n}} (v_i - \overline{V}_{\_0})^2}{\mathrm{n} - 1}} \tag{17}$$

Calculation example on basis of (fig. 25):

Table 13. Calculation of the experimental standard deviation of the mean

n	v_i	$\left(v_i - \overline{V}_{\_0}\right)^2$
1	0.95	0.342225
2	0.95	0.342225
3	0.75	0.148225
4	0.5	0.018225
5	0.25	0.013225
6	0.05	0.099225
7	0.05	0.099225
8	0.05	0.099225
9	0.05	0.099225
10	0.05	0.099225
arithmetical mean		0.136025

$$S_{\overline{Dev.}} = \sqrt{\frac{0.136025}{10 - 1}} = 0.123$$

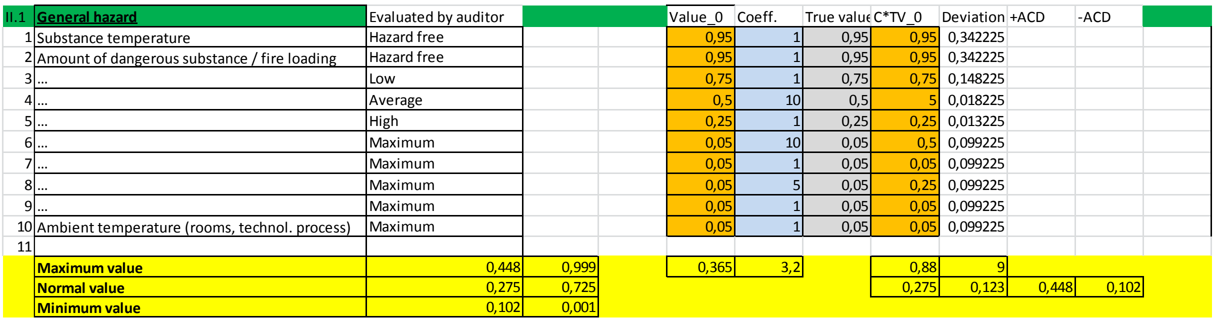
7.4.2.3 Additional consideration of the standard deviation by the calculations

Additionally to the consideration of the experimental standard deviation of the mean, the "three-sigma rule" is equally considered in the calculations. Due to the large number of possible interconnections between the nodes (of an event tree), which build the worst and best case scenarios and limited ability of the weighting factors (tables 8, 9), the consideration of the "three-sigma rule" is expediently.

“In statistics, the so-called ["three-sigma rule"] is a shorthand used to remember the percentage of values that lie within a band around the mean in a normal distribution with a width of one, two and three standard deviations, respectively […]: 68.27%, 95.45% and 99.73% of the values lie within one, two and three standard deviations of the mean, respectively. In mathematical notation, these facts can be expressed as follows, where *x* is an observation from a normally distributed random variable, *μ* is the mean of the distribution, and *σ* is its standard deviation” (https://en.wikipedia.org/wiki/68%E2%80%9395%E2%80%9399.7_rule 2016):

$$\Pr\left(\mu-\sigma \le x \le \mu+\sigma\right) \approx 0.6827$$
$$\Pr\left(\mu-2\sigma \le x \le \mu+2\sigma\right) \approx 0.9545$$
$$\Pr\left(\mu-3\sigma \le x \le \mu+3\sigma\right) \approx 0.9973$$

The decision of the consideration of two standard deviations was made by the author referring on (Ниворожкина et al. 2005; Кремер 2006; Белько et al. 2004). Thus, a deviation of 5% is implemented in the calculations (fig. 26: +ACD, -ACD) and gives the chance to evaluate the calculated result with maximum and minimum values (± 0.05):



II.1	**General hazard**	Evaluated by auditor			Value_0	Coeff.	True valu	C*TV_0	Deviation	+ACD	-ACD	
1	Substance temperature	Hazard free			0,95	1	0,95	0,95	0,342225			
2	Amount of dangerous substance / fire loading	Hazard free			0,95	1	0,95	0,95	0,342225			
3	...	Low			0,75	1	0,75	0,75	0,148225			
4	...	Average			0,5	10	0,5	5	0,018225			
5	...	High			0,25	1	0,25	0,25	0,013225			
6	...	Maximum			0,05	10	0,05	0,5	0,099225			
7	...	Maximum			0,05	1	0,05	0,05	0,099225			
8	...	Maximum			0,05	5	0,05	0,25	0,099225			
9	...	Maximum			0,05	1	0,05	0,05	0,099225			
10	Ambient temperature (rooms, technol. process)	Maximum			0,05	1	0,05	0,05	0,099225			
11												
	Maximum value	0,448	0,999		0,365	3,2		0,88	9			
	Normal value	0,275	0,725					0,275	0,123	0,448	0,102	
	Minimum value	0,102	0,001									

Figure 26. Consideration of two standard deviations: maximum and minimum values.

Thus, considering the deviation and the "three-sigma rule" by the calculations leads to a further component of the extended semi-quantitative method in development (fig. 27):

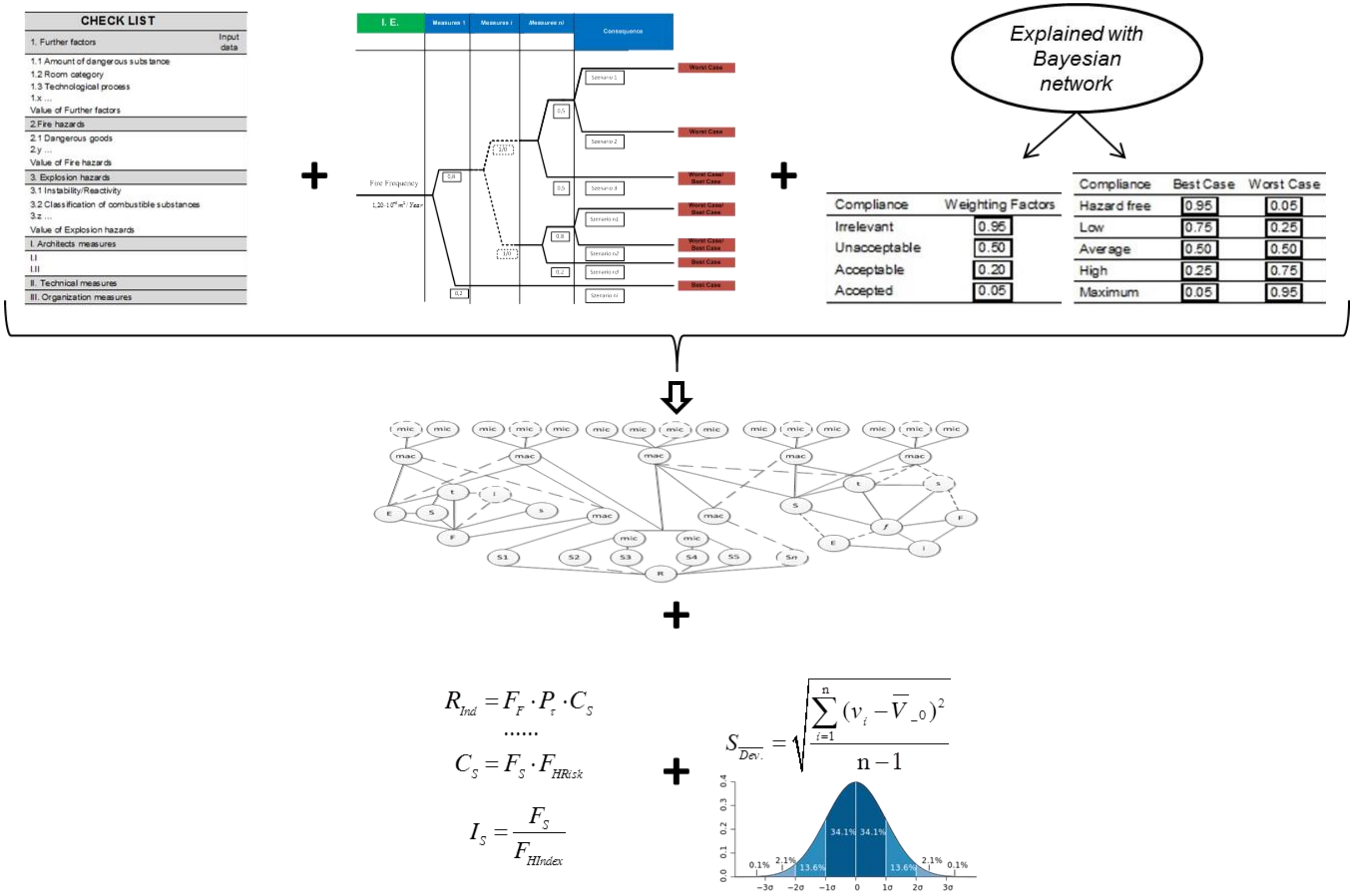


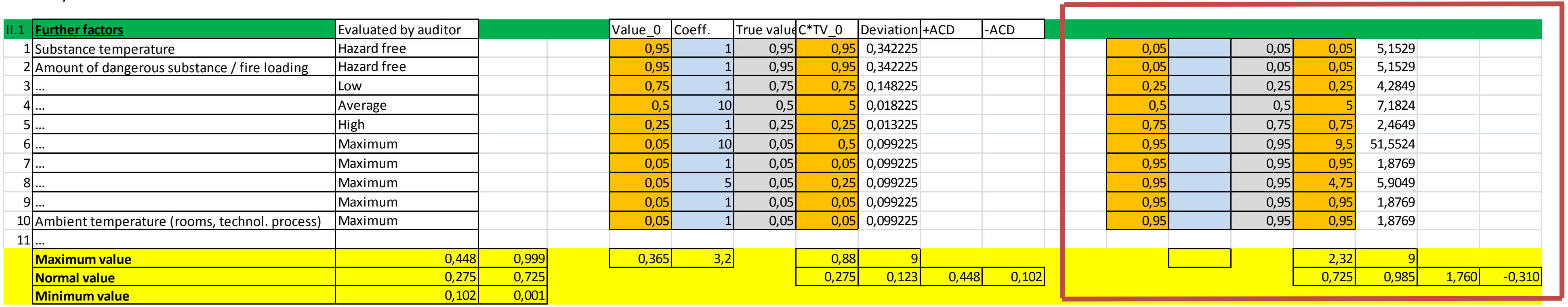
Figure 27. Stepwise development of the extended semi-quantitative method.

7.4.3 Synopsis of the II step. Evaluation of hazards

This section generalizes the II step of the risk assessment:

- Evaluation of the micro parameters by the auditor (substance temperature, amount of dangerous substance etc.),
- Calculation of The Normal value (0.365)
- Recalculation of The Normal value if for certain micro parameters the correction factor will by defined (the Normal value C*TV_0)
- Calculation of the deviations for each micro parameter
- Consideration of the two standard deviations and calculation of the maximum and minimum values.

Thus, the calculated values are determined in other calculations of "hazard factorial indicator - for Index"



II.1	**Further factors**	Evaluated by auditor			Value_0	Coeff.	True value	C*TV_0	Deviation	+ACD	-ACD								
1	Substance temperature	Hazard free			0,95	1	0,95	0,95	0,342225				0,05		0,05	0,05	5,1529		
2	Amount of dangerous substance / fire loading	Hazard free			0,95	1	0,95	0,95	0,342225				0,05		0,05	0,05	5,1529		
3	...	Low			0,75	1	0,75	0,75	0,148225				0,25		0,25	0,25	4,2849		
4	...	Average			0,5	10	0,5	5	0,018225				0,5		0,5	5	7,1824		
5	...	High			0,25	1	0,25	0,25	0,013225				0,75		0,75	0,75	2,4649		
6	...	Maximum			0,05	10	0,05	0,5	0,099225				0,95		0,95	9,5	51,5524		
7	...	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
8	...	Maximum			0,05	5	0,05	0,25	0,099225				0,95		0,95	4,75	5,9049		
9	...	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
10	Ambient temperature (rooms, technol. process)	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
11	...																		
	Maximum value	0,448	0,999		0,365	3,2		0,88	9							2,32	9		
	Normal value	0,275	0,725					0,275	0,123	0,448	0,102					0,725	0,985	1,760	-0,310
	Minimum value	0,102	0,001																

Figure 28. II step of the risk assessment (“Factor of hazard - for Risk“ (Worst case scenarios)).

Values for further calculations of “hazard factorial indicator - for Risk“ are determined identically. For the worst case scenario the weighting factors from table 9 are used automatically here, e.g. for the micro parameter “Substance temperature” the weighting factor is 0.05. Other mathematical calculations are the same as before.

For a better overview of the interconnections see Attachment “Overview of the interconnections and function of the II step”

7.4.4 Synopsis of the II step. Evaluation of Explosion and Fire hazards, Further factors which have an influence on the explosion and fire hazards

The Explosion and Fire hazards are calculated identically as Further factors. Therefore, the following calculated values are defined in the II step:

Macro parameters for Further factors:

Table 14. Further factors (cf. figure 28, yellow fields)

	For Index	For Risk
Maximum value	0.448	0.999
Normal value	0.275	0.725
Minimum value	0.102	0.001

Macro parameters for Fire hazards:

Table 15. Fire hazards.

	For Index	For Risk
Maximum value	0.737	0.647
Normal value	0.545	0.455
Minimum value	0.353	0.263

Macro parameters for Explosion hazards:

Table 16. Explosion hazards.

	For Index	For Risk
Maximum value	0.867	0.507
Normal value	0.680	0.320
Minimum value	0.493	0.133

Based on these macro parameters, the “hazard factorial indicators - for Index” are calculated as:

$$F_{HRisk} = \overline{H}_{fut} \cdot \overline{H}_{f} \cdot \overline{H}_{ex} = \frac{1}{x}\sum_{i=1}^{x} H_{i,fut} \cdot \frac{1}{y}\sum_{i=1}^{y} H_{i,f} \cdot \frac{1}{z}\sum_{i=1}^{z} H_{i,ex} \qquad (7)$$

- Maximum value of the “hazard factorial indicators - for Index”:

  $F_{HIndex} = 0.448 \cdot 0.737 \cdot 0.867 = 0.28619$

- Normal value of the “hazard factorial indicators - for Index”:

  $F_{HIndex} = 0.275 \cdot 0.545 \cdot 0.680 = 0.10192$

- Minimum value of the “hazard factorial indicators - for Index”:

  $F_{HIndex} = 0.108 \cdot 0.353 \cdot 0.493 = 0.01777$

Similar calculations are carried out for the “hazard factorial indicators - for Risk”:

- Maximum value of the “hazard factorial indicators - for Index”:

  $F_{HRisk} = 0.999 \cdot 0.647 \cdot 0.507 = 0.32776$

- Normal value of the “hazard factorial indicators - for Index”:

  $F_{HRisk} = 0.725 \cdot 0.455 \cdot 0.320 = 0.10556$

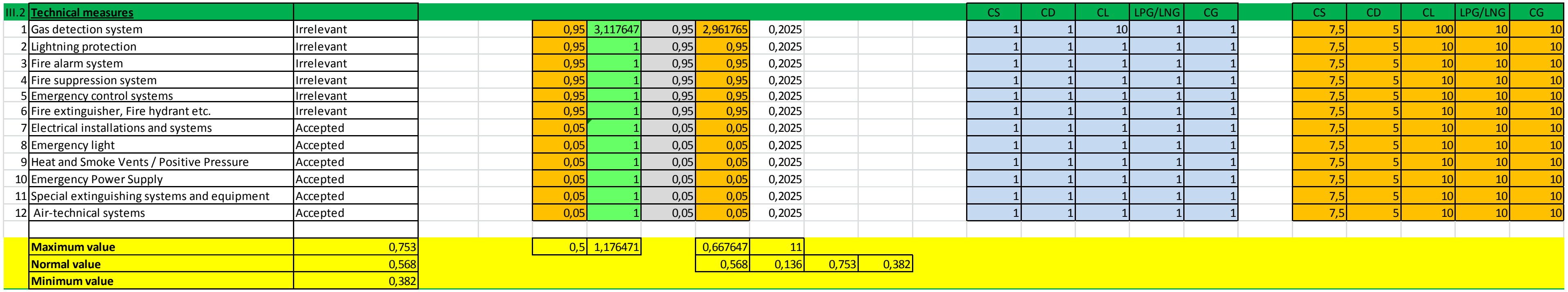
- Minimum value of the “hazard factorial indicators - for Index”:

  $F_{HRisk} = 0.001 \cdot 0.263 \cdot 0.133 = 3.49 \cdot 10^{-5}$

These values will be considered by the calculation of the safety index I_S (eq. 8) and safety coefficient C_S (eq. 5), described as follows in chapter 7.4.7.

7.4.5 III step. Evaluation of Safety measures

As in the steps described before, the auditor has to do the compliance check of the safety parameters:



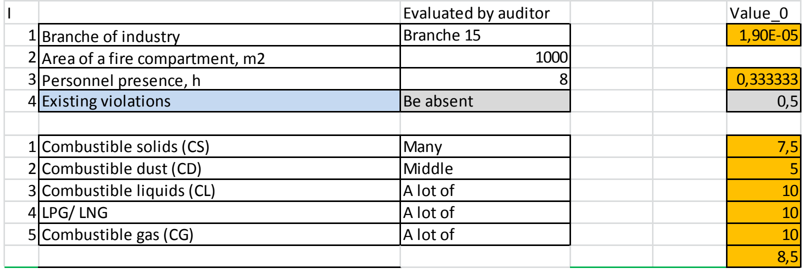
III.2	Technical measures										CS	CD	CL	LPG/LNG	CG	CS	CD	CL	LPG/LNG	CG
1	Gas detection system	Irrelevant	0,95	3,117647	0,95	2,961765	0,2025				1	1	10	1	1	7,5	5	100	10	10
2	Lightning protection	Irrelevant	0,95	1	0,95	0,95	0,2025				1	1	1	1	1	7,5	5	10	10	10
3	Fire alarm system	Irrelevant	0,95	1	0,95	0,95	0,2025				1	1	1	1	1	7,5	5	10	10	10
4	Fire suppression system	Irrelevant	0,95	1	0,95	0,95	0,2025				1	1	1	1	1	7,5	5	10	10	10
5	Emergency control systems	Irrelevant	0,95	1	0,95	0,95	0,2025				1	1	1	1	1	7,5	5	10	10	10
6	Fire extinguisher, Fire hydrant etc.	Irrelevant	0,95	1	0,95	0,95	0,2025				1	1	1	1	1	7,5	5	10	10	10
7	Electrical installations and systems	Accepted	0,05	1	0,05	0,05	0,2025				1	1	1	1	1	7,5	5	10	10	10
8	Emergency light	Accepted	0,05	1	0,05	0,05	0,2025				1	1	1	1	1	7,5	5	10	10	10
9	Heat and Smoke Vents / Positive Pressure	Accepted	0,05	1	0,05	0,05	0,2025				1	1	1	1	1	7,5	5	10	10	10
10	Emergency Power Supply	Accepted	0,05	1	0,05	0,05	0,2025				1	1	1	1	1	7,5	5	10	10	10
11	Special extinguishing systems and equipment	Accepted	0,05	1	0,05	0,05	0,2025				1	1	1	1	1	7,5	5	10	10	10
12	Air-technical systems	Accepted	0,05	1	0,05	0,05	0,2025				1	1	1	1	1	7,5	5	10	10	10
	Maximum value	0,753	0,5	1,176471		0,667647	11													
	Normal value	0,568				0,568	0,136	0,753	0,382											
	Minimum value	0,382																		

Figure 29. III step of the risk assessment (III.2 technical measures).

The main distinction of the evaluation of the technical measures to others parameters (e.g. explosion hazards etc.) or organizational measures and space-planning activities, is that the auditor does not evaluate the correction coefficient $C_{Coeff.}$ described in chapter 7.4.2.1. This correction coefficient $C_{Coeff.}$ is based on the dangerous substances. In the I step the auditor estimates the amount of dangerous substances with the help of default values (chapter 7.4.1.2):

CS	CD	CL	LPG/LNG	CG
7,5	5	100	10	10
7,5	5	10	10	10
7,5	5	10	10	10
7,5	5	10	10	10
7,5	5	10	10	10
7,5	5	10	10	10
7,5	5	10	10	10
7,5	5	10	10	10
7,5	5	10	10	10
7,5	5	10	10	10
7,5	5	10	10	10
7,5	5	10	10	10

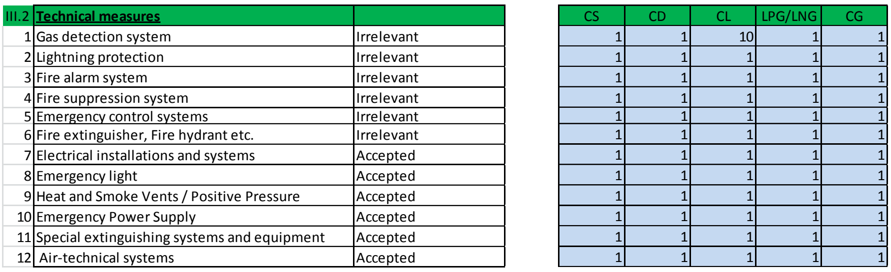
Figure 30. Extract from III step 2. Technical measures



I		Evaluated by auditor	Value_0
1	Branche of industry	Branche 15	1,90E-05
2	Area of a fire compartment, m2	1000	
3	Personnel presence, h	8	0,333333
4	Existing violations	Be absent	0,5
1	Combustible solids (CS)	Many	7,5
2	Combustible dust (CD)	Middle	5
3	Combustible liquids (CL)	A lot of	10
4	LPG/ LNG	A lot of	10
5	Combustible gas (CG)	A lot of	10
			8,5

Figure 31. Extract from I step evaluation of the evaluated dangerous substance

The auditor has to establish the interrelation between dangerous substance(s) (and proceeding from the substance of resulting threat) and the technical measures, which exists. These interrelations must be evaluated by the auditor in a table (“blue” colored in fig. 32):

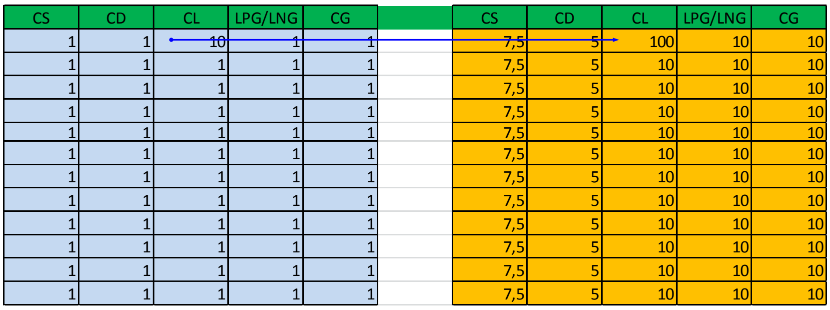


III.2	Technical measures	
1	Gas detection system	Irrelevant
2	Lightning protection	Irrelevant
3	Fire alarm system	Irrelevant
4	Fire suppression system	Irrelevant
5	Emergency control systems	Irrelevant
6	Fire extinguisher, Fire hydrant etc.	Irrelevant
7	Electrical installations and systems	Accepted
8	Emergency light	Accepted
9	Heat and Smoke Vents / Positive Pressure	Accepted
10	Emergency Power Supply	Accepted
11	Special extinguishing systems and equipment	Accepted
12	Air-technical systems	Accepted

CS	CD	CL	LPG/LNG	CG
1	1	10	1	1
1	1	1	1	1
1	1	1	1	1
1	1	1	1	1
1	1	1	1	1
1	1	1	1	1
1	1	1	1	1
1	1	1	1	1
1	1	1	1	1
1	1	1	1	1
1	1	1	1	1
1	1	1	1	1

Figure 32. Extract from III step. Interrelation between technical measures and the threats of the dangerous substances.

The evaluation of the interrelations uses the scaling $Interrelation = \{1,2,3,...,10\}$. Thus, efficiency of operation of the protection system against this substance is estimated. In (fig. 32) only one interrelation factor was changed from 1 to 10 (CL = Combustible liquids). This factor has an influence on the weighting factor, which was evaluated in the I step - amount of dangerous substance(s):



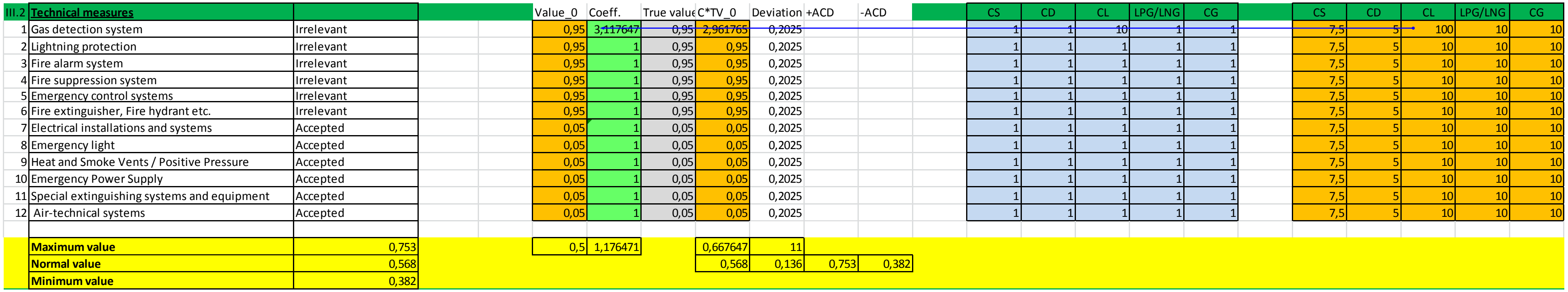
CS	CD	CL	LPG/LNG	CG		CS	CD	CL	LPG/LNG	CG
1	1	10	1	1		7,5	5	100	10	10
1	1	1	1	1		7,5	5	10	10	10
1	1	1	1	1		7,5	5	10	10	10
1	1	1	1	1		7,5	5	10	10	10
1	1	1	1	1		7,5	5	10	10	10
1	1	1	1	1		7,5	5	10	10	10
1	1	1	1	1		7,5	5	10	10	10
1	1	1	1	1		7,5	5	10	10	10
1	1	1	1	1		7,5	5	10	10	10
1	1	1	1	1		7,5	5	10	10	10
1	1	1	1	1		7,5	5	10	10	10
1	1	1	1	1		7,5	5	10	10	10

Figure 33. Extract from III step. Influence on the weighting factors, which was evaluated for the dangerous substances (arrow).

The interrelation factor is multiplied with the weighting factor, characterised by the amount of dangerous substance(s): (10 · 10= 100). This value has an influence on the correction coefficient $C_{Coeff.}$:

$$C_{Coeff.} = \frac{7.5 + 5 + 100 + 10 + 10}{8.5 \cdot 5} = 3.11764 \tag{18}$$

Thus, the correction coefficient is calculated as the sum of weighting factors, characterised by the amount of <u>all</u> dangerous substances, divided by the arithmetical mean of these weighting factors $(\frac{1}{m}\sum_{m=1}^{m}\text{weighting factors of amount dangerous substances})$ and their quantity (*q=5)* :



III.2	**Technical measures**		Value_0	Coeff.	True value	C*TV_0	Deviation	+ACD	-ACD	CS	CD	CL	LPG/LNG	CG	CS	CD	CL	LPG/LNG	CG
1	Gas detection system	Irrelevant	0,95	3,117647	0,95	2,961765	0,2025			1	1	10	1	1	7,5	5	100	10	10
2	Lightning protection	Irrelevant	0,95	1	0,95	0,95	0,2025			1	1	1	1	1	7,5	5	10	10	10
3	Fire alarm system	Irrelevant	0,95	1	0,95	0,95	0,2025			1	1	1	1	1	7,5	5	10	10	10
4	Fire suppression system	Irrelevant	0,95	1	0,95	0,95	0,2025			1	1	1	1	1	7,5	5	10	10	10
5	Emergency control systems	Irrelevant	0,95	1	0,95	0,95	0,2025			1	1	1	1	1	7,5	5	10	10	10
6	Fire extinguisher, Fire hydrant etc.	Irrelevant	0,95	1	0,95	0,95	0,2025			1	1	1	1	1	7,5	5	10	10	10
7	Electrical installations and systems	Accepted	0,05	1	0,05	0,05	0,2025			1	1	1	1	1	7,5	5	10	10	10
8	Emergency light	Accepted	0,05	1	0,05	0,05	0,2025			1	1	1	1	1	7,5	5	10	10	10
9	Heat and Smoke Vents / Positive Pressure	Accepted	0,05	1	0,05	0,05	0,2025			1	1	1	1	1	7,5	5	10	10	10
10	Emergency Power Supply	Accepted	0,05	1	0,05	0,05	0,2025			1	1	1	1	1	7,5	5	10	10	10
11	Special extinguishing systems and equipment	Accepted	0,05	1	0,05	0,05	0,2025			1	1	1	1	1	7,5	5	10	10	10
12	Air-technical systems	Accepted	0,05	1	0,05	0,05	0,2025			1	1	1	1	1	7,5	5	10	10	10
	Maximum value	0,753	0,5	1,176471		0,667647	11												
	Normal value	0,568				0,568	0,136	0,753	0,382										
	Minimum value	0,382																	

Figure 34. Extract from III. Step. Influence on the correction coefficient (in this example equal 3.117647).

The auditor estimates the technical measures with the compliances (table 8). Further calculations of the “new” Value_0 for the technical measures (in this example “Gas detection system”) are calculated identically as described in chapter 7.4.2.1: multiplication of the *Values_0* with the correction coefficient $C_{Coeff.}$ (in fig. 34 designated as C*TV_0):

$$C\cdot TV\_0_i = C_{Coeff\cdot i}\cdot v_i = 3.117647\cdot 0.95 = 2.96176$$

After the arithmetical mean of the “new” Value_0 is calculated:

$$\overline{C\cdot TV\_0} = \frac{1}{m}\sum_{i=1}^{m} C\cdot TV\_0_i \qquad (13)$$

$$\overline{C\cdot TV\_0} = \frac{1}{m}\sum_{i=1}^{m} C\cdot TV\_0_i = \frac{1}{10}\cdot\left(2.961765+0.95+0.95+0.95+0.95+0.95+0.05+0.05+0.05+0.05+0.05+0.05\right) = 0.66764$$

“Normal, maximum and minimum values” are calculated identically as for the hazards, describes in the chapters before.

7.4.5.1 Explanation of the influence of the Interrelation factor

This chapter describes the influence of the Interrelation factor on the calculated “Normal value” and, as a result, on the risk criteria. This description is presented by an example, which includes the changes of the interrelation factor and the “Normal value” (table 17):

Table 17. Explanation of the influence of the interrelation factor.

	Accepted technical measure (installation)		Irrelevant technical measure (installation)	
Interrelation factor	10	1	10	1
Normal value	0.369	0.425	0.568	0.5

If the auditor evaluates the technical measure (installation) as “accepted” and this installation has a big influence on the threat of the dangerous substance, the risk decreases (0.369). If the installation is “accepted” but has a small influence on the substance, the risk increases (0.425).

If the auditor evaluates the technical measure (installation) as “irrelevant” and this installation has a high influence on the threat of the dangerous substance, the risk increases (0.568). If the installation is “irrelevant” but has a small influence on the substance, the risk decreases in comparison to the scenario described before (0.5).

Thus, it is possible to draw a conclusion that the offered interrelation factor has a logical function in the calculation of the values.

7.4.5.2 Interrelations and their evaluation

The check list of the technical measures can include different micro parameters, which can have an influence on the one or other substance. An example of such scenario is given in (fig. 35), with the 12 micro parameters (fig. 34) and the maximal possible number of dangerous substances:

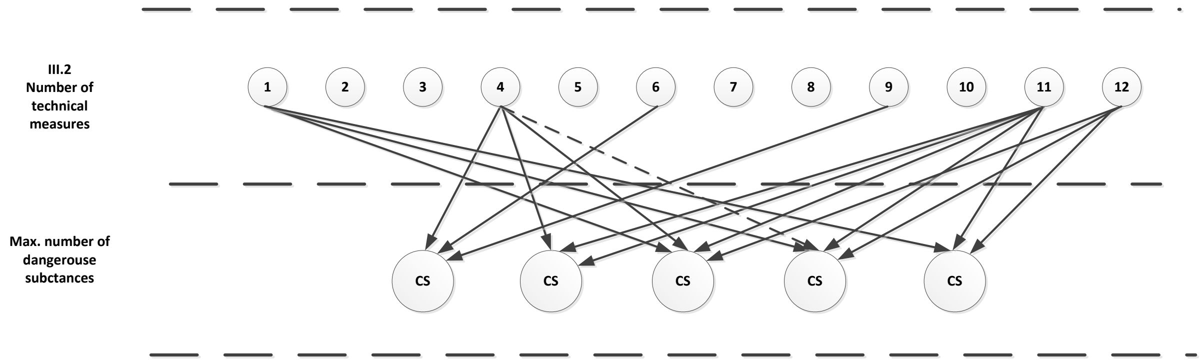


Figure 35. Possibilities of the interrelations.

Due to the increasing experience concerning such interrelations an alternative system can be developed later. Such a system could support the auditor giving him concrete advice with which interrelation factor the assessment should be carried out. However when assessing specific substances (e.g. dusts) this advice should only be considered as an example because these factors are dependent on substance properties.

7.4.6 Synopsis of the III step. Evaluation of Space-planning, Technical and Organisational measures

The Space-planning and Organizational measures are calculated identically as hazards. The Technical measures are equally calculated, except with some differences, described in the chapter before.

Therefore, the following calculated values are defined in the III step:

Macro parameters for Space-planning activities:

Table 18. Space-planning activities.

Maximum value	0.868
Normal value	0.500
Minimum value	0.132

Macro parameters for Technical measures:

Table 19. Technical measures.

Maximum value	0.753
Normal value	0.568
Minimum value	0.382

Macro parameters for Organisational measures:

Table 20. Organisational measures.

Maximum value	0.686
Normal value	0.500
Minimum value	0.314

Based on these macro parameters, the safety factorial indicator F_S is calculated as:

$$F_S = \overline{M}_{arch} \cdot \overline{M}_{tech} \cdot \overline{M}_{org} = \frac{1}{n}\sum_{i=1}^{n} M_{i,arch} \cdot \frac{1}{m}\sum_{i=1}^{m} M_{i,tech} \cdot \frac{1}{k}\sum_{i=1}^{k} M_{i,org} \qquad (6)$$

- Maximum value of the safety factorial indicator F_S:

  $F_S = 0.868 \cdot 0.753 \cdot 0.686 = 0.44837$

- Normal value of the safety factorial indicator F_S:

  $F_S = 0.500 \cdot 0.568 \cdot 0.500 = 0.14188$

- Minimum value of the safety factorial indicator F_S:

  $F_S = 0.132 \cdot 0.382 \cdot 0.314 = 0.01582$

These values will be considered by the calculation of the safety index I_S and safety coefficient C_S described as follows in chapter 7.4.7.

7.4.7 IV step. Calculation of individual risk, safety index and common class of hazard

For the calculation of the individual risk:

$$R_{Ind} = F_F \cdot P_\tau \cdot C_S \tag{3}$$

the equation (3) needs to know the next parameters: F_F = frequency of a fire at the enterprise [m^2/a]; P_τ = probability of presence of the personnel; C_S = safety coefficient.

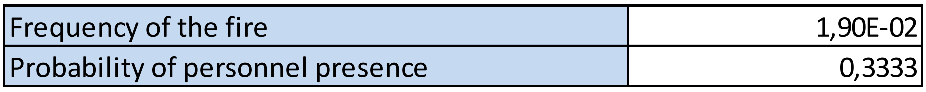
As mentioned in chapter 7.3.1 the frequency of a fire at the enterprise is dependent on the frequency of the fire at the corresponding industry branch and the area of the considered object (I step, chapter 7.4.1):

$$F_F = 1.90 \cdot 10^{-5} \cdot 1000 = 1.90 \cdot 10^{-2}$$

The probability of personal presence (chapter 7.3.2) is:

$$P_\tau = \frac{\tau}{24} = \frac{8}{24} = 0.3333$$

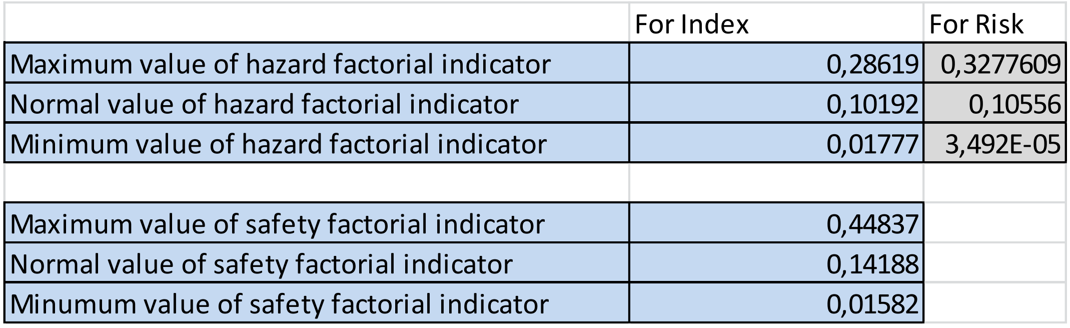
This information is given in the output table automatically (visualised as an extract from MS Excel prototype tool in fig.36):



Frequency of the fire	1,90E-02
Probability of personnel presence	0,3333

Figure 36. Extract from IV step. Output data.

The calculated values of the hazards (II step) and safety measures (III step) are also summarized in the output table (visualised as an extract from MS Excel prototype tool in fig.37):



	For Index	For Risk
Maximum value of hazard factorial indicator	0,28619	0,3277609
Normal value of hazard factorial indicator	0,10192	0,10556
Minimum value of hazard factorial indicator	0,01777	3,492E-05
Maximum value of safety factorial indicator	0,44837	
Normal value of safety factorial indicator	0,14188	
Minumum value of safety factorial indicator	0,01582	

Figure 37. Extract from IV step. Output data.

The C_S safety coefficient is calculated automatically:

$$C_S = F_S \cdot F_{Hrisk} \tag{5}$$

- Maximum value of the safety coefficient:

$$C_S = 0.44837 \cdot 0.32776 = 1.47 \cdot 10^{-1}$$

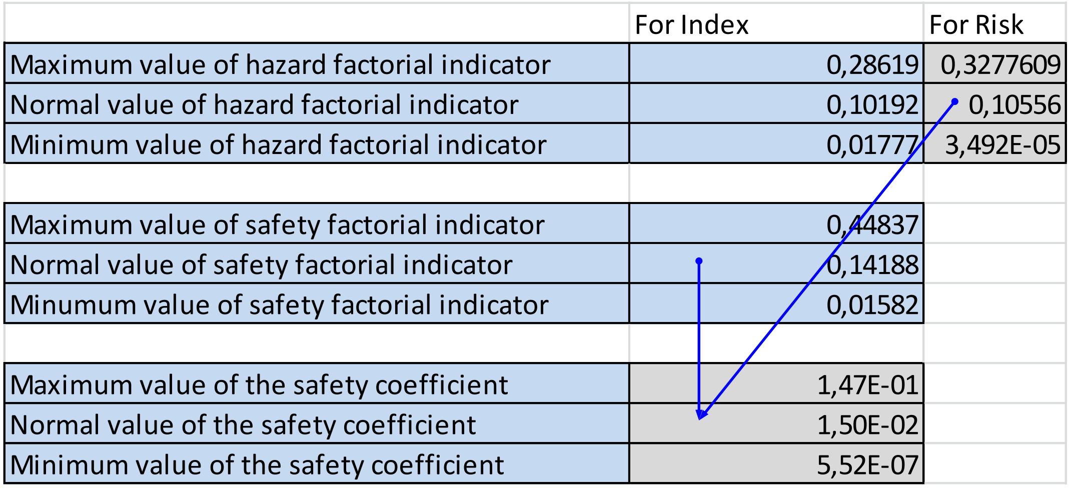
- Normal value of the safety coefficient:

$$C_S = 0.14188 \cdot 0.10556 = 1.50 \cdot 10^{-2}$$

- Minimum value of the safety coefficient:

$$C_S = 0.01582 \cdot 3.492 \cdot 10^{-5} = 5.52 \cdot 10^{-7}$$

This information is given in the output table automatically (visualised as an extract from MS Excel prototype tool in fig.38):



	For Index	For Risk
Maximum value of hazard factorial indicator	0,28619	0,3277609
Normal value of hazard factorial indicator	0,10192	0,10556
Minimum value of hazard factorial indicator	0,01777	3,492E-05
Maximum value of safety factorial indicator	0,44837	
Normal value of safety factorial indicator	0,14188	
Minumum value of safety factorial indicator	0,01582	
Maximum value of the safety coefficient	1,47E-01	
Normal value of the safety coefficient	1,50E-02	
Minimum value of the safety coefficient	5,52E-07	

Figure 38. Extract from IV step. Output data of the safety coefficient and its correlation to the safety factorial indicator and hazard factorial indicator - for Risk.

The resulting risk prioritization and safety index I_S values and their evaluation are given in tables 21, 22:

Table 21. Data output mask of individual risk.

Individual risk R_{Ind}		Compliance indicator for risk
Maximum value of the individual risk	$9.31 \cdot 10^{-4}$ [1/a]	1
Normal value of the individual risk	$9.49 \cdot 10^{-5}$ [1/a]	1
Minimum value of the individual risk	$3.50 \cdot 10^{-9}$ [1/a]	0

Overview of the calculated individual risk:

- Maximum value of the individual risk:

$$R_{Ind} = F_F \cdot P_\tau \cdot C_S = 1.90 \cdot 10^{-2} \cdot 0.3333 \cdot 1.47 \cdot 10^{-1} = 9.31 \cdot 10^{-4} \quad [1/\mathrm{a}]$$

- Normal value of the individual risk:

$$R_{Ind} = F_F \cdot P_\tau \cdot C_S = 1.90 \cdot 10^{-2} \cdot 0.3333 \cdot 1.50 \cdot 10^{-1} = 9.49 \cdot 10^{-4} \quad [1/\mathrm{a}]$$

- Minimum value of the individual risk:

$$R_{Ind} = F_F \cdot P_\tau \cdot C_S = 1.90 \cdot 10^{-2} \cdot 0.3333 \cdot 5.52 \cdot 10^{-7} = 3.50 \cdot 10^{-9} \quad [1/\mathrm{a}]$$

If R_{Ind} > value of the acceptable risk, e.g. 10^{-6} [1/a], then the compliance factor for risk is 1.

If R_{Ind} ≤ value of the acceptable risk, then the compliance factor for risk is 0.

Parallel to the individual risk estimation the safety index I_S is calculated. Its function is to additionally assess and evaluate the calculated risk adequately:

$$I_S = \frac{F_S}{F_{HIndex}} \tag{8}$$

where F_{HIndex} = factorial indicator of hazard, which dependents on the best case path of ETA (thus, the “hazard factorial indicators - for Index” is considered by the calculation).

As mentioned in chapter 7.3.6 the safety index bases on the common indexing method – weighting the safety measures and hazards.

The main distinction of the calculation of safety index I_S to the C_S safety coefficient, is in the weighting:

- The minimum value of the safety factorial indicator F_S must be divided by the maximum value of the “hazard factorial indicators - for Index” F_{HIndex}

and vice versa

- The maximum value of the safety factorial indicator F_S must be divided by the minimum value of the “hazard factorial indicators - for Index” F_{HIndex}

Such calculation gives more exact results of the maximum and minimum value of the safety index. In other words, for the determination of the highest safety, the maximum value of the safety factorial indicator, which is dependent on the macro and micro parameters of the safety measures, must be weighted with minimum value of the hazard factorial indicator. The same rule applies for the determination of the lowest safety: the minimum value of the safety factorial indicator must be weighted with maximum value of the hazard factorial indicator.

The auditor can see the output data of this calculation in a table (in this example table 22):

Table 22. Data output mask of safety index.

Safety index I_S		Compliance indicator for index
Maximum value of the safety index	25.23328	1
Normal value of the safety index	1.39209	1
Minimum value of the safety index	0.05527	0

Overview of the calculated safety index:

- Maximum value of the safety index:

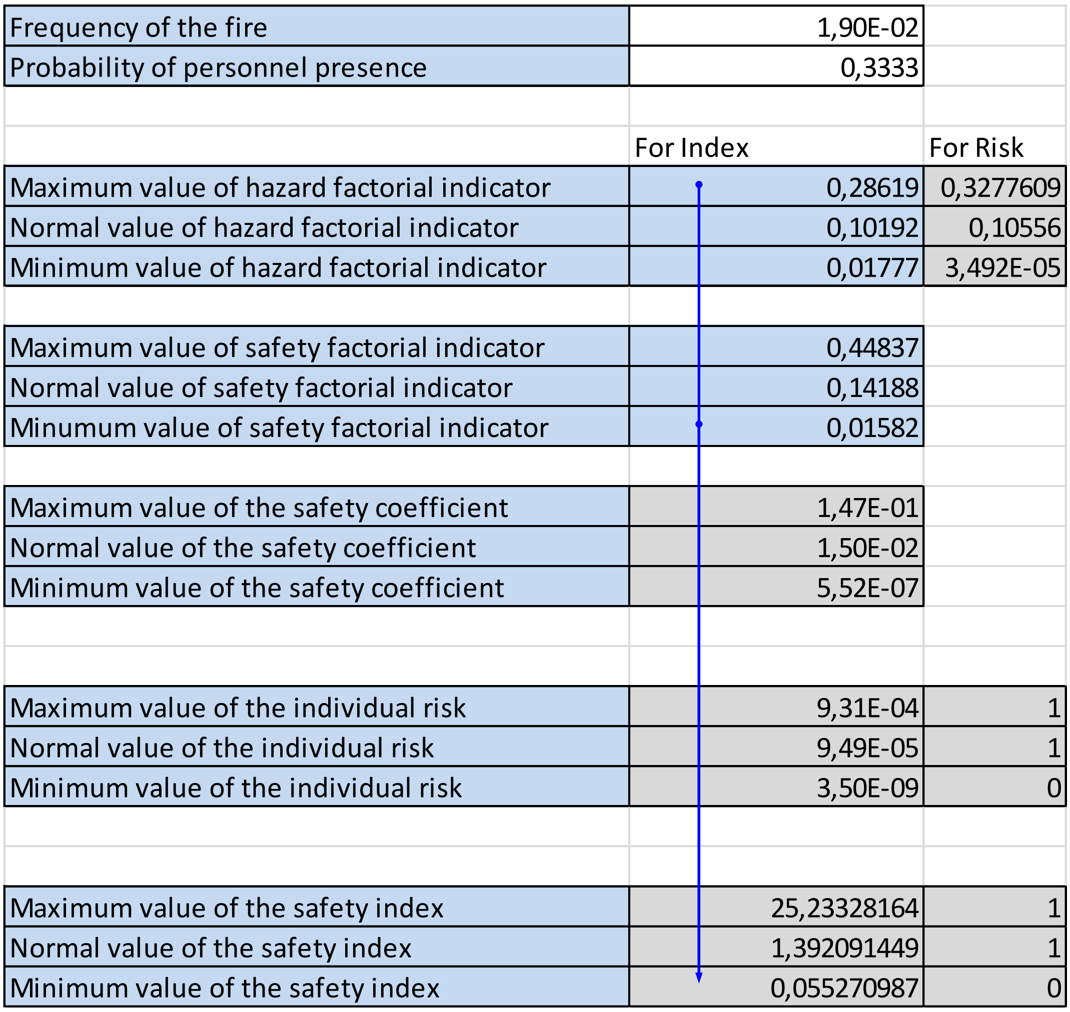
$$I_S = \frac{0.44837}{0.01777} = 25.23328$$

- Normal value of the safety index:

$$I_S = \frac{0.1488}{0.10192} = 1.39209$$

- Minimum value of the safety index:

$$I_S = \frac{0.01582}{0.28619} = 0.05527$$



	For Index	For Risk
Frequency of the fire	1,90E-02	
Probability of personnel presence	0,3333	
Maximum value of hazard factorial indicator	0,28619	0,3277609
Normal value of hazard factorial indicator	0,10192	0,10556
Minimum value of hazard factorial indicator	0,01777	3,492E-05
Maximum value of safety factorial indicator	0,44837	
Normal value of safety factorial indicator	0,14188	
Minumum value of safety factorial indicator	0,01582	
Maximum value of the safety coefficient	1,47E-01	
Normal value of the safety coefficient	1,50E-02	
Minimum value of the safety coefficient	5,52E-07	
Maximum value of the individual risk	9,31E-04	1
Normal value of the individual risk	9,49E-05	1
Minimum value of the individual risk	3,50E-09	0
Maximum value of the safety index	25,23328164	1
Normal value of the safety index	1,392091449	1
Minimum value of the safety index	0,055270987	0

Figure 39. Extract from IV step: Output data of the safety index and it's correlation to the safety factorial indicator and hazard factorial indicator - for Index.

If $I_S > 1$, then the compliance indicator for index is 1.

If $I_S = 1$, then the compliance indicator for index is 0.5.

If $I_S < 1$, then the compliance indicator for index is 0.

The common class of hazard is the sum of existing violations (example of I step) and the compliance indicators for risk and index.

Table 23. Data output mask of Common class of hazard

Common class of hazard	Middle	4.5

For the definition of the common class of hazard a rating scale exists and the input table is as shown in table 24:

Table 24. Common class of hazard.

Common class of hazard	Sum of existing violations and the compliance indicators
Minimal	1
Low	2
Moderate	3
Middle	4
Increased	5
High	6
Maximum	7
Maximum	8
Maximum	9

Thus, the last component of the extended semi-quantitative approach is presented in (fig. 40):

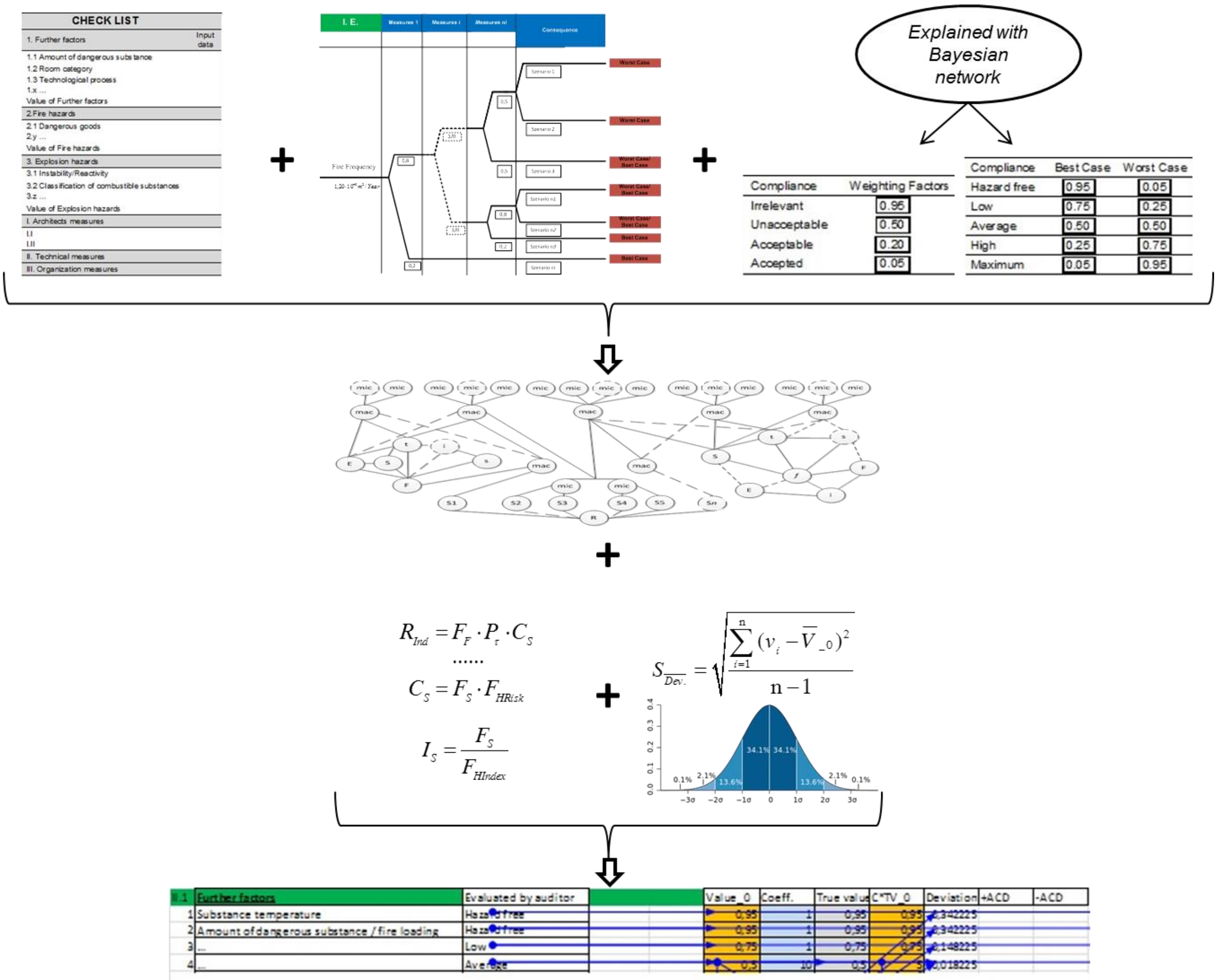


Figure 40. Stepwise development of the extended semi-quantitative method.

7.4.8 IV step. Graphical visualization of the calculated results

For a better overview, the auditor can draw conclusions about:

- the rate between calculated risk and index
- which hazard has a higher influence on the calculated risk
- the rate among the existing measures

with the help of additional diagrams.

7.4.8.1 Diagram of the rate between risk and index

For the creation of the diagram, which shows the rate between risk and index, the calculated values of the individual risk and safety index are used. Because these values differ in their mathematical role (e.g. the calculated maximum value of the individual risk is $R_{Ind}= 9.31 \cdot 10^{-4}$ [1/a] and the calculated maximum value of the safety index is $I_S= 25.23328$), the following equations (19 to 25) allow to recalculate these values in a form, which is adequate to build the requested diagram (fig. 41):

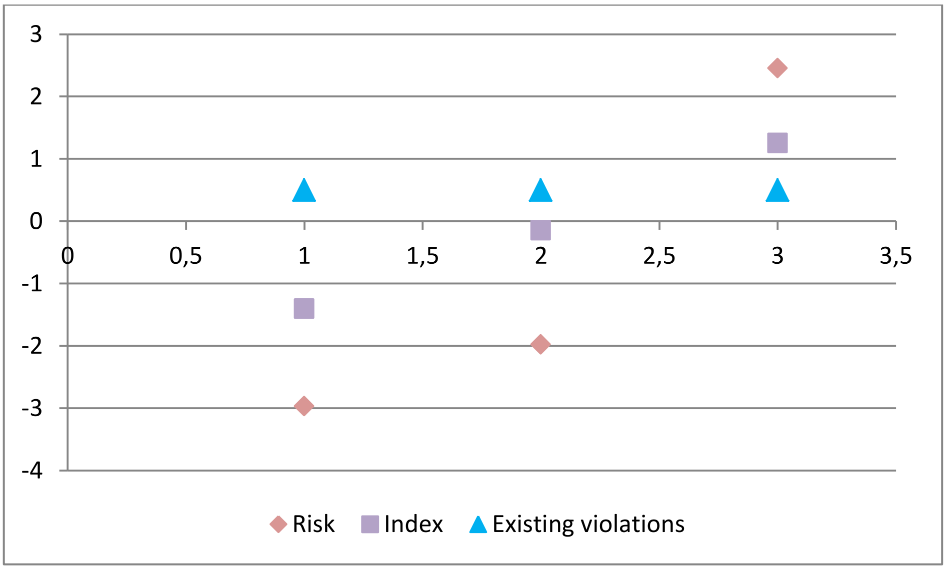


Figure 41. Extract from IV step: graphical overview of the calculated values.

Calculated data, presented in the table 25 are used:

Table 25. Recalculated values for the diagram.

	Risk	Index	Exist. violations	
G1	-2.96883	-1.40197	0.5	
G2	-1.97704	-0.14367	0.5	
G3	2.45616	1.25750	0.5	
	2	2	0	4
	50.0%	50.0%	0.0%	4

The data for risk are obtained by:

$$G1=-\log_{10}\left(\frac{R_{ind.\max}}{10^{-6}}\right)=-\log_{10}\left(\frac{9.31\cdot 10^{-4}}{10^{-6}}\right)=-2.96883 \qquad (19)$$

$$G1=-\log_{10}\left(\frac{R_{ind.\mathrm{norm}}}{10^{-6}}\right)=-\log_{10}\left(\frac{9.49\cdot 10^{-5}}{10^{-6}}\right)=-1.97704 \qquad (20)$$

$$G1=-\log_{10}\left(\frac{R_{ind.\min}}{10^{-6}}\right)=-\log_{10}\left(\frac{3.50\cdot 10^{-9}}{10^{-6}}\right)=2.45616 \qquad (21)$$

The data for index are obtained by:

$$G1=-\log_{10}\left(I_{S.\max}\right)=-\log_{10}\left(25.23328164\right)=-1.40197 \qquad (22)$$

$$G1=-\log_{10}\left(I_{S.\mathrm{norm}}\right)=-\log_{10}\left(1.392091449\right)=-0.14367 \qquad (23)$$

$$G1=-\log_{10}\left(I_{S.\min}\right)=-\log_{10}\left(0.055270987\right)=1.25750 \qquad (24)$$

The data for existing violations are obtained by:

$$G1,G2,G3=1-\left(\text{weighting factor}\right)=1-\left(0.5\right)=0.5 \qquad (25)$$

As presented in chapter 7.4.7 the auditor has output tables with the calculated results of the individual risk and safety index, which are used in the equations described above:

Table 26. Data output mask of individual risk.

Individual risk R_{Ind}		Compliance indicator for risk
Maximum value of the individual risk	$9.31 \cdot 10^{-4}$ [1/a]	1
Normal value of the individual risk	$9.49 \cdot 10^{-5}$ [1/a]	1
Minimum value of the individual risk	$3.50 \cdot 10^{-9}$ [1/a]	0

Table 27. Data output mask of safety index.

Safety index I_S		Compliance indicator for index
Maximum value of the safety index	25.23328	1
Normal value of the safety index	1.39209	1
Minimum value of the safety index	0.05527	0

The compliance indicator for risk and index can be also found in (table 28) in the results column:

Table 28. Extract from: Recalculated values for the diagram.

Risk	Index	Exist. violations	
1+1=2	1+1=2	0	4
50.0%	50.0%	0.0%	4

The values of the existing violation are determined as follows:

Table 29. Weighting factors for evaluation of the existing violations.

Compliance	Weighting Factors	Recalculated value for graph
Be absent	0.5	0
Are insignificant	1	1
Are present	2	2
In large volume	3	3

Based on these recalculated values, which are represented as parts, the recalculation in percent is also conducted and presented in a diagram (fig. 42):

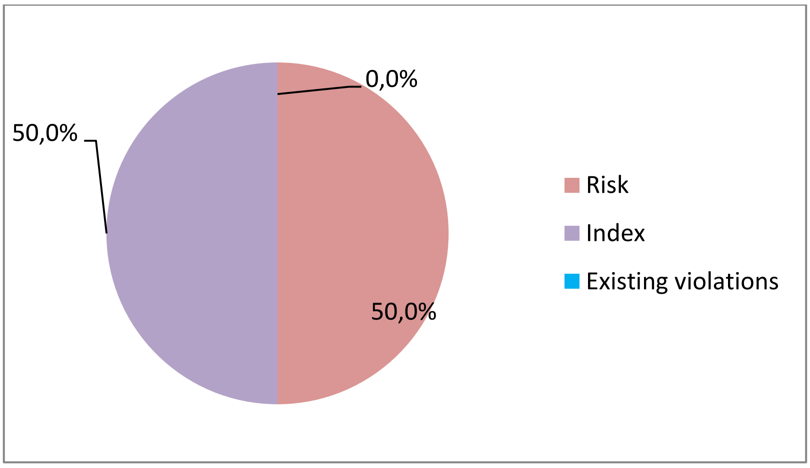


Figure 42. Extract from IV step: overview diagram of the risk, index and existing violations.

The auditor can draw a conclusion from the relation of the percent distribution of the calculated risk and index.

7.4.8.2 Synopsis: diagram of the rate between risk and index

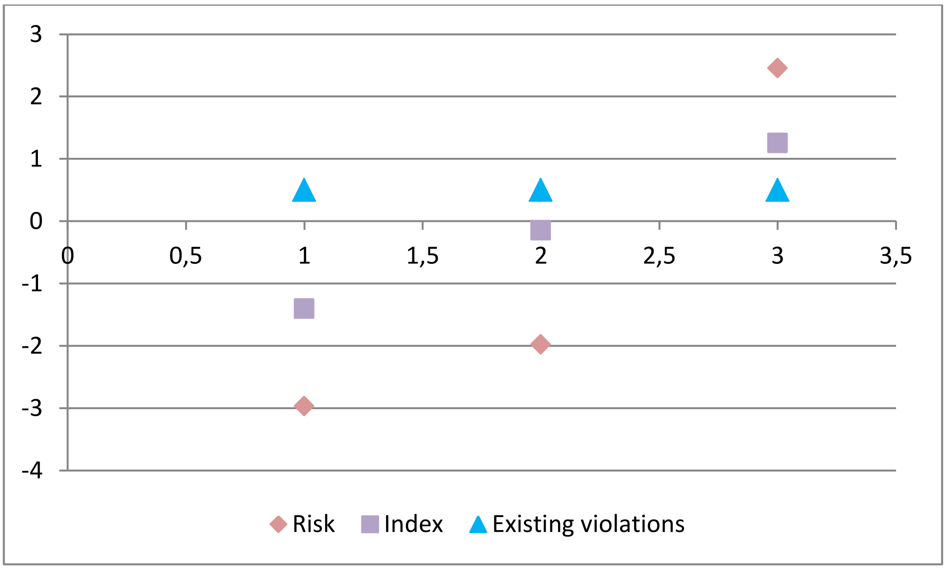


Figure 43. Extract from IV step: graphical overview of the calculated values.

The auditor can see in the diagram how the risk is spread. As in the example output table of the *common class of hazard* shows, the calculated hazard is evaluated as "middle":

Table 30. Data output mask of common class of hazard.

Common class of hazard	Middle	4.5

At the same time, the curve “Risk” in the diagram can be lower or higher as the zero line (x-axis) of the actual calculation of the common class of hazard. It means that, if the main part of the “Risk” curve is below the zero line, the danger is higher.

A better overview can be provided via a comparison of the relation of the rate with the risk and index. The “Index” curve only considers the evaluated macro and micro parameters by the auditor, while the “Risk” curve additionally considers the area of the considered object and the time of personnel presence, that in turn increases the hazards and threats.

Consequently influencing on one or another parameter, the auditor can change the results of the common class of hazard or manage the hazards and threats in detail.

7.4.8.3 Graphical overview of hazards and safety measures

Additional support for the auditor is visualised in diagrams:

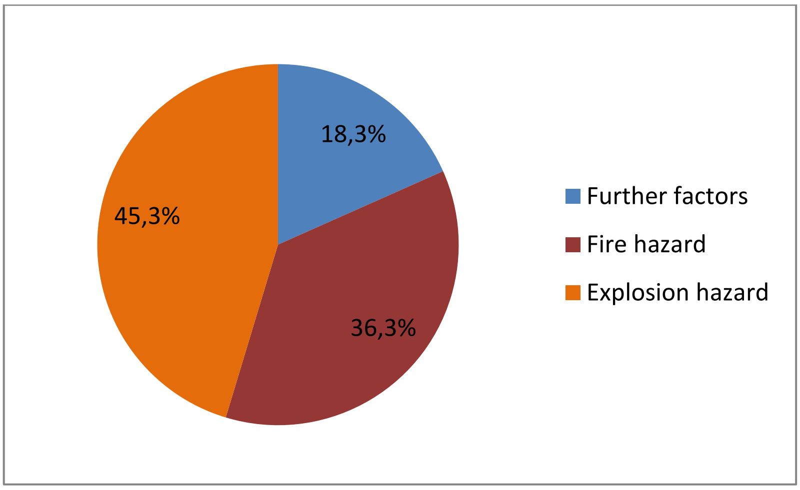


Figure 44. Extract from IV step: overview of hazards.

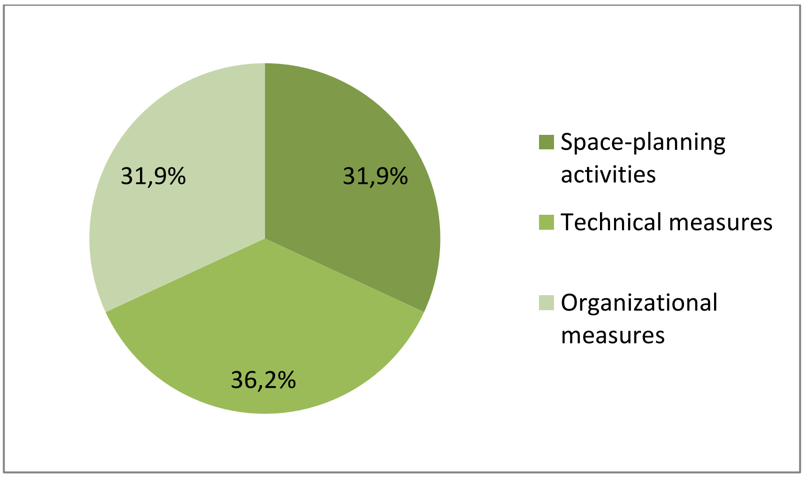


Figure 45. Extract from IV step: overview of safety measures.

With the help of such diagrams the auditor can influence certain micro parameters to change the results of the calculated individual risk.

7.5 Conclusions of the extended semi-quantitative approach for individual risk assessment

The field of quantitative or semi-quantitative risk analysis is comprehensive, multi-layered and complex. A systematic consideration of the research subject has been missing until today. Therefore, this dissertation seeks to develop a systematic method. The developed and presented method of a semi-quantitative risk analysis for the support of the risk calculation could be the subject of a discussion carried out from different points of view. The following aspects mentioned are a summary of the most important arguments which were discussed with the author at length.

The survey about operative indexing and QRA methods and applications in the field of EFP showed that a knowledge gap existed as well as an adequate implementation is missing until today. The number of commercial indexing and QRA application programs is surprisingly small. Furthermore these tools are only applicable for fire risks and do not consider explosion risks and hazards. Currently there is no clarity which of the specified application programs are more preferable to the quantitative analysis. Often, these approaches do not asses risk but hazards (i.e. ignoring the frequency parameter of risk) or only weight and evaluate the overall levels of fire safety of buildings, which is characteristic for indexing methods.

The methodological deficit lies in the fact of the change to a more flexible normalization of the regulations in the European countries. This includes a qualitative risk assessment aspect, which allows more flexibility regarding the audit. Nevertheless, such a so-called “new approach” has its advantages and disadvantages. The minimized restrictions in the field of explosion and fire risk assessment quickly result in the danger of a superficial and rough estimate of risk. Thus, the actual risk will not be assessed correctly. Among others there is no other approach to support the auditor to determine the explosion risk parallel to the already considered fire risk. Considering that the traditional approach of the rigid application of norms is now replaced with more flexible ones allowing alternative design decisions there is clearly a need for the development of new methods.

Due to the above mentioned problem definition a method was developed by the combination of the semi-quantitative and indexing approaches, which cannot only be applied in the field of fire risk assessment but also in the field of explosion risk assessment. By combining the two methods the resulting probabilistic method allows to carry out an audit, which bases on weighting procedures utilizable for risk rating and benchmarking.

The probabilistic model of the individual risk assessment discussed in this dissertation considers the most important aspects in the field of EFP such as:

- semi-quantitative risk assessment, based on the developed extended risk equation of the author
- controls probability of hazard and safety measures, based on an implemented ETA approach which is transformed into a more complex graph with an interconnection of different worst and best case scenarios and which is therefore implemented in a check list procedure that gives information about the risk spectrum of estimates
- the evaluation of the existing requests of the check list is supported by the determined weighting factors which place a great emphasis on the probabilistic approach concerning the whole concept

The expediency of the submitted weighting factors is discussed and the proof of the possibility of their applicability will be proposed in a reasonable way by a Bayesian network.

A problem still exists in the database of the frequencies of undesired events, in this respect the frequencies of a fire or of an explosion for a specific enterprise. The value of such a frequency is considered in the risk calculation. Therefore, recommendations were given by this critical examination. Among others examples of different useful databases were presented.

The uniqueness of the presented method lies in the robust, easy to understand approach that combines various parameters into a more stringent decision making process. The transformation of the ETA approach into a check list allows the consideration of a big number of scenarios, which are dependent from aspects causing explosions and fires, as well as aspects reducing explosion and fire hazards.

Additional advantages of the developed method are:

- the implementation of mathematical approaches as for instance the experimental standard deviation of the mean, also known as the uncorrected sample standard deviation or the standard deviation of a sample

and

- the consideration of the standard deviation or error ratios in the calculation of the individual risk values. None of the existing approaches or tools considers these. In turn such deviations must be duly considered due to the fact that the auditor cannot use the complete scale from 0 to 100% for the assessment of the check list.

The developed method is still depending on expert judgment. However the auditor is supported with data and weightings factors.

The presented method only calculates the individual risk but it can be used for other field of risk estimation such as material damage, building damage and interruption damage. To phrase it differently the optimization of the developed application or combination of it with other existing tools allows the auditor to evaluate the risk of undesired events, e.g. Crystal Ball® software as offered by (Kustosz 2013) for the monetary assessment of damage events (explosions).

8 Extended quantitative approach for consequence assessment

After preceding semi-quantitative approach for individual risk assessment it is advisable to follow the causes-effect chain by (Compes 1974) (fig. 46) because the calculated probability value of the individual risk does not give a statement about “When?” the undesirable scenario can happen. Therefore, it is important to assess the worst case scenarios, in other words to estimate the consequences. Thus, the auditor should additionally estimate the risk with regard to the potential accident scenarios and their impact (if → when…).

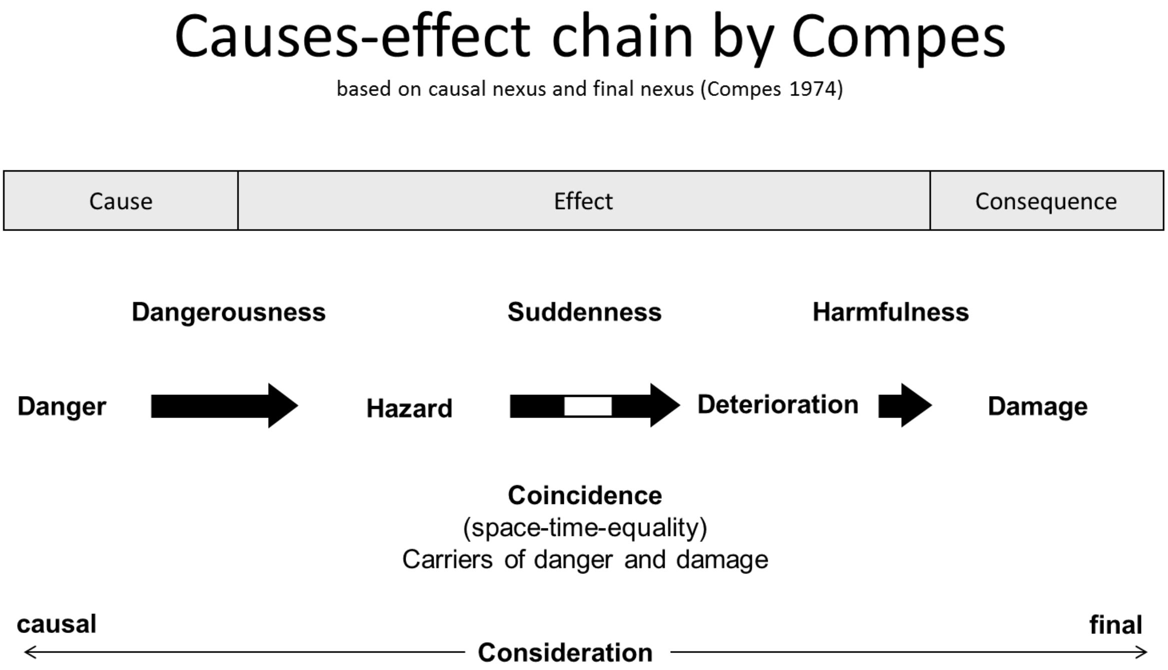


Figure 46. Cause-effect chain by (Compes 1974).

The part “Extended quantitative approach for consequence assessment” gives the auditor an option to calculate the physical effects and consequences (e.g. pool fire, explosion, fireball, jet fire) of hazardous substances, e.g. by releasing them from industrial plants, such as vessels, reactors, pumps and pipelines. “Although, the [CPI] has brought off measurements in industrial safety for a long time, there are still major accidents caused by technical failures of devices and systems, human errors, intentional acts, external events among many others.

In order to continuously improve safety engineering in general, it is a major task of industry, insurance and academia to build up a sound knowledge base about the potential accident scenarios” (Leksin et al. 2015).

There is a range of application programs (chapter 4.2) for risk assessment to calculate physical effects. Differences of the application programs are in their mathematical models, which are described in various standards.

However “from a quantity of different international technical standards, guidelines and ordinances, which describe the calculation of the physical effects of hazardous substances, no existing universal method is accepted as obligatory in the international or European-standard regulations in the field of [EFP]. Therefore, in some countries such as the Netherlands documents, e.g. the CPR-guidelines which are used in fields of labor safety, transport safety and fire safety exist. In Russia there are standards alike.

[…] authorities, enterprises and insurance companies use a bundle of different standards or [approaches]. As a consequence, the difference between standards complicates the point-by-point comparison of results and their representativeness” (Leksin et al. 2015).

8.1 Principle of the consequence assessment

As already designated in (chapter 4.2) the EFFECTS (TNO 2015) is a most common instrument on the European level for consequence assessment. This application program is based on different approaches described in the Dutch CPR-guidelines. Maintenances, optimisations as well as improvement of the EFFECTS (TNO 2015) have developed historically and have been supported for many years.

The extended quantitative approach for consequence assessment is based on a comparison of standards of two different legislative bodies: the Russian “Method to define the computed value of fire risks in industrial facilities” (Order No. 404 2009, Order No. 649 2010) and the TNO EFFECTS (CPR14E 2006) framework and the associated tool TNO EFFECTS using the YAWS Database (TNO EFFECTS 2014). The comparison of these two legislative bodies compares the accident scenarios as pool fire models (fig. 47) and the explosion model (fig. 48). The results of this comparative study are considered to improve risk assessment procedures in EFP.

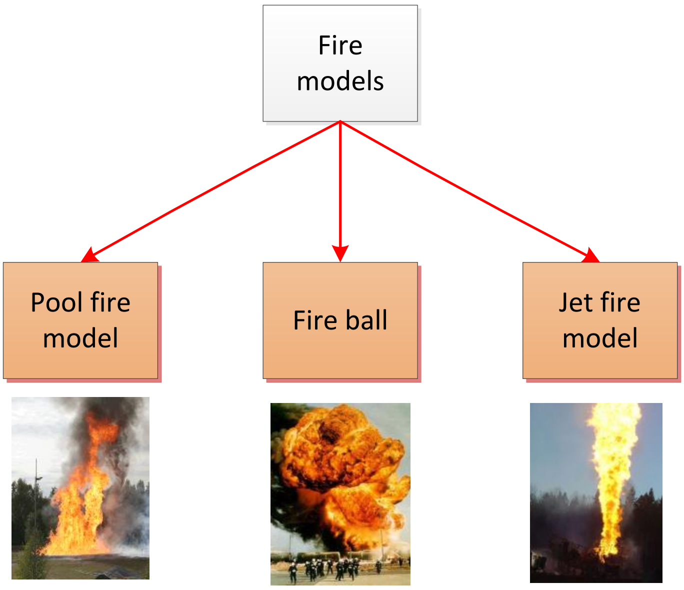


Figure 47. Fire models.

There are different types of explosions, but the most common accident scenario in the CPI is the confined or unconfined vapour cloud explosion, which will be presented in the comparison between the Dutch and Russian standards in chapter 8.5.

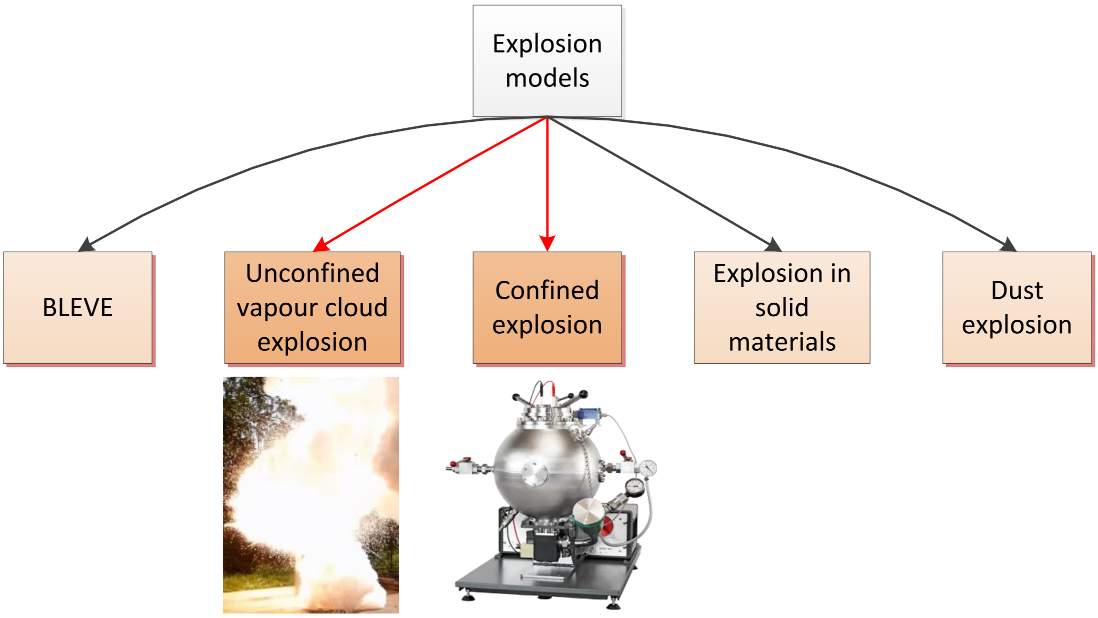


Figure 48. Explosion model.

In dependence of a substance and its aggregation state (liquid; gas; gas compressed to a liquid) in the vessel under specific conditions, one distinguishes between different accident scenarios. These are the paths of an event tree and the initiating event of this tree demands the release of the hazardous substance (see also Attachment “Event trees”). The most probable and most dangerous scenarios must be calculated and analysed.

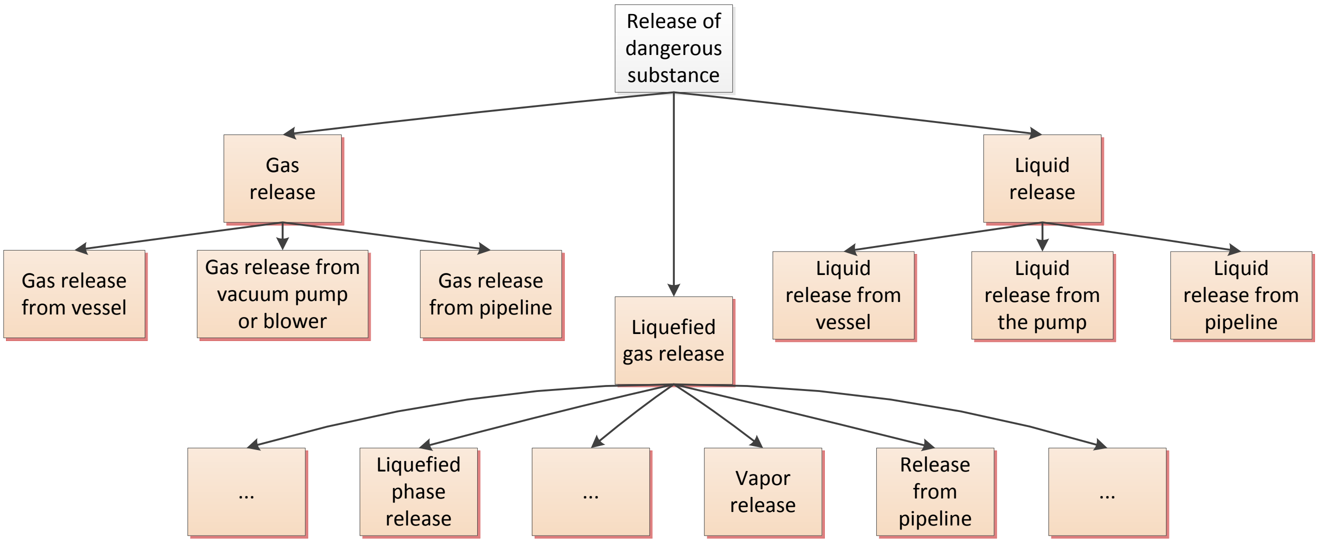


Figure 49. Example of different scenarios.

The remaining chapters are structured as follows: chapter 8.2 compares the pool fire models, chapter 8.3 compares the fire ball models, chapter 8.4 compares the jet fire model and chapter 8.5 compares the explosion models of the Russian and Dutch approaches.

8.2 Comparison of the pool fire models

The standards, described in chapter 8.1, consider cylindrical pool fire models and base on analogous models, i.e. the thermal parameters and atmospheric characteristics are comparable to each other.

Following chapters 8.2.1 – 8.2.7 are a quotation from (Leksin et al. 2015).

8.2.1 Russian approach

All notations in this chapter are translated and harmonized by the author from the Russian ordinance, i.e. (Order No. 404 2009) and its addition (Order No. 649 2010). All references and data are from this ordinance unless specified otherwise.

The heat radiation (heat flux) q [kW/m^2] of the pool fire of flammable liquids, combustible liquids and liquid petroleum gas (LPG) is determined by:

$$q = E_f \cdot F_q \cdot \tau \tag{26}$$

where E_f = actual surface emissive power (SEP) of the flame [kW/m^2] (notation according to (CPR14E 2006)); F_q = view factor; τ = atmospheric transmissivity.

The E_f can be defined on the basis of the available experimental data or with the help of table 31:

Table 31. SEP depending from the pool diameter d and the burning flux at still weather conditions m'.

Fuel	E_f [kW/m^2] at d [m]					m'
	10	20	30	40	50	[kg/m^2·s]
LPG (Methan)	220	180	150	130	120	0.08
LPG (Propan–Butan)	80	63	50	43	40	0.10
Gasoline	60	47	35	28	25	0.06
Diesel	40	32	25	21	18	0.04

Note: For pool fire diameters < 10 [m] or > 50 [m], the SEP is identical to the diameter of 10 [m] and 50 [m] respectively.

In absence of data for oil and oil products E_f can be defined as follows:

$$E_f = 140 \cdot e^{-0.2 \cdot d} + 20 \cdot \left(1 - e^{-0.12 \cdot d}\right) \tag{27}$$

where d = pool fire diameter [m].

In absence of data for one-component liquids it is allowed to define E_f as follows:

$$E_f = \frac{0.4 \cdot m' \cdot H_{SG}}{\left(1 + 4 \cdot \dfrac{L}{d}\right)} \tag{28}$$

where m' = burning flux at still weather conditions [kg/m^2·s]; H_{SG} = heat of combustion [kJ/kg] (in the Russian original $H_{\text{Сг}}$); L = average height of the flame [m]. In the absence of data for one-component liquids it is allowed to define m' as follows:

$$m' = \frac{0.001 \cdot H_{SG}}{L_g + C_P \left(T_b - T_a\right)} \tag{29}$$

where L_g = vaporization heat of the flammable material at its boiling point [kJ/kg]; C_p = specific heat capacity at constant pressure [kJ/kg·K]; T_b = liquid boiling temperature [K]; T_a = ambient temperature [K].

For compounding mixed liquids, the major substance defines E_f and m'.

The view factor F_q is defined as:

$$F_q = \sqrt{F_V^2 + F_H^2} \tag{30}$$

where F_V^2, F_H^2 = factors of irradiancy for vertical and horizontal platforms, defined for the platforms located in 90° sector in the direction of the flame inclination with the help of the equations (31 to 40); cf. (Atallah 1990):

$$\begin{aligned} F_V = \frac{1}{\pi} \cdot \Bigg\{ & -E \cdot \operatorname{arctg} D + E \cdot \left[\frac{a^2 + (b+1)^2 - 2 \cdot b \cdot (1 + a \cdot \sin\theta)}{A \cdot B} \right] \cdot \operatorname{arctg}\left(\frac{A \cdot D}{B} \right) + \dots \\ & \dots + \frac{\cos\theta}{C} \cdot \left[\operatorname{arctg}\left(\frac{a \cdot b - F^2 \cdot \sin\theta}{F \cdot C} \right) + \operatorname{arctg}\left(\frac{F^2 \cdot \sin\theta}{F \cdot C} \right) \right] \Bigg\} \end{aligned} \tag{31}$$

$$\begin{aligned} F_H = \frac{1}{\pi} \cdot \Bigg\{ & \operatorname{arctg}\left(\frac{1}{D} \right) + \frac{\sin\theta}{C} \cdot \left[\operatorname{arctg}\left(\frac{a \cdot b - F^2 \cdot \sin\theta}{F \cdot C} \right) + \operatorname{arctg}\left(\frac{F^2 \cdot \sin\theta}{F \cdot C} \right) \right] - \dots \\ & \dots - \left[\frac{a^2 + (b+1)^2 - 2 \cdot (b + 1 + a \cdot b \cdot \sin\theta)}{A \cdot B} \right] \cdot \operatorname{arctg}\left(\frac{A \cdot D}{B} \right) \Bigg\} \end{aligned} \tag{32}$$

$$a = \frac{2 \cdot L}{d} \tag{33}$$

$$b = \frac{2 \cdot X}{d} \tag{34}$$

$$A = \sqrt{\left(a^2 + (b+1)^2 - 2 \cdot a \cdot (b+1) \cdot \sin\theta\right)} \tag{35}$$

$$B = \sqrt{\left(a^2 + (b-1)^2 - 2 \cdot a \cdot (b-1) \cdot \sin\theta\right)} \tag{36}$$

$$C = \sqrt{\left(1 + \left(b^2 - 1\right) \cdot \cos^2\theta\right)} \tag{37}$$

$$D = \sqrt{\left(\frac{b-1}{b+1}\right)} \tag{38}$$

$$E = \frac{a \cdot \cos\theta}{b - a \cdot \sin\theta} \tag{39}$$

$$F = \sqrt{\left(b^2 - 1\right)} \tag{40}$$

where X = distance from the geometrical center source to the receiver [m]; d = pool fire diameter [m]; L = flame length [m]; θ = flame tilt angle (angle between flame centerline and surface normal) – according to the Russian ordinance defined as: flame deviation angle from a vertical under the influence of a wind.

For the platforms located out of the specified sector and also in cases of lack of a wind, the factors of irradiancy for vertical and horizontal platforms are calculated by equations (31 to 40) and (43), accepting $\theta = 0$.

The pool fire diameter is:

$$d = \sqrt{\frac{4 \cdot F}{\pi}} \tag{41}$$

where F = pool surface [m^2].

Flame length L is calculated as:

$$L = \begin{cases} 55 \cdot d \cdot \left(\dfrac{m'}{\rho_a \cdot \sqrt{g \cdot d}} \right)^{0.67} \cdot u_*^{0.21}: & u_* \geq 1 \\ 42 \cdot d \cdot \left[\dfrac{m'}{\rho_a \cdot \sqrt{g \cdot d}} \right]^{0.61}: & u_* \leq 1 \end{cases} \tag{42), (43}$$

where

$$u_* = \frac{w_0}{\sqrt[3]{\dfrac{m' \cdot g \cdot d}{\rho_\Pi}}} \tag{44}$$

and where m' = burning flux at still weather conditions [kg/m^2·s]; ρ_a = density of air [kg/m^3]; ρ_Π = vapour density of the flammable materials by boiling point [kg/m^3]; w_0 = wind velocity [m/s]; g = gravitational acceleration [9.81 m/s^2].

Flame deviation corner from a vertical under the influence of a wind is:

$$\cos\theta = \begin{cases} 1, & \text{if } u_* < 1 \\ u_*^{-0.5}, & \text{if } u_* \geq 1 \end{cases} \tag{45}$$

Atmospheric transmissivity τ is:

$$\tau = \exp\left[-7 \cdot 10^{-4} \cdot \left(X - 0.5 \cdot d \right) \right] \tag{46}$$

8.2.2 Dutch approach

Many readers presumably know the Dutch TNO EFFECTS and the associated software tool (cf. TNO EFFECTS 2014). For this, and as the Dutch approach uses mainly the same model as the Russian approach, TNO EFFECTS is outlined by its input parameters in the following.

TNO EFFECTS offers data input modes for different model parameter quantification options. The options “show only simple parameters” and “show only normal parameters” provide default values and bases on standard parameters. The mode “show expert parameters” is discussed next. At a first glance, all specified parameter data are demanded from the auditor, i.e. scenario characteristics on pool fire, atmospheric and personal injury. However the auditor may use some default input data in case of lacking some parameter data.

TNO EFFECTS comes up with an extended and single data input mask which goes beyond the presentation constraints of this chapter. Tables 32 to 34 structure the input process according the scenario characteristics mentioned above. Terminology is retained unchanged. Substance data are from (CPR18E 2005) database (state: 22.07.1999).

Table 32. Data input of pool parameter characteristics.

Description	Input Data
Chemical name	…
Pool size determination	Confined or Unconfined fixed feed
Total mass release, [kg]	
Pool surface pool fire, [m^2]	…
Height of the receiver, [m]	…
Height of the confined pool above ground level, [m]	…
Temperature of the pool, [°C]	…
Pool burning rate, [kg/m^2·s]	Calculate/*Default* or User defined
Value of pool burning rate, [kg/(m^2·s)]	*Default = 0.1*
Fraction combustion heat radiate	*Default =0.35*
Soot fraction	Calculate/*Default* or User defined

As above-mentioned, the auditor may also use some default input values in the “show expert parameters” mode (italicised in tables 32 and 34).

Table 33. Data input of the atmospheric characteristics.

Description	Input Data
Wind speed at 10 [m] height, [m/s]	…
Ambient temperature, [^{o}C]	…
Ambient relative humidity, [%]	…
Amount of CO_2 in atmosphere	…
Predefined wind direction	User defined

	(N, NNE, etc.)
Wind comes from (North = 0 degrees), [deg]	…

Wind direction in table 33 is defined by the common section of a compass rose.

Table 34. Data input of personal damage characteristics.

Description	Input Data
Distance from center of the pool (Xd), [m]	…
Maximum heat exposure duration, [s]	…
Calculate contours for	1st degree burns, 2nd degree burns, lethal burns, physical effects
Take protective effects of clothing into account	Yes/no
Percentage of mortality for contour calculations, [%]	*Default = 1*
Heat radiation damage Probit A, [$s\cdot(W/m^2)^n$]	*Default = -36.38*
Heat radiation damage Probit B	*Default = 2.56*
Heat radiation damage Probit N	*Default = 1.33*

By default, the probit function of equation (47), as given in (CPR16E 2005), has been used to calculate the impact of heat radiation on human life:

$$\mathrm{Pr} = -36.38 + 2.56 \cdot \ln\left(q^{4/3} \cdot t\right) \tag{47}$$

where q = the heat radiation level [W/m^2] and t = the exposure duration in seconds, which is assumed maximal 20 [s].

This probit value is then mapped to a fraction of mortality in the interval [0; 1]. This implies a Probit A of -36.38, Probit B = 2.56, and Probit N = 4/3 for lethal burns. [A Probit A of -39.83, Probit B = 3.0186, and Probit N = 4/3 for 1st degree burns and Probit A of -43.14, Probit B = 3.0186, and Probit N = 4/3 for 2nd degree burns].

The quantitative measure of the effect on human life is also defined as probability of loss of life. It was defined by the relationship (Less 1986) using the probit function:

$$Y(r) = k_1 + k_2 \cdot \ln(V) \tag{48}$$

where $Y(r)$ = the percentage of vulnerable resources which sustain injury or damage; k_1, k_2 = parameters to specify accidents (defined also as “constants” in the majority literature); V = the product of intensity or concentration of received hazardous agent to an exponent n and the duration of exposure in seconds or minutes. For thermal radiation:

$$V = I^{4/3} \cdot t \tag{49}$$

which defines the thermal dose in $[(kW/m^2)^{4/3} \cdot s]$. The TNO EFFECTS refer for these constants on (Eisenberg at al. 1975)

The output mask of TNO EFFECTS summarizes the calculation results. Table 35 lists all quantified parameters.

Table 35. Quantified parameters in TNO EFFECTS (Data output).

Parameters	Parameters
Max Diameter of the Pool Fire, [m]	
Heat radiation at X, [kW/m^2]	View factor, F_q
1% Third degree (Lethal) burns distance, [m]	Atmospheric transmisivity, [%]
Combustion rate, [kg/s]	Flame temperature, [^{o}C]
Duration of the pool fire, [s]	Length of the flame, [m]
Heat emission from fire surface, [kW/m^2]	Calculated pool surface area, [m^2]
Flame tilt, [deg]	Weight ratio of CO$_2$/chemical, [%]

8.2.3 Comparison

To resume the described Russian method, the equation (26) of the calculation of the heat flux is the same as in (Mudan 1984) or (TNO EFFECTS 2014, CPR14E 2006) which is based on (Rew & Hulbert 1996). Equation (28) calculates the SEP similar to the equation in (TNO EFFECTS 2014, CPR14E 2006). The difference is in the considered “Fraction of the generated heat radiated form the flame surface”, which is determined in equation (28) as the factor 0.4 and in (TNO EFFECTS 2014) as 0.35, in spite of the fact that this value depends on properties of substance. The (TNO EFFECTS 2014) determines this factor 0.35 because there is no chemical relied value available at the time of the development of the (CPR14E 2006) model. However the new version tool of the EFFECTS Version 10 will include the so-called two zone pool fire model, which is based on the work of (Rew & Hulbert 1996). The Russian method uses the equation (27) additionally for oil and oil products. This correlation was adapted by (Mudan 1984) using data from gasoil, kerosene and JP-5. The calculation of the m' burning rate at still weather conditions of equation (29), the view factor of equation (30) and the pool diameter of equation (41) are the same in both methods.

By the calculation of the flame length of equation (42) the (TNO EFFECTS 2014) uses the version of (Thomas 1963), which implements the influence of the wind on the flame length and if $u_* \le 1$ then $u_* = 1$. The difference to the Russian method is that if $u_* \le 1$, the flame length is calculated by equation (43) of (Thomas 1963) upon laboratory measurements of fire on wood.

An exact calculation of the atmospheric transmissivity τ is intricate, depending on the radiator temperature, the absorption and the flame temperature. The Russian approach uses the simplified equation (50). (TNO EFFECTS 2014) defines τ as:

$$\tau_a = 1 - \alpha_W - \alpha_C \qquad (50)$$

The atmospheric transmissivity τ_a measures the absorbed heat, emitted by fire and absorbed by the air in between the radiator and the observer. Without absorption factors, τ_a equals to 1. The absorption factors α_W and α_C depend upon the properties of the main absorbing components (H_2O and CO_2) in the air. The absorption factors α_W and α_C are estimated by using the graphs from (Hottel 1967), which can also be found in (CPR14E 2006).

8.2.4 Prototype tool of the Russian approach

To compare the two tools, the Russian approach was transformed into a tool.

Chapter 8.2.1 outlined the Russian approach from the side of the equations to have an overview about the parameters from which the calculated heat flux depends on, and this chapter introduces the method in form of an MS Excel prototype which gives the auditor a simple option to calculate the heat flux, depending on the distance, maximum diameter of the pool fire and the injury based on the probit function. Therefore, the auditor must only enter the next parameters:

- Substance
- Total mass released [m^3] (marked by the author as $V_{ж}$);
- Coefficient of the released mass. It depends on the surface of the drip pan (marked by the author as f_p);
- Pool surface pool fire [m^2] (marked by the author as F_{psp}).

The database of the tool prototype is implemented for the following substances: LPG, LNG, gasoline, diesel and oil (petroleum product). If the auditor has other substances (e.g. hexane) he must enter additional properties of the substance, as the L_g vaporisation heat of the flammable material at its boiling point [kJ/kg]; C_p specific heat capacity at constant pressure [kJ/kg·K]; T_b the liquid boiling temperature [K]; T_a ambient temperature [K] – to calculate the m' burning rate at still weather conditions [$kg/m^2 \cdot s$] and the H_{SG} heat of combustion [kJ/kg] – to calculate the E_f actual surface emissive power of the flame [kW/m^2].

Also w_0 [m/s] wind velocity and $\rho_П$ [kg/m^3] vapour density of the flammable materials by boiling point can be considered.

After the input of these data, the results are:

for a set of heat flux values $q=\{10.5, 7.0, 4.2, 1.4\}$ the tool gives the distance from the center of the pool fire [m]. The heat flux figures are chosen from (Siegel et al. 2001) and (Order No. 404 2009).

At the same time the tool calculates the probit function Pr for the entered distance (table 36) and gives the probability (%) of the lethal outcome (probability of fatality to personnel) as output:

Table 36. Data output table.

Parameter	Output (example)
Pr	5.570
Q, [%]	71.555

For a set of probabilities of fatality to personnel [%] $Q = \{99.9, 90.0, 50.0, 10.0, 1.0\}$ the tool gives the distance from the center of the pool fire [m].

In the Russian approach the calculated probit function has been used for the exposure to heat radiation and used another equation, based on (Tsao and Perry 1979):

$$\Pr = -12.8 + 2.56 \cdot \ln\left(t \cdot q^{\frac{4}{3}} \right) \tag{51}$$

where q = the heat radiation level in [W/m^2] and t = the exposure duration in [sec], which is calculated by:

$$t = t_0 + \frac{x}{u} \tag{52}$$

where t_0 = time in which the person finds the fire and makes the decision about further actions (can be accepted as 5 seconds) [s]; x = distance from the location of the person to a safety zone [m] (the safety zone is defined by heat flux $q \le 4$ [kW/m^2]); u = average speed of the movement of the person to a safety zone [m/s] (u = 5 [m/s]).

The probit value is transferred to a fraction of mortality of 1.

8.2.5 Calculation

For the comparison of Dutch and Russian standards, three different substances (Gasoline, Propane and Methanol) and four kinds of scenarios of a pool fire with a pool surface F=1000 [m^2] and F=100 [m^2], and wind velocity w_0=0.1 [m/s] and w_0=7 [m/s] were chosen. Thus, there is a chance to compare 12 scenarios. As the Dutch method measures the heat flux of the height of the receiver in 1.5 meter and the Russian method does not consider this parameter, the problem is solved to compare the Russian method with two calculated results in TNO EFFECTS in 1.5 (default value) [m] and 0 [m] of the height of the receiver. (The author assume, that the Russian approach uses 0 [m] as default value).

The results of the comparison of the 12 calculated scenarios are presented in tables 37 to 39:

Table 37. Comparison of calculated heat flux q for Gasoline.

Scenario	Approach	Distance *m* [m] from the surface			
		20	45	70	100
		Heat flux *q* [kW/m^2]			
Gasoline 1000 m^2	Russian	17.5	6.0	2.8	1.4
	TNO 1.5	50.0	10.8	5.0	2.5

0.1 m/s	TNO 0.0	33.5	10.3	4.9	2.8
Gasoline 1000 m² 7.0 m/s	Russian	28.8	18.5	8.1	2.4
	TNO 1.5	118.8	28.1	9.8	3.0
	TNO 0.0	56.6	26.5	9.6	3.0
Gasoline 100 m² 0.1 m/s	Russian	7.7	1.8	0.8	0.4
	TNO 1.5	6.7	1.5	0.6	0.3
	TNO 0.0	6.1	1.5	0.6	0.3
Gasoline 100 m² 7.0 m/s	Russian	32.0	3.6	0.8	0.3
	TNO 1.5	20.9	1.5	0.4	0.2
	TNO 0.0	17.8	1.5	0.4	0.2

At F=1000 [m^2] according to the Russian approach by increase the wind velocity from w_0=0.1 [m/s] to w_0=7 [m/s] the heat flux at 20 meter distance increases on 65%, while TNO EFFECTS shows an increase more than twice (at a height of the receiver 1.5 meter) and approximately same by height of the receiver 0 meter. By the increase of the distance the difference in the Russian approach between the heat flux between wind velocity w_0 = 0.1 [m/s] and w_0 =7 [m/s] is bigger than in TNO EFFECTS, especially considering a distance of 70 meters.

By the increase of the distance from the center of the pool fire the calculated heat flux in both approaches becomes comparable.

At F=100 [m^2] the calculated heat flux in Russian approach is bigger, but by w_0=0.1 [m/s] the results are comparable. By increase of the wind velocity the difference between the approaches increases and the Russian approach gives a higher result.

Table 38. Comparison of calculated heat flux q for Propane.

Scenario	Approach	Distance *m* [m] from the surface			
		20	45	70	100
		Heat flux *q* [kW/m²]			
Propane 1000 m² 0.1 m/s	Russian	26.0	9.6	5.0	2.6
	TNO 1.5	50.9	11.0	5.1	2.6
	TNO 0.0	34.1	10.5	5.0	2.5
Propane 1000 m² 7.0 m/s	Russian	41.1	24.2	13.6	5.6
	TNO 1.5	120.8	28.1	10.0	3.1
	TNO 0.0	57.6	26.9	9.8	3.1
Propane 100 m² 0.1 m/s	Russian	11.3	3.1	1.3	0.7
	TNO 1.5	6.8	1.5	0.6	0.3
	TNO 0.0	6.2	1.5	0.6	0.3
Propane 100 m² 7.0 m/s	Russian	37.2	8.5	2.0	0.7
	TNO 1.5	21.3	1.5	0.4	0.2
	TNO 0.0	18.0	1.5	0.4	0.2

At $F=100$ [m^2] the differences are bigger in the Russian approach.

By the comparison of the scenarios for Gasoline and Propane it can be seen, that for the bigger pool surface area, the calculated heat flux is bigger in TNO EFFECTS and if the pool surface is smaller, the calculated heat flux is bigger in the Russian approach. The reason is that by determining of the surface emissive power E_f for Gasoline and Propane the Russian method uses the table 33 and for Methanol table 41 it uses the equation (28). By increasing of the pool surface (table 31) the surface emissive power E_f decreases, but based on the equation (28) with increase of the pool diameter the surface emissive power E_f increases too.

Table 39. Comparison of calculated heat flux *q* for Methanol.

Scenario	Approach	Distance *m* [m] from the surface			
		20	45	70	100
		Heat flux *q* [kW/m²]			
Methanol 1000 m² 0.1 m/s	Russian	37.4	10.2	4.2	1.9
	TNO 1.5	28.8	6.1	2.8	1.4
	TNO 0.0	19.3	5.8	2.7	1.4
Methanol 1000 m² 7.0 m/s	Russian	55.3	23.9	5.2	1.7
	TNO 1.5	66.5	15.4	5.3	1.6
	TNO 0.0	31.6	14.5	5.2	1.6
Methanol 100 m² 0.1 m/s	Russian	5.2	1.0	0.4	0.2
	TNO 1.5	4.0	0.9	0.4	0.2
	TNO 0.0	3.7	0.9	0.4	0.2
Methanol 100 m² 7.0 m/s	Russian	13.7	0.8	0.3	0.1
	TNO 1.5	12.1	0.9	0.2	0.1
	TNO 0.0	10.3	0.9	0.2	0.1

The overall comparison shows the following results: by a pool surface of F=1000 [m^2] the difference of the calculated heat flux in the distance near the fire (till 45 meters) is very high. This can be seen by the substances Gasoline and Propane. The TNO EFFECTS results are twice as big as in the Russian approach.

Thereby by a pool surface of F=100 [m^2] the results in the Russian approach are at least twice as big as by TNO EFFECTS, independent from the wind velocity.

Whereby for a pool surface of F=100 [m^2] and F=1000 [m^2] and wind velocity w_0=7 [m/s] the differences are much higher, as by wind velocity w_0=0.1 [m/s].

Thus, by the increase of the wind velocity the calculated heat flux increases between the two methods.

By F=1000 [m^2] and w_0=7 [m/s] the heat flux increases in TNO EFFECTS. And by F=100 [m^2] and w_0=7 [m/s] the heat flux is higher in the Russian approach.

Closest values to each other are in the next scenarios:

- *Propane*, *F=1000* [m^2], w_0*=0.1* [m/s] at a distance 70 and 100 meter;
- *Methanol*, *F=100* [m^2], w_0*=0.1* [m/s] at a distance 70 and 100 meter and by w_0*=7* [m/s] at a distance of 100 meter;

Most different values are in the next scenarios:

- *Gasoline*, *F=1000* [m^2], w_0*=7* [m/s] the difference increases from the center of the pool fire; considering a distance of 20 meters the difference is between 28.8 [kW/m²] (Russian approach) and 118.8 [kW/m²] (TNO in 1.5 meter height of the receiver). The same scenario considering *Propane* also shows such a huge difference between both approaches.
- By *Propane*, *F=100* [m^2], w_0*=7* [m/s] from a distance of 45 meters the heat flux in the Russian approach is 8.5 [kW/m²] and by TNO EFFECTS 1.5 [kW/m²].

As table 39 shows, the results in the scenarios with Methanol are approximately the same, but for substances as Gasoline and Propane, and also for supposed others like LPG and Diesel, the calculated heat flux can be more or less compared with the Russian approach depending on the pool surface area.

8.2.6 Reference values

Due to the distinction of the corresponding results, they were compared with the experimental data described in (Koseki 1989). This report includes experiments with incident heat flux measurement data at a distance of 5 times the pool diameter from the center of the pool fires. These experiments are done with Heptane, Gasoline, Kerosene and Hexane. Because the ambient conditions are not reported, the atmospheric conditions are assumed: ambient pressure 1.01325 [Pa], ambient temperature 293 [K], relative humidity 70 [%]. Because of the TNO tool version used by the author is based on the YAWS Database it was only possible to compare the results with one substance – Gasoline. The compared results are presented in table 40:

Table 40. Comparison of the Russian and Dutch approaches with experimental data tests by (Koseki 1989).

Diameter of the pool fire, [m]	3	6	10	22.3
Pool fire area, [m^2]	7.07	28.27	78.54	390.57
Distance from the surface, [m]	15	30	50	111.5

Measured heat flux at x/D=5 based on experimental data by Koseki, [kW/m^2]	1.9	1.1	0.76 (average)	0.4
Heat flux calculated by the Russian approach, [kW/m^2]	1.74	1.45	1.26	0.72
Heat flux calculated by the TNO 1.5 meter height of the receiver, [kW/m^2]	0.87	0.68	0.57	0.45
Heat flux calculated by the TNO 0 meter height of the receiver, [kW/m^2]	0.83	0.68	0.57	0.45

This comparison shows that the calculated results in the Russian approach are more comparable for the small diameters of the pool fire and for the bigger diameters the TNO EFFECTS results are comparable. But the downsides of these results are the same as in the conclusions based on tables 37 to 39: by the increase of the distance from the center of the pool fire the calculated heat flux becomes comparable.

Table 41 shows the comparison of the results of the Russian approach and the experimental data for other substances:

Table 41. Comparison of the Russian approach with experimental data tests by (Koseki 1989).

	Heptane	Kerosene		Hexane	
Diameter of the pool fire, [m]	6	30	50	3	6
Pool fire area, [m^2]	28.27	706.9	1963.5	7.07	28.27
Distance from the surface, [m]	30	150	250	15	30
Measured heat flux at x/D=5 based on experimental da-ta by Koseki, [kW/m^2]	2.22	0.43	0.23	2.23	1.28
Heat flux calculated by the Russian approach, [kW/m^2]	2.43	0.3	0.21	3.31	2.11

This comparison shows that the calculated results in the Russian approach do not always differ depending on the surface area (pool fire diameter). It is possible to draw the conclusion that the calculated heat flux in both methods does not only depend on the surface area of the pool but rather also on which material properties are used and considered.

8.2.7 Synopsis

As mentioned in chapter 8.2.5, Gasoline and Propane computations result in most different values. This section scrutinizes the causes in detail. The main reason is the different calculation of SEP in the Russian and Dutch approach. The Dutch use equation (28) for all substances in consideration (CPR14E 2006):

$$E_f = \frac{0.35 \cdot m' \cdot H_{SG}}{\left(1 + 4 \cdot \frac{L}{d}\right)} \tag{53}$$

The Russian approach uses a slightly different equation (28) (Factor 0.4 instead of 0.35) for one-component liquids only (cf. chapter 8.2.5). As a consequence, the results for, e.g. one-component liquid Methanol, are broadly similar. The influence of the small difference for the scenarios with Methanol can be observed in the different calculation of the atmospheric transmissivity τ (cf. equations 46 and 50), as well as they have an impact on the equation of the heat flux (cf. equation 26)

For substances as Gasoline, Propane among others, the Russian approach uses experimental data, as given in table 31. As shown in table 31, the SEP value becomes smaller when increasing pool diameter *d*. This is in contrast to equation (28) in which the increasing of the pool diameter, the SEP increases too.

In summary, the Dutch approach only relies on equation (53) for all substances, whereas the Russian approach also uses experimental outcomes (cf. table 31) and differentiates between substances (τ one-component liquids, oil and oil products). For this, the Russian approach is considered to be closer to reality.

Further the Dutch approach is conservative for the scenarios of pool fires for Gasoline and Propane (i.e, $F=1000$ [m^2], $w_0=7$ [m/s] and $w_0=0.1$ [m/s]). Which in turn, it overestimates the needed level of measures in the field of fire safety and, in consequence, financial expenses.

Moreover, the Dutch results are often unexpected for Gasoline, Propane and Methanol computations when considering heat fluxes in 0 and 1.5 meters. The results differ in twice the amount and are bigger at 1.5 meters.

8.2.8 Conclusions

"[…] both approaches rest upon the same physical models of an idealized black body, the implementation shows differences. For instance, also different probit function and constants are used in both approaches. For this, it is not surprising that the models in use are slightly different. Furthermore both ordinances are industry standards which imply their design for practical oriented purposes and eased feasibility. Again, there are differences. The comparison of models, results, contact with reality and feasibilities gives hints towards methodological improvements and tool development.

The differences [can] raise the question on closeness to reality of analysis results of both approaches. As there is a common lack of data, it is impossible for anyone to verify models and results” (Leksin et al. 2015). Logically, in both approaches it should be questioned: „Do the calculated heat flux values reflect real conditions?”

The answer to this question can be found in large-scale tests by the Technical Research Institute of Sweden SP (ETANKFIRE 2015) performed in the ETANKFIRE project 2015.

“The thermal radiation from pool fires burning ethanol is less than that from similar fires of petrol, which is confirmed by test results from 2 m^2 pool fires…[…] The difference between petrol and ethanol fires is expected to increase further for even larger fuel surface areas, as ethanol seems to be less dependent on the size of the fuel surface area. As present-day fuel storage tanks for ethanol often have a considerably larger area than the 250 m^2 that were used in the trials…[…] The results (fig. 50) are striking: close to the fire, an ethanol fire radiates 2-3 times as much heat as a petrol fire, with the radiant density still being about twice as high further away” (Firesafetysearch 2015).

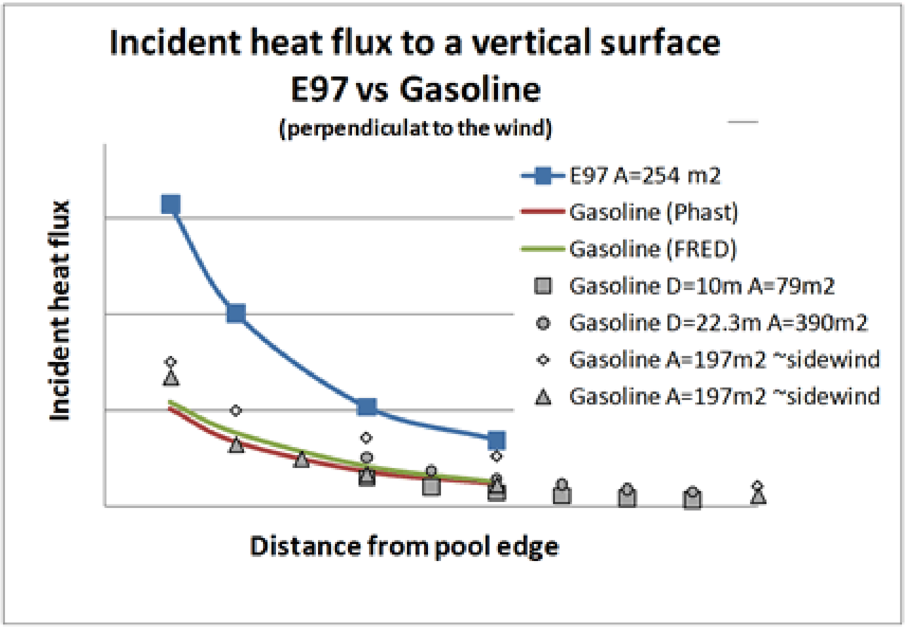


Figure 50. Extract from (Firesafetysearch 2015).

“Radiant heat fluxes from the 254 m² tank trial of ethanol (E97) (blue) and calculated values for a corresponding petrol fire (green/red lines). For comparison, the (fig. 50) also shows some experimental results from similar petrol fires (grey symbols)” (Firesafetysearch 2015).

The analytical comparison of Dutch and Russian standards demonstrates that the Russian approach with the calculated results of the heat flux values for gasoline and methanol reflects the real conditions properly.

“As shown, the Russian approach and the according MS Excel tool prototype, is easier [to apply - as] it requires less inputs (only 3 inputs), which gives a better chance for the auditor to view the serviceability (e.g. with regard to operational resource requirements and efficiency). The Dutch tool TNO EFFECTS has also the possibility to view the option called “show only simple parameters” or using the “Defaults” – however the defaults are not appropriate and safe for every scenario” (Leksin et al. 2015).

8.3 Comparison of the fire ball models

The standards, described in chapter 8.1, consider the fire ball models. Both standards figure out different understanding of formation of a fire ball. For instance the Dutch approach considers the fire ball from a BLEVE (boiling liquid expanding vapour cloud explosion) effect. This is described in more detail in chapter (8.3.2). The input data also differ. So, the Dutch approach, e.g. needs the burst pressure of the vessel due to the BLEVE effect and other atmospheric characteristics. The Russian approach uses the mass which is released and the thermal parameters of the substance. For the calculation of a typical BLEVE effect the Russian approach uses a model described in (GOST 12.3.047-2012 2012) in order to calculate the overpressure by an explosion of the vessel and the positive phase duration.

Thus, the comparison of the Dutch and Russian approaches cannot be significant because of different models. Nevertheless, both approaches can be compared with different scenarios.

8.3.1 Russian approach

There are three possibilities for the formation of a fire ball:

- Emission of combustible gas and its instant ignition;
- Emission of LPG or LNG, its instant evaporation and ignition;
- Emission of vapours of overheated liquid, instant evaporation stills part of liquid and its ignition.

All notations in this chapter are translated and harmonized by (A. Leksin) from the Russian ordinance, i.e. (Order No. 404 2009) and its addition (Order No. 649 2010). All references and data are from this ordinance unless specified otherwise.

The heat radiation (heat flux) q [kW/m^2] of the fire ball is determined by the same equation (26) in pool fire:

$$q = E_f \cdot F_q \cdot \tau \tag{26}$$

where E_f = actual surface emissive power (SEP) of the flame [kW/m^2] (notation according to (CPR14E 2006)); F_q = view factor; τ = atmospheric transmissivity.

E_f can be quantified by experimental data (table 31) or uses 350 kW/m^2 as default value.

The view factor is defined with the equation by:

$$F_q = \frac{D_S^2}{4 \cdot \left(H^2 + r^2\right)} \tag{54}$$

where H = height from the center of the fire ball [m]; D_S = effective diameter of the fire ball [m]; r = distance measured over the ground of the projected centre of the fire ball on the ground under the fire ball, and the object [m].

The effective diameter of the fire ball is defined as:

$$D_S = 6.48 \cdot m^{0.325} \tag{55}$$

where m = total mass released [kg]; D_S = effective diameter of the fire ball [m].

The height from the center of the fire ball H can be equal D_S.

The duration time of the fire ball is defined as:

$$t_S = 0.852 \cdot m^{0.26} \tag{56}$$

The Atmospheric transmissivity τ for the fire ball is defined as:

$$\tau = \exp\left[-7.0 \cdot 10^{-4} \cdot \left(\sqrt{r^2 + H^2} - \frac{D_S}{2}\right)\right] \tag{57}$$

8.3.2 Dutch approach

The Dutch approach and the associated software tool (cf. TNO 2015) distinguish the fire ball model in two different calculations. The first one is the “Fireball: Instantaneous gas release”, which calculates only the total mass released and the radius of a fireball. The heat flux is not considered in the calculation results. The second model is the so-called: Static BLEVE model – the heat flux of a fire ball is caused by a BLEVE and starts the computation with the estimation of the amount of fuel which is involved in the BLEVE.

Similar to chapter 8.2.2 the mode “shows expert parameters” is discussed next. The auditor may use default input data in case of lacking parameter data.

Tables 42 to 44 structures the input process. Terminology is retained unchanged. Substance data are from (CPR18E 2005) database (state: 22.07.1999).

Table 42. Data input of vessel characteristics.

Description	Input Data
Chemical name	…
Type of BLEVE calculation	Static BLEVE model or Dynamic BLEVE model
Total mass in vessel, [kg]	
Initial temperature in vessel, [°C]	…
Burst pressure of the vessel, [bar]	…
Height of the receiver [m]	…

As above-mentioned, the auditor may also use some default input values in the “show expert parameters” mode (italicised in tables 42 and 44).

Table 43. Data input of the atmospheric characteristics.

Description	Input Data
Ambient temperature, [^{o}C]	…
Ambient relative humidity, [%]	…
Amount of CO_2 in atmosphere	…

Depending on the contours for effects or consequences, table 44 gives the chance to calculate the physical effects (heat radiation level) or burn degrees (heat radiation damage basted on probit function).

Table 44. Data input of personal damage characteristics.

Description	Input Data
Distance from center of the vessel (Xd), [m]	…
Maximum heat exposure duration, [s]	…
X – coordinate of release, [m]	…
Y – coordinate of release, [m]	…
Calculate contours for	1st degree burns, 2nd degree burns, lethal burns, physical effects
Heat radiation level (lowest) for first contour plot, [kW/m^2]	*Default = 1*
Heat radiation level for second contour plot, [kW/m^2]	*Default = 3*
Heat radiation level (highest) for third contour plot, [kW/m^2]	*Default = 10*
Take protective effects of clothing into account	*Yes/No*
Correction lethality protection clothing	*Default = 0.14*
Percentage of mortality for contour calculations, [%]	*Default = 1*

Heat radiation damage Probit A, [$s\cdot(W/m^2)^n$]	*Default = -36.38*
Heat radiation damage Probit B	*Default = 2.56*
Heat radiation damage Probit N	*Default = 1.333*

The probit function is identically calculated as the pool fire model (chapter 8.2.2). The output mask of TNO EFFECTS summarizes the calculation results. Table 45 lists all quantified parameters.

Table 45. Quantified parameters in TNO EFFECTS (Data output).

Parameters	Parameters
Duration of the Fire Ball, [s]	(Max.) view factor at Xd
Max. diameter of the Fire Ball, [m]	Atmospheric transmissivity at Xd, [%]
Max. height of the Fire Ball	Heat radiation dose at Xd, [$s(kW/m^2)^{4/3}$]
Surface emissive power (max.), [kW/m^2]	Percentage first degree burns at Xd, [%]
Heat radiation first contour at, [m]	Percentage second degree burns at Xd, [%]
Heat radiation second contour at, [m]	Percentage third degree burns at Xd, [%]
Heat radiation third contour at, [m]	Flame temperature, [^oC]
(Max.) heat radiation level at Xd	

8.3.3 Comparison

To resume the described Russian method, the equation (26) of the calculation of the heat flux differs from the Dutch approach, which uses instead the actual emissive power (SEP) the maximum surface emissive power from a flame without soot. Thus, the equation (28) is also different in both approaches and the maximum surface emissive power SEP_{max} from a flame without soot (TNO EFFECTS 2014) is:

$$SEP_{\max} = F_S \cdot m \cdot \Delta H_C / \left(1 + 4 \cdot L / D\right) \tag{58}$$

where F_S = fraction of the generated heat which is radiated from the flame surface; m = burning rate [kg/m^2 s]; ΔH_C = heat of combustion [J/kg]; L = average height of the flame [m]; D = pool diameter [m].

According to (Roberts 1982) “the thermal radiation output from a fireball was characterised in terms of the fraction of combustion energy released through radiation, and its dependence on the release pressure” (CPR14E 2006), which follows the equation:

$$F_S = c_6 \cdot \left(P_{SV}\right)^{0.32} \tag{59}$$

where P_{SV} = saturated vapour pressure before the release [N/m^2]; c_6 = 0.00325 [(N/m^2)$^{-0.32}$].

The calculations of the view factor differ in both methods. The Dutch approach "estimate[s] the heat radiation surrounding a fire requires the characterization of the flame geometry. The computation of the heat intensity at a given location around a fire requires the computation of the geometric view factor. The current (TNO EFFECTS 2014) implementation contains the calculation algorithms for several flame geometries" as described by (Mudan 1987). The view factor at a distance X from the fire ball is calculated as:

$$F_{view} = \left(\frac{r_{fb}}{X}\right)^2 \tag{60}$$

where r_{fb} = radius of the fire ball [m]; X = distance from the centre of the fire ball to the radiated object [m].

The calculation of the D_S effective diameter of the fire ball (equation (55)) and the t_S duration time of the fire ball (equation (56)) are the same in both methods.

The calculation of the atmospheric transmissivity τ by the Dutch approach is the same as in the pool fire model. However the Russian approach uses the simplified equation (46).

8.3.4 Prototype tool of the Russian approach

To compare the two tools, the Russian approach was transformed into a tool as in the example with the pool fire model.

Chapter 8.3.1 outlines the Russian approach from the side of the equations and the procedure of the calculated model.

This chapter introduces the method by MS Excel prototype tool which gives the auditor an option to calculate the heat flux, depending on the distance; duration time of the fire ball; effective diameter and radius of the fire ball; the injury based on the probit function. The auditor only must enter the next parameters:

- Total mass released [kg] (marked by the author as *m*);
- Actual surface emissive power (SEP) [kW/m^2] (marked by the author as E_f). The MS Excel prototype tool uses the value 350 kW/m^2 by default.

After the input of these data, the results are:

for a set of heat flux values $q = \{10.5,\ 7.0,\ 4.2,\ 1.4\}$ the tool gives the distances from the center of a fire ball [m]. The heat flux figures are chosen from (Siegel et al. 2001) and (Order No. 404 2009).

At the same time the tool calculates the heat flux and the probit function Pr for the entered distances (table 46) and gives the probability (%) of the lethal outcome (probability of fatality to personnel) as output:

Table 46. Data output table.

Parameter	Output (example)
Pr	6.555
Q, [%]	94.00

For a set of probabilities of fatality to personnel [%] $Q = \{99.9,\ 90.0,\ 50.0,\ 10.0,\ 1.0\}$ the tool gives the distance from the center of a fire ball [m].

The probit function is calculated identically to the pool fire model (see chapter 8.2.4)

8.3.5 Calculation

For the comparison of Dutch and Russian standards, the scenarios:

- 1000 kilogram propane gas release and its instant ignition
- 40000 kilogram gasoline release and its instant ignition

were chosen. The Dutch approach uses 25 bar for the burst pressure of the vessel as a default value. Most gas tanks have exactly this burst pressure (some burst pressures are 16 bar), therefore it is assumed, that the Russian approach uses the same default value but does not consider it in the calculations. The changing of the burst pressure of the vessel from 25 bar to 16 bar does not have big influence on the calculated heat flux depending on the distance to the radiated object.

As the Dutch method measures the heat flux of the height of the receiver in 1.5 meter and the Russian method does not consider this parameter (the height of the receiver is 0 meter). The problem is solved by determination of the height of the receiver in TNO EFFECTS as 0 meters and by the recalculation of the distance from the centre of the fire ball to the radiated object (fig. 51):

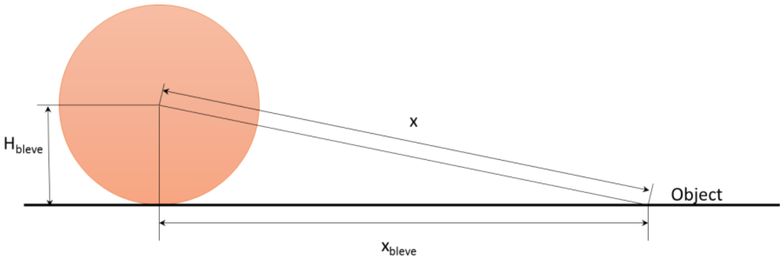


Figure 51. Fire ball. Distances in Russian and Dutch approaches.

where X_{bleve} = distance from the centre of the fire ball to the radiated object according to the Russian approach [m]; X = distance from the centre of the fire ball to the radiated object according to the Dutch approach [m]; H_{bleve} = radius of the fire ball [m].

Thus, if X_{bleve} = 100 meters, then X = 104.57 meters. These recalculations depending on the distances must be considered in the results of the comparison of approaches. Table 47 presents the calculated heat flux for propane gas release:

Table 47. Comparison of the calculated heat flux *q* depending from the distance from the centre of the fire ball to the radiated object for propane.

Approach	Heat flux *q* [kW/m²]			
	10.5	7.0	4.2	1.4
	Distance *m* [m] from the surface			
Russian	156.8	194.2	250.5	417.3
TNO	114	144	190	330

The diameter and duration of the fire ball are the same in both approaches (D_S = 61.175 meters; t_S = 5.1338 seconds). The calculated distances depending on the heat flux have a distinction of ca. 30%. There can be different influences of the calculated results: from the burst pressure value of the vessel to the consideration of the different models in both approaches (Russian fire ball approach vs. Dutch fire ball (Static BLEVE model) approach). The Russian approach also uses a default value of SEP 350 kW/m^2 and calculated result of the Dutch of SEP is 247.6 kW/m^2. This difference has an influence on the calculated results:

Table 48. Comparison of the calculated heat flux *q* depending from the distance from the centre of the fire ball to the radiated object for propane by an SEP value of 247.6 in both approaches.

Approach	Heat flux *q* [kW/m²]			
	10.5	7.0	4.2	1.4
	Distance *m* [m] from the surface			
Russian	128.9	161.7	210.9	356.6
TNO	114	144	190	330

By the changing in the Russian MS Excel prototype tool of the input parameter – SEP form 350 to 247.6 kW/m^2 the calculated distances depending on the heat flux has a distinction of ca. 10%.

Table 49 presents the calculated heat flux for gasoline release:

Table 49. Comparison of the calculated heat flux *q* depending from the distance from the centre of the fire ball to the radiated object for gasoline.

Approach	Heat flux *q* [kW/m²]			
	10.5	7.0	4.2	1.4
	Distance *m* [m] from the surface			
Russian	465.7	566.9	712.1	1086.9
TNO	435	545	714	1230

The calculated results are similar in both methods. The major difference lies in the distances for the heat flux value of 1.4 kW/m². The calculated value of TNO EFFECTS is bigger which can be explained by the different calculation of the atmospheric transmissivity τ. The calculated SEP (340 kW/m^2) value in TNO EFFECTS is near to the Russian default value.

8.3.6 Conclusions

As mentioned in chapter 8.3 both standards based on different fire ball models that can raise the question in the significance of their comparison and the conservative sides of both approaches at first sight. The associated TNO EFFECTS tool with the option “shows only simple parameters” is also easy in the handling for the auditor, as the Russian MS Excel prototype tool. Although, both standards are based on different models, the results are surprisingly similar. It is not possible to exclude that both approaches are close to reality.

Depending on the used value of SEP in the Russian approach, the calculated distances in some scenarios could be bigger in comparison to the calculated results of the Dutch approach, but not more than ca. 30%. If the Russian approach calculates the SEP value separately or uses the experimental data from table 31, the calculated results of the heat flux will be similar or identical in both approaches.

8.4 Comparison of the jet fire models

The standards, described in chapter 8.1, consider the jet fire model (named also as jet flames or torch fire in different literature). Both standards based on different understanding and visualization of the formation of a jet flame. (For a better understanding of the differences, it is necessary to consider both models in the following chapters). The Dutch approach only calculates the jet flames for LPG and LNG is the gas phase. The Russian approach can be used for the calculations of a jet flame of compressed combustible gases, steam and liquid phase LPG, LNG, flammable liquid and combustible liquid under pressure. The input data also differ. The Russian approach only needs the mass flow rate and the surface emissive power of the substance in the input data's. But additionally data are needed for the calculation of the mass flow rate. In contrast the Dutch approach needs more input data. These data are also important for determination of the mass flow rate.

Thus, the comparison of the Dutch and Russian approaches is complicated because of the different visualization and understanding. These factors will be analyzed and compared in the next chapters.

8.4.1 Russian approach

All notations in this chapter are translated and harmonized by (A. Leksin) from the Russian ordinance, i.e. (Order No. 404 2009) and its addition (Order No. 649 2010). All references and data are from this ordinance unless specified otherwise.

When carrying out an assessment of fire hazards of the burning torch at the jet expiration of the compressed combustible gases, steam and liquid phase LPG, LNG, flammable liquid and combustible liquid under pressure, it is allowed to accept the following boundary conditions:

- the zone of direct contact of a flame with surrounding objects is defined by the torch sizes;
- length of a torch of L_F does not depend on the direction of the expiration of a product and of a wind speed;
- bigger danger is constituted by horizontal torches where conditional probability of realization should be accepted equal 0.67;
- defeat of the person in a horizontal torch happens in 30° sector with a radius which is equal to the torch length;

- impact of a horizontal torch on the equipment leading to its destruction (cascade development of accident) happens in 30° sector, which is limited by the radius. The radius is equal to the length of a torch L_F;
- outside the specified sector at distances from L_F to $1.5L_F$, the heat flux from a horizontal torch is 10 kW/m^2;
- the heat flux from vertical torches can be determined by the same equations as in the pool fire model (eq.26, 30-40 and 46), accepting the L equal L_F, d equal D_F, θ equal 0, E_f can be determined with the equations (27-29) or the table 31 depending on the type of fuel. In the absence of data and impossibility to calculate E_f it is allowed to accept as 200 [kW/m^2];
- by an expiration of the liquid phase of LPG or LNG from a hole with an equivalent diameter up to 100 mm at instant ignition there is a full combustion of the expiring product in a torch without formation of an pool fire;
- by an instant ignition of a stream of gas, the possibility of formation of overpressure is allowed not to be considered
- horizontal torches are not considered in the Russian approach.

The flame length [m] (length of frustum) by a jet flame is defined as:

$$L_F = K \cdot G^{0.4} \tag{61}$$

where G = mass flow rate [kg/s]; K = empirical coefficient (12.5 expiration of compressed gases; 13.5 expiration of the steam phase of LPG or LNG; 15 expiration of the liquid phase of LPG or LNG).

The torch length by the jet expiration of combustible liquids is defined by the range (height) of a stream of liquid.

The width of a torch D_F [m] by a jet flame is defined as:

$$D_F = 0.15 \cdot L_F \tag{62}$$

8.4.2 Dutch approach

The Dutch approach base on a geometric solid flame shape model (Chamberlain 1987) and is modified according to (Cook et al. 1987, Boot 2016).

This model was developed by wind tunnel experiments and a wide range of natural gases among other field tests onshore and offshore. “The model represents the flame as a frustum of a cone, radiating as a solid body with a uniform surface emissive power. Correlation describing the variation of flame shape and surface emissive power under a wide range of ambient and flow conditions” (CPR14E 2006). As mentioned in chapter 8.4, the Dutch approach only calculates the jet flames for gases.

TNO EFFECTS comes up with an extended and single data input mask (expert parameters) which goes beyond the presentation constraints of this chapter. Tables 50 to 52 structure the input process according the scenario characteristics mentioned above. Terminology is retained unchanged. Substance data are from (CPR18E 2005) database (state: 22.07.1999).

Table 50. Data input of jet fire characteristics.

Description	Input Data
Chemical name	…
(Calculated) Mass flow rate, [kg/s]	…
Exit temperature, [°C]	
Exit pressure, [bar]	…
Hole diameter, [mm]	…
Hole rounding	User defined, rounded edges, sharp edges, pipe contraction
Discharge coefficient	*Default = 1*
Outflow angle in XZ plane (0° = horizontal; 90° = vertical), [deg]	Calculate/*Default* or User defined
Release height (Stack height), [m]	*Default = 0.1*
Flame temperature, [°C]	*Default =0.35*
Max. heat exposure duration, [s]	Calculate/*Default* or User defined
Height of the receiver, [m]	

The problem in the input data of jet fire characteristics is in the value of the mass flow rate. If the auditor uses the “defaults”, the tool considers this parameter as 10 [kg/s] by a default value of the exit pressure 6.5 [bar] and exit temperature 20 [°C] independent from the substance. Such “defaults” are not appropriate and safe for every scenario. The input mask shows, that the mass flow rate must be calculated. (TNO EFFECTS 2014) has a separate option to calculate the mass flow rate, but parameters of the pipeline (e.g. initial temperature in equipment, initial (absolute) pressure within the pipeline, pipeline length, pipeline diameter, hole diameter etc.) must be known.

Table 51. Data input of the atmospheric characteristics.

Description	Input Data
Wind speed at 10 [m] height, [m/s]	…
Ambient temperature, [°C]	…
Ambient relative humidity, [%]	…
Amount of CO_2 in atmosphere	…
Percentage of the flame covered by soot, [%]	…
Predefined wind direction	User defined (N, NNE, etc.)
Wind comes from (North = 0 degrees), [deg]	…

Wind direction in table 51 is defined by the common section of a compass rose.

Table 52. Data input of personal damage characteristics.

Description	Input Data
Distance from release (Xd), [m]	…
X - coordination, [s]	…
Y - coordination, [s]	…
Calculate contours for	1st degree burns, 2nd degree burns, lethal burns, physical effects
Heat radiation level (lowest) for first contour plot, [kW/m^2]	*Default = 1*
Heat radiation level for second contour plot, [kW/m^2]	*Default = 3*
Heat radiation level (highest) for third contour plot, [kW/m^2]	*Default = 10*
Take protective effects of clothing into account	Yes/no
Correction lethality protection clothing	
Percentage of mortality for contour calculations, [%]	*Default = 1*
Heat radiation damage Probit A, [$s \cdot (W/m^2)^n$]	*Default = -36.38*
Heat radiation damage Probit B	*Default = 2.56*
Heat radiation damage Probit N	*Default = 1.333*
Resolution for surface discretization	Low, medium, high, very high

The probit function is calculated identical to the pool fire model (chapter 8.2.2).
The output mask of TNO EFFECTS summarizes the calculation results.

Table 53 lists all quantified parameters.

Table 53. Quantified parameters in TNO EFFECTS (Data output).

Parameters	Parameters
Type of flow of the jet	Surface emissive power (max), [kW/m^2]
Exit velocity of expanding jet, [m/s]	Surface emissive power (actual), [kW/m^2]
Angle between hole and flame axis (alpha) , [deg]	Atmospheric transmissivity at Xd, [%]
Frustum lift off height (b), [m]	View factor at Xd
Width of frustum base (W1), [m]	Heat radiation at Xd, [kW/m^2]
Width of frustum tip (W2), [m]	1% First degree burns distance, [m]
Length of frustum (flame) (Rl), [m]	1% Second degree burns distance, [m]
Surface area of frustum, [m^2]	1% Third degree (Lethal) burns distance, [m]

8.4.3 Comparison

To resume the described Russian method, the equation (26) of the calculation of the heat flux differs to the Dutch approach, which uses instead the actual emissive power (SEP) the actual surface emissive power of the frustum (SEP_{act}), which is the average radiation emittance (emissive power) of the flame surface:

$$SEP_{act} = F_S \cdot \frac{Q'}{A} \tag{63}$$

where F_S = fraction of the combustion energy radiated from the flame surface; Q' = combustion energy per second [J/s]; A = surface area of the flame [m^2].

To determine the fraction of the heat radiated from the flame surface the equation (64) is used:

$$F_S = 0.21 \cdot e^{(-0.00323 \cdot u_j)} + 0.11 \tag{64}$$

$$Q' = m' \cdot \Delta H_C \tag{65}$$

where u_j = jet velocity [m/s]; m' = mass flow rate [kg/s]; ΔH_c = heat of combustion [J/kg].

As shown, the fraction of the heat radiated from the flame surface is based on the equation (64) “but potentially modified with molar mass correction according to (Cook et al. 1987, Boot 2016)

Calculations of the parameter, which are considered in the equation, are complicated to comprehend due to the absence this data in the TNO EFFECTS tool “Help” Desk.

It is supposed, that equations from ((CPR14E 2006) chapters 6.5.3.1 – 6.5.3.5) are used.

The calculation of the view factor is similar in both methods and uses the equations (30 to 40) of the pool fire model. The difference is that the Dutch approach "takes into account the lift-off of the flame, change in distance to the object due to lift-off and the change of the angle under which the object observes the flame" (CPR14E 2006):

$$X' = \left(\left(b \cdot \sin\Theta_j \right)^2 + \left(X - b \cdot \cos\Theta_j \right)^2 \right)^{1/2} \tag{66}$$

$$\Theta' = 90^0 - \Theta_j + \alpha - \arctan\left(\frac{b \cdot \sin\Theta_j}{X - b \cdot \cos\Theta_j} \right) \tag{67}$$

$$R = \frac{\left(W_1 + W_2 \right)}{4} \tag{68}$$

where X' = distance from the centre of the bottom plane of a lifted-off flame to the object [m]; X = distance from the centre of the flame without lift-off to the object [m]; Θ' = angle between the centreline of a lifted-off flame and the plane between the centre of bottom of the lifted-off flame and the object [°]; b = frustum lift-off height [m]; Θ_j = angle between hole axis and the horizontal in the vertical plane [°]; α = angle between hole axis and the flame axis [°]; W_1 = width of frustum base [m]; W_2 = width of frustum tip [m]; R = radius of the flame [m].

In the equations (42, 43 and 45) of the pool fire model the $X = X'$, $L = R_1$, $\Theta = \Theta'$.

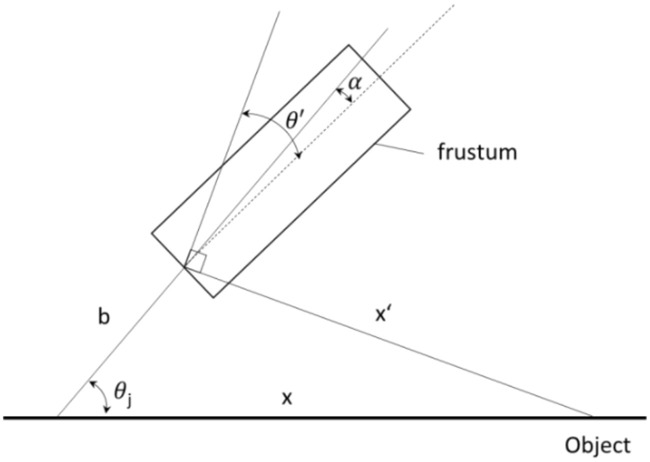


Figure 52. Distances, lengths and angles required for the calculation of a lifted-off flame (CPR14E 2006).

As the (fig. 52) shows, there are two widths of the frustum contrary to the Russian approach.

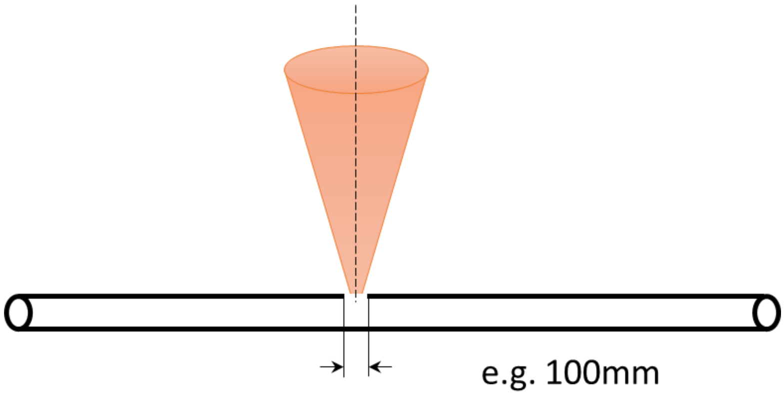


Figure 53. Tourch fire in the Russian approach.

The length of frustum (flame) in the Dutch approach differs to the Russian calculation:

$$R_1 = \left(L_b^2 - b^2 \cdot \sin^2(\alpha)\right)^{1/2} - b \cdot \cos(\alpha) \tag{69}$$

where L_b = flame length, flame tip to centre of exit plane [m]; X = distance from the centre of the flame without lift-off to the object [m]; b = frustum lift-off height [m].

$$b = L_b \cdot \frac{\sin K\alpha}{\alpha} \tag{70}$$

where $K = 0.185 \times e^{-20R_W} + 0.015$; R_W = ratio of wind speed to the jet speed. “In still air (α = 0°), b is equal to 0.2 × L_b. For ‘lazy’ flames pointing directly into high winds (α = 180°), b = 0.015 × L_b” (CPR14E 2006). The Russian tool does not consider the wind velocity.

Therefore, both approaches use different models for the calculation of the heat flux, flame length and the widths of a jet fire.

8.4.4 Synopsis

Due to the complexity of the Dutch approach: not full distinctness between equations described in (CPR14E 2006) and used in the associated tool TNO EFFECTS (TNO EFFECTS 2014) the solution was to recalculate the example from (CPR14E 2006) chapter “6.6.2 Jet flames”. This gives the author the chance to compare the calculations between (CPR14E 2006) and (TNO EFFECTS 2014). The scenario is:

decompression of a high pressure pipeline (hole diameter 100 [mm], choked flow) with methane gas and a distance release point to receiver 150 [m]:

Table 54. Comparison of the example between (CPR14E 2006) and (TNO EFFECTS 2014) (Data output).

Parameters	CPR14E 2006	TNO EFFECTS 2014
Width of frustum base (W1), [m]	0.7169	0.1405
Width of frustum tip (W2), [m]	40.8475	9.4703
Surface emissive power (actual), [kW/m^2]	21.95	375.11
Atmospheric transmissivity at Xd, [%]	67.302	66.072
View factor at Xd	0.0282	0.0018
Heat radiation at Xd, [kW/m^2]	0.417	0.466

The comparison shows that the associated tool TNO EFFECTS calculates the parameters with additional corrections, which could not be found out in the “Help” Desk of the tool. Also it is not found out how was calculated the initial pressure of 100 [bar] for the input data.

8.4.5 Prototype tool of the Russian approach

To compare the two tools, the Russian approach was transformed into a tool alike before.

Chapter 8.4.1 and 8.4.3 outlined the Russian approach from the side of the equations and the procedure of the calculated model.

This chapter introduces the method in form of an MS Excel prototype which gives the auditor a simple option to calculate the heat flux, depending from the distance; flame length; width of a torch; the injury based on the probit function. The auditor must enter the next parameters:

- Substance
- Mass flow rate [kg/s] (marked by the author as G);
- Actual surface emissive power (SEP) [kW/m^2] (marked by the author as E_f);
- Burning flux at still weather conditions [kg/m^2·s] (marked by the author as m');
- Empirical coefficient (marked by the author K)

The database of the tool prototype is programmed for the following substances: LPG, LNG, gasoline, diesel and oil (petroleum product). If the auditor has other substances (e.g. hexane) he must enter additional properties of the substance, as the L_g vaporisation heat of the flammable material at its boiling point [kJ/kg]; C_p specific heat capacity at constant pressure [kJ/kg·K]; T_b the liquid boiling temperature [K]; T_a ambient temperature [K] – to calculate the m' burning rate at still weather conditions [kg/m^2·s] and the H_{SG} heat of combustion [kJ/kg] – to calculate the E_f actual surface emissive power of the flame [kW/m^2].

The w_0 [m/s] wind velocity and $\rho_П$ [kg/m^3] vapour density of the flammable materials at the boiling point is not considered in the Russian approach and tool.

There is also a problem in the calculation of the mass flow rate in the Russian approach, as in the Dutch, described in chapter 8.4.3. The Russian approach uses an equation (71) from (Order No. 404 2009) to determine the mass flow rate:

$$G = A_{hol} \cdot \mu \cdot \left[P_V \cdot \rho_V \cdot \gamma \cdot \left(\frac{2}{\gamma + 1} \right)^{\frac{(\gamma+1)}{(\gamma-1)}} \right]^{1/2} \tag{71}$$

where A_{hol} = area of the hole [m^2]; P_V = initial pressure in the pipeline [Pa]; γ = heat capacity ratio of the gas; μ = flow coefficient 0.8; ρ_V = density of gas at the initial pressure in the pipeline (P_V) [kg/m^3]. This equation is used for the calculation of the mass flow rate from a tank, but due to the lack of an equation for a pipeline, the mass flow rate is calculated as presented.

The output results are:

for a set of heat flux values $q = \{10.5,\ 7.0, 4.2, 1.4\}$ the tool gives the distance from the center of the jet fire (fig. 53) [m]. The heat flux figures are chosen from (Siegel et al. 2001) and (Order No. 404 2009).

At the same time the tool calculates the heat flux and the probit function Pr for the entered distance (table 55) and gives the probability (%) of the lethal outcome (probability of fatality to personnel) as output:

Table 55. Data output table.

Parameter	Output (example)
Pr	3.720
Q, [%]	10.03

For a set of probabilities of fatality to personnel [%] $Q = \{99.9, 90.0, 50.0, 10.0, 1.0\}$ the tool gives the distance from the center of a jet fire [m].

8.4.6 Calculation

For the comparison of Dutch (TNO EFFECTS 2014) and Russian standards, three scenarios with hydrogen, methane and propane gas release and its instant ignition were chosen. The hole diameter in the pipeline is 100 [mm]; exit temperature 20 [°C]; exit pressure, as the default value of (TNO EFFECTS 2014) is 6.5 [bar]. It has been solved to use the equation (71) from the Russian approach to calculate the mass flow rate of the hydrogen:

$$G = A_{hol} \cdot \mu \cdot \left[P_V \cdot \rho_V \cdot \gamma \cdot \left(\frac{2}{\gamma + 1} \right)^{\frac{(\gamma+1)}{(\gamma-1)}} \right]^{1/2} \tag{71}$$

ρ_V = density of the hydrogen by the initial pressure in the pipeline (P_V = 650000 Pa) can be calculated with the ideal gas law:

$$P \cdot V = \frac{m}{M} \cdot R \cdot T \tag{72}$$

$$P = \frac{m}{M \cdot V} \cdot R \cdot T \tag{72}$$

Definition of density is:

$$\rho = \frac{m}{V} \tag{73}$$

Therefore:

$$\rho_V = \frac{P \cdot M}{R \cdot T} = \frac{650000 \cdot 2 \cdot 10^{-3}}{8.31 \cdot (273 + 20)} = 0.5339 \text{ kg/m}^3$$

The heat capacity ratio of hydrogen at the exit temperature 20 [^{o}C] is γ = 1.410. Therefore, the mass flow rate is:

$$G = \frac{\pi}{4} \cdot 0.1^2 \cdot 0.8 \cdot \left[6.5 \cdot 10^5 \cdot 0.5339 \cdot 1.410 \cdot \left(\frac{2}{1.410 + 1} \right)^{\frac{(1.410+1)}{(1.410-1)}} \right]^{1/2} = 2.5 \text{ kg/s}$$

The Dutch method (TNO EFFECTS) measures the heat flux of the height of the receiver in 1.5 meter and the Russian method does not consider this parameter. The results of the comparison are presented in tables 56 to 58:

Table 56. Comparison of the calculated heat flux *q* depending on the distance from the centre of the jet fire to the radiated object for hydrogen.

Approach	Heat flux *q* [kW/m²]			
	10.5	7.0	4.2	1.4
	Distance *m* [m] from the surface			
Russian	2.4	3.5	5.6	14.2
TNO	-	-	16	38

The length of frustum (flame) is similar in both methods: the Russian approach calculates the value with 18.0 [m] and the Dutch approach with 20.3 [m]. The Russian approach calculates the value of the surface emissive power (SEP) which is 29.7 [kW/m^2] while the Dutch calculated result is 147.9 [kW/m^2]. However, the maximum heat flux value in the Dutch approach is 5.6 [kW/m^2] by a distance from release of 6 [m].

The same scenario is compared for methane.

The density of the methane by the initial pressure in the pipeline is:

$$\rho_V = \frac{P \cdot M}{R \cdot T} = \frac{650000 \cdot 16.04 \cdot 10^{-3}}{8.31 \cdot (273+20)} = 4.282 \text{ kg/m}^3$$

The heat capacity ratio of methane by exit temperature 20 [°C] is $\gamma = 1.320$.

Therefore, the mass flow rate is:

$$G = \frac{\pi}{4} \cdot 0.1^2 \cdot 0.8 \cdot \left[6.5 \cdot 10^5 \cdot 4.282 \cdot 1.320 \cdot \left(\frac{2}{1.320+1} \right)^{\frac{(1.320+1)}{(1.320-1)}} \right]^{1/2} = 7.1 \text{ kg/s}$$

Table 57. Comparison of the calculated heat flux *q* depending on the distance from the centre of the jet fire to the radiated object for methane.

Approach	Heat flux *q* [kW/m²]			
	10.5	7.0	4.2	1.4
	Distance *m* [m] from the surface			
Russian	21.2	28.2	38.2	71.2
TNO	-	-	12	39

The length of frustum (flame) is similar in both methods: the Russian approach calculates the value with 27.4 [m] and the Dutch approach with 26.2 [m]. The Russian approach use the default value of the surface emissive power (SEP) which is

220 [kW/m^2] while the Dutch calculated result is 99 [kW/m^2]. However the maximum heat flux value in the Dutch approach is 4.5 [kW/m^2] at a distance from release of 7 [m].

The same scenario is compared for propane.
The density of the methane at the initial pressure in the pipeline is:

$$\rho_V = \frac{P \cdot M}{R \cdot T} = \frac{650000 \cdot 44.1 \cdot 10^{-3}}{8.31 \cdot (273 + 20)} = 11.77 \text{ kg/m}^3$$

The heat capacity ratio of propane at exit temperature 20 [°C] is $\gamma = 1.130$.
Therefore, the mass flow rate is:

$$G = \frac{\pi}{4} \cdot 0.1^2 \cdot 0.8 \cdot \left[6.5 \cdot 10^5 \cdot 11.77 \cdot 1.130 \cdot \left(\frac{2}{1.130 + 1} \right)^{\frac{(1.130+1)}{(1.130-1)}} \right]^{1/2} = 11.1 \text{ kg/s}$$

Table 58. Comparison of the calculated heat flux *q* depending on the distance from the centre of the jet fire to the radiated object for propane.

Approach	Heat flux *q* [kW/m^2]			
	10.5	7.0	4.2	1.4
	Distance *m* [m] from the surface			
Russian	11.7	16.8	25.4	52.6
TNO	-	13	31	68

The length of frustum (flame) is similar in both methods: the Russian approach calculates the value with 35.4 [m] and the Dutch approach with 33.1 [m]. The Russian approach uses the default value of the surface emissive power (SEP) which is 80 [kW/m^2] while the Dutch calculated result is 151.9 [kW/m^2]. However the maximum heat flux value in the Dutch approach is 7.4 [kW/m^2] at a distance from release of 9 [m].

8.4.7 Conclusions

In all three scenarios the maximum heat fluxes are the biggest in the Russian approach. This is due to the different understanding and visualization of the jet flame. The Dutch approach considers the beginning of the burning of the jet flame not directly at the depressurized hole (e.g. with a hole diameter of 100 [mm]), as considered the Russian approach, but with a calculated distance from the depressurized hole (fig. 54):

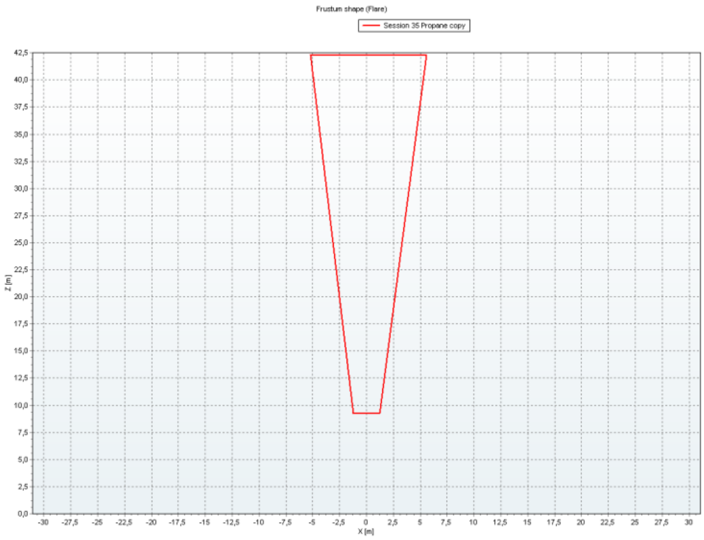


Figure 54. Visualization of a jet flame on basis of the Dutch model (TNO EFFECTS 2014).

Such understanding and visualization of the jet flame can be closer to the reality for certain scenarios. But at the same time it depends on the mass flow rate respectively on the pressure in the pipeline. Such model explains the small values of the heat fluxes in the Dutch approach. The heat radiation in such a scenario is spread differently. For a better overview, an extract of the associated TNO EFFECTS tool is present in the following (fig. 55):

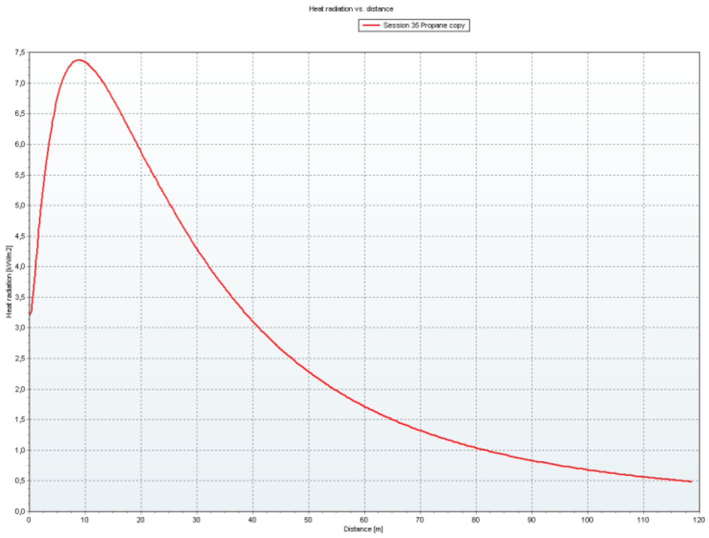


Figure 55. Heat radiation vs. distance. Propane release scenario (TNO EFFECTS 2014).

The overall comparison of both approaches shows the following results:

- Scenario with hydrogen:
  the distances from the centre of the jet fire to the radiated object are twice as big as in the Dutch approach;
- Scenario with methane:
  the distances from the centre of the jet fire to the radiated object are bigger in the Russian approach;
- Scenario with propane:
  the distances from the centre of the jet fire to the radiated object are similar in both approaches.

Such distinctions are explained by the difference in the building of the jet flame and substance properties.

Despite of the different equations for calculating of the length of the frustum, the results are similar. This hints at the high quality of the complicated calculations in the Dutch approach and right empirical coefficients in the equation of the Russian approach.

Unfortunately the literature research of data taken from experimental studies of jet flames has not given the desirable results in comparison to the described scenarios with reference values. As described in (Order No. 404 2009, Order No. 649 2010) and (CPR14E 2006) both models are based on a scale of experiments, which does not allow to draw conclusions which model is closer to reality. The advantage of the Russian approach consists of the possibility to calculate the jet flame for different substances, inter alia for steam and liquid phase of LPG and LNG, flammable liquids, combustible liquids under pressure and the probit function for the considered scenario.

8.5 Comparison of the explosion models

The standards, described in chapter 8.1, consider similar vapour cloud explosion models based on the multi energy concept. This concept is described more detailed in the chapter 8.5.2 of the Dutch approach.

8.5.1 Russian approach

All notations in this chapter are translated and harmonized by (A. Leksin) from the Russian ordinance, i.e. (Order No. 404 2009) and its addition (Order No. 649 2010). All references and data are from this ordinance unless specified otherwise.

Basic data for calculation of the vapour cloud explosion are:

- type of the combustible substance containing in a cloud;
- concentration of combustible substance in the mixture C_G (in the Russian original $C_Г$);
- stoichiometric concentration of combustible substance with the air C_{ST} (in the Russian original C_{CT});
- mass quantity of flammable part of the cloud M_T with a concentration between the lower explosive limit (LEL) and upper explosive limit (UEL). It is allowed to accept the M_T equal to the mass of the combustible substance containing in a cloud taking into account a coefficient Z – participations of combustible substance in explosion. In absence of the data, coefficient Z can be accepted as 0.1. At a jet stationary expiration of combustible gas, the M_T should be calculated taking into account the stationary distribution of concentration of combustible gas in a [jet] stream.
- heat of combustion H_{SG} [kJ/kg] (in the Russian original $E_{УД}$)
- speed of sound in ambient air C_0 (usually is accepted equal 340 m/s)
- degree of obstruction (Information about the degree of the clutter surrounding surface
- Total combustion energy (of the combustible mixture) *E:*

$$E = \begin{cases} M_T \cdot H_{SG}, \quad C_G \le C_{ST} \\ M_T \cdot H_{SG} \cdot \dfrac{C_{ST}}{C_G}, \quad C_G > C_{ST} \end{cases} \tag{74}$$

At the calculation of the parameters of the combustion cloud located at the earth surface, the size of a total (effective) energy stock doubles.

The expected mode of combustion cloud depends on the type of combustible substance and degree of clutter of surrounding space.

Classification of combustible substances by sensitivity degree

Substances, which are capable to build an explosive atmosphere with the air, are divided into four classes dependent on the sensitivity to initiation of explosive processes:

Class 1 – especially sensitive substances;

Class 2 – sensitive substances;

Class 3 – moderately sensitive substances;

Class 4 – slightly sensitive substances.

Few examples are given in table 59. If the auditor cannot find the required substance in table 59, it should be classified by analogy with the substances which are available in the table. If there are not specific data of the substance, the worst case must be considered using the Class 1.

Table 59. Classification of combustible substances by sensitivity degree.

Class 1	Class 2	Class 3	Class 4
Acetylene	Acrylonitrile	Acetaldehyde	Benzene
Vinyl acetylene	Acrolein	Acetone	Decane
Hydrogen	Butane	Gasoline	Orthodichlorobenzene
Hydrazine	Butene	Vinyl acetate	Dodecane
Isopropyl nitrate	1,3-Butadiene	Vinyl chloride	Methane
Methylacetylene (Propyne)	1,3-Pentadiene	Hexane	Toluene
Nitromethane	Propane	Isooctane	Methyl mercaptan
Propylene oxide	Propylene (Propene)	Methylamine	Chloromethane
Ethylene oxide	Carbon disulfide	Methylacetate	Carbon monoxide
Ethyl nitrate	Ethane	Methyl butyl ketone (MBK or 2-Hexanone)	Styrene
	Ethylene	Methyl propyl ketone (MPK or 2-Pentanone)	
	Dimethyl ether	Methyl ethyl ketone (MEK or Butanone)	
	Divinyl ether	Octane	
	Methylbutyl ether (MTBE)	Pyridine	
	The broad fraction of light hydrocarbons	Hydrogen sulfide	
		Methanol	
		Ethanol	
		1-Propanol	
		Amyl alcohol	
		Isobutanol	

Isopropyl alcohol
Cyclohexane
Ethyl formate
Chloroethane

During an assessment of scales of defeat at the overpressure (shock waves) the distinction of chemical compounds on the heat of combustion, which is used for calculation of the total energy reserve, has to be considered. For typical hydrocarbons the value of specific heat of combustion is taken into consideration H_{SG0} = 44 MJ/kg. For other combustible substances at the calculations the specific energy release is used:

$$H_{SG} = \beta \cdot H_{SG0} \tag{75}$$

where β = correction parameter. For some substances the correction parameter β can be found in table 60:

Table 60. Classes of combustible substances in combination with the correction parameter β.

Class of combustible substances	β	Class of combustible substances	β
Class 1		Class 2	
Acetylene	1.10	Cumene	0.84
Methylacetylene (Propyne)	1.05	Methylamine	0.70
Vinyl acetylene	1.03	Methanol	0.45
Ethylene oxide	0.62	Ethanol	0.61
Hydrazine	0.44	1-Propanol	0.69
Isopropyl nitrate	0.41	Amyl alcohol	0.79
Ethyl nitrate	0.30	Cyclohexane	1.00
Hydrogen	2.73	Acetaldehyde	0.56
Nitromethane	0.25	Vinyl acetate	0.51
		Gasoline	1.00
Class of combustible substances	β	Hexane	1.00
Class2		Isooctane	1.00
Ethylene	1.07	Pyridine	0.77
Diethyl ether	0.77	Cyclopropane	1.00
Diphenyl ether	0.77	Ethylamine	0.80
Propylene oxide	0.70		
Acrolein	0.62	Class of combustible substances	β
Carbon disulfide	0.32	Class 4	
Butane	1.00	Methane	1.14
Butene	1.00	1,1,1-Trichloroethane	0.15
1,3-Butadiene	1.00	Chloromethane	0.12
1,3-Pentadiene	1.00	Benzene	1.00
Ethane	1.00	Decane	1.00
Dimethyl ether	0.66	Dodecane	1.00

Diisopropyl ether	0.82	Toluene	1.00
The broad fraction of light hydrocarbons	1.00	Methyl mercaptan	0.53
Propylene (Propene)	1.00	Carbon monoxide	0.23
Propane	1.00	Dichloroethane	0.24
		Dichlorobenzene	0.42
Class of combustible substances	β		
Class 3			
Vinyl chloride	0.42		
Hydrogen sulfide	0.34		
Acetone	0.65		

Classification of the obstruction (clutter surrounding surface)

The character of the surface obstruction has an influence on the flame speed in the combustion cloud and, therefore on the parameters of the pressure wave. The characteristics of the surface obstruction are divided into four classes:

Class I – existence of long pipes, cavities, the cavities filled with gas mixture at which combustion it is possible to expect formation of turbulent streams of the products of combustion having not more than three times the size of a detonation cell of this mixture. If the size of a detonation cell for this mixture is not known, the minimum characteristic size of streams is accepted as 5 cm for substances of a Class 1, 20 cm for substances of a Class 2, 50 cm for substances of a Class 3 and 150 cm for substances of a Class 4;

Class II – highly cluttered surface: existence of half-closed volumes, high density of placement of processing and technological equipment, wood, large number of repeating obstacles;

Class III – average cluttered surface: freestanding processing and technological plants, storage tanks;

Class IV – little clutter and free surface.

Classification of combustion modes clouds

For an assessment of the impact of combustion of a cloud the possible modes of combustion are divided into six classes based on the speed of their distribution:

Class 1 – detonation or burning with a speed of the flame front 500 m/s and more;

Class 2 – deflagration, flame front speed 300 – 500 m/s;

Class 3 – deflagration, flame front speed 200 – 300 m/s;

Class 4 – deflagration, flame front speed 150 – 200 m/s;

Class 5 – deflagration, the flame front speed is calculated as:

$$u = k_1 \cdot M_T^{1/6} \tag{76}$$

where k_1 = constant = 43; M_T = mass quantity of flammable part of the cloud [kg];

Class 6 – deflagration, the flame front speed is calculated as:

$$u = k_2 \cdot M_T^{1/6} \tag{77}$$

where k_2 = constant = 26; M_T = mass quantity of flammable part of the cloud [kg].

The expected mode of a combustion of a cloud is assigned with the help of the table 61, depending on the class of combustible substance and the class of clutter of surrounding surface:

Table 61. Determination of the combustion mode.

Class of the combustible substance	Class of the obstruction			
	I	II	III	IV
1	1	1	2	3
2	1	2	3	4
3	2	3	4	5
4	3	4	5	6

By the determination of the maximum speed of the flame front, for the modes of combustion classes 2 – 4, the visible speed of the flame front must be calculated with the equation (76):

$$u = k_1 \cdot M_T^{1/6} \tag{76}$$

If the calculated value is more than the maximum speed of the corresponding speed (corresponding to the determinate class), this new value must be accepted to the upper bound of range of the expected speeds of combustion of a cloud.

Calculation of the maximum overpressure and positive impulse

Parameters of the pressure wave (overpressure *ΔP* and positive impulse I^+) are calculated proceeding from the expected combustion mode of a cloud (depending on the distance from the center of a cloud).

Class 1 mode of combustion of a cloud

The corresponding dimensionless distance is calculated with the equation (78):

$$R_x = R / \left(E / P_0\right)^{1/3} \tag{78}$$

where R = distance from the center of the cloud [m]; P_0 = atmospheric pressure [Pa]; E = total combustion energy [J].

Values of the dimensionless pressure P_x and the impulse I_x are determined by equations (79, 80) (for gas-steam-air mixes):

$$\ln\left(P_x\right) = -1.124 - 1.66 \cdot \left(\ln\left(R_x\right)\right) + 0.260 \cdot \left(\ln\left(R_x\right)\right)^2 \tag{79}$$

$$\ln\left(I_x\right) = -3.4217 - 0.898 \cdot \left(\ln\left(R_x\right)\right) + 0.260 \cdot \left(\ln\left(R_x\right)\right)^2 \tag{80}$$

The equations (79, 80), are fair for values R_x more than R_k = 0.2. If $R_x < R_k$, the P_x=18 and in the equation (80) instead R_x must be used the value R_x=0.14.

Values of the overpressure and the positive impulse are determined:

$$\Delta P = P_x \cdot P_0 \tag{81}$$

$$I^+ = I_x \cdot P_0^{2/3} \cdot E^{1/3} / C_0 \tag{82}$$

Class 2-6 mode of combustion of a cloud

The corresponding dimensionless distance is calculated with the equation (78).

Values of the dimensionless pressure P_x and the impulse I_x are determined by equations (83, 84):

$$P_{x1} = \left(\frac{u^2}{C_0^2}\right) \cdot \left(\frac{\sigma - 1}{\sigma}\right) \cdot \left(\frac{0.83}{R_x} - \frac{0.14}{R_x^2}\right) \tag{83}$$

$$I_{x1} = W \cdot \left(1 - 0.4 \cdot W\right) \cdot \left(\frac{0.06}{R_x} + \frac{0.01}{R_x^2} - \frac{0.0025}{R_x^3}\right) \tag{84}$$

$$W = \frac{u}{C_0} \cdot \left(\frac{\sigma - 1}{\sigma} \right) \tag{85}$$

where σ = extent of expansion of combustion products (for gas-steam-air mixes it is allowed to accepted as 7, for the dust-air mixes it is allowed to accepted as 4); u = visible speed of the flame front [m/s].

By the deflagration of the dust-air explosive atmosphere the total combustion energy E must be multiplied with the coefficient $(\sigma\text{-}1)/\sigma$.

Equations (83, 84) are fair for values R_x more than $R_{kp1} = 0.34$. If $R_x < R_{kp1}$ instead R_x in the equations (83, 84) the value must be used R_{kp1}.

Values of the overpressure and the positive impulse are calculated with the equations (81, 82). Instead of P_x and I_x the auditor uses the values P_{x1} and I_{x1} in the equations (81, 82).

8.5.2 Dutch approach

The Dutch approach uses the so-called Multi-Energy model to calculate the vapour cloud explosion. “The Multi-Energy concept is based on the observation that the explosive potential of a vapour cloud is primarily determined by the obstructed and/or partially confined parts of the cloud” (Mercx et al. 2000). However the (CPR14E 2006) describes the concept of the Multi-Energy method as an generally accepted practical model, which represent best mechanics of an unconfined vapour cloud explosion, but at the same time “the application in practice though is hampered due to the lack of appropriate guidance for application as some aspects are still not yet fully described due to the lack of experimental data”.

More information about the Multi-Energy model can be found in (Eggen 1998, CPR14E 2006, K. van Windergen et al. 1995).

Similar to chapter 8.2.2 the mode “shows expert parameters” is discussed next. As in the pool fire example (chapter 8.2.2) the auditor may use some default input data in case of lacking some parameter data. Table 62 structures the input process. Terminology is retained unchanged. Substance data are taken from (CPR18E 2005) database (state: 22.07.1999).

Table 62. Data input. Model: Explosion (Multi Energy model) version: 5.03.

Description	Input Data
Chemical name	…
Ambient pressure, [bar]	…
Total mass in explosive range, [kg]	…
Fraction of flammable cloud confined	User defined/*Default = 0.08*
Curve number	User defined
Distance from release (Xd), [m]	…
Offset between release point and cloud centre, [m]	User defined/*Default = 0*
Threshold overpressure, [mbar]	User defined/*Default = 100*
X-coordinate of release, [m]	User defined/*Default = 0*
Y-coordinate of release, [m]	User defined/*Default = 0*
Predefined wind direction	User defined (N, NNE, etc.)
Wind comes from (North = 0 degrees), [deg]	…

where:

- “Total mass in explosion range is the explosive mass at time t – explosive mass in gas cloud at time of study t (semi-continuous and instantaneous releases) or at any time (continuous releases). [This mass must be calculated or determine. TNO EFFECTS (CPR14E 2006) framework uses another model].
- Fraction of flammable cloud confined – that’s the volume percentage of the explosive cloud (part of the vapour cloud within explosive limits) which is confined/obstructed.

[As a default, the value from the System Parameters value "Fraction confined mass ME" will be used].

The fraction of flammable cloud confined is of great importance, as the mass of chemical found in the confined region is the one used by the model to do the calculations. This means that for a given scenario, the results obtained will be the same if we put 2,000 kg in "Total mass in explosive range" and 50% in "Fraction of flammable cloud confined" (so 1,000 kg of confined explosive mass) or we input 10,000 kg in "Total mass in explosive range" and 10% in "Fraction of flammable cloud confined" (1,000 kg of confined explosive mass as well).

It has been experimentally demonstrated, as can be found in the 3rd edition of the Yellow Book, that only the confined/obstructed parts of the explosive cloud contribute to the deflagration/detonation phenomenon” (TNO EFFECTS 2014).

- Curve Number

As described in (CPR14E 2006, Kinsella 1993) three blast source strength factors must be defined by the choice of the explosion type:

– degree of obstruction by obstacles inside the vapour cloud,

– ignition energy,

– degree of confinement.

For more information see (paragraph 5.5.2 CPR14E 2006).

As described in (TNO EFFECTS 2014): “the multi-energy method is based upon experimental graphs in which the required value depends upon the distance from the vessel and the type of explosion. 10 different types of explosion are considered, and have a curve associated to them”. Those are:

- 1: Very weak deflagration
- 2: Very weak deflagration
- 3: Weak deflagration
- 4: Weak deflagration
- 5: Medium deflagration
- 6: Strong deflagration
- 7: Strong deflagration
- 8: Very strong deflagration
- 9: Very strong deflagration
- 10: Detonation

The results of categorising are expressed in table 63 which assigns the class (curve) numbers corresponding to the various combinations of the boundary and initial conditions:

Table 63. Initial blast strength index (CPR14E 2006).

Blast strength category	Ignition strength (High / Low)	Obstruction (High / Low / None)	Parallel plane (Confined / Unconfined)	Class
1	H	H	C	7 - 10
2	H	H	U	7 - 10
3	L	H	C	5 - 7
4	H	L	C	5 - 7
5	H	L	U	4 - 6
6	H	N	C	4 - 6
7	L	H	U	4 - 5

8	H	N	U	4 - 5
9	L	L	C	4 - 5
10	L	L	U	2 - 3
11	L	N	C	1 - 2
12	L	N	U	1

Here, the (CPR14E 2006) gives a remark: “as this information is not available presently it is advised to choose a source strength class number 10. The result will be conservative as the class number is lower in almost all cases.”

- Offset between release point and cloud center – this is the distance between the point where the release of the chemical started (from a vessel, a broken pipe, an evaporating pool) and the position of the center mass of the confined explosive cloud. See figure in ‘Distance from release (Xd)’ for more information (TNO EFFECTS 2014).
- Threshold overpressure – this is the overpressure value (in mBar) for which [the auditor] wants to calculate the distance from the center mass position where it is reached (output value). It is also the threshold value to be used when calculating the output contour plot of all the positions where this overpressure is reached (TNO EFFECTS 2014).

The output mask of TNO EFFECTS summarizes the calculation results. Table 64 lists all quantified parameters:

Table 64. Quantified parameters in TNO EFFECTS (Data output).

Parameters	Parameters
Confined mass in explosive range, [kg]	Dist. from center mass of cloud at threshold overpressure, [m]
Total combustion energy, [MJ]	Blast-wave shape at Xd
Peak overpressure at Xd, [mbar]	Damage (general description) at Xd
Peak dynamic pressure at Xd, [mbar]	Damage to brick houses at Xd
Pressure impulse at Xd, [Pa·s]	Damage to typical American-style houses at Xd
Positive phase duration at Xd, [ms]	Damage to structures (empirical) at Xd

8.5.3 Comparison

For the calculation of the p_{dyn} – peak dynamic pressure in blast-wave (in Russian version ΔP – overpressure) both approaches use the same equation (81). In the Dutch approach the same equation looks as:

$$p_{dyn} = p_{dyn}' \cdot p_a \tag{86}$$

there p_{dyn}'= scaled dynamic pressure in blast-wave (in Russian approach it is the P_x – dimensionless pressure). Here the first difference between the approaches can be observed. In the Russian approach the dimensionless pressure is determined with the equation (79) or equation (83) depending on the class: mode of combustion of a cloud. For the determination of the scaled dynamic pressure in blast-wave the Dutch approach uses the graph (fig. 56):

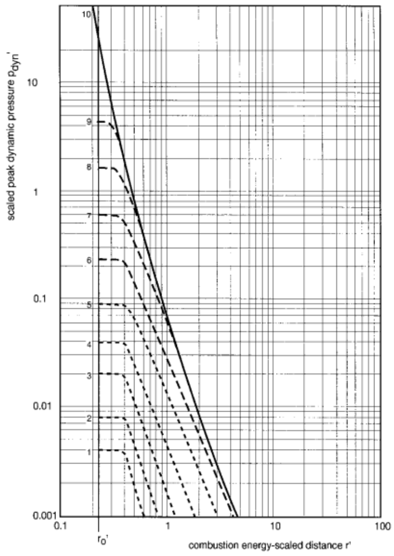


Figure 56. Multi-Energy method blast chart: peak dynamic pressure (CPR14E 2006, p. 5.36).

To determine the scaled dynamic pressure (dimensionless pressure) it is necessary to know the scaled distance r' (in Russian version – dimensionless distance). Both approaches use the equation (78).

For the calculation of the i_S – positive side-on impulse of blast-wave (in Russian version – positive impulse, determined with the equation (82) the Dutch approach uses a similar equation (87) :

$$i_S = \frac{1}{2} \cdot P_S \cdot t_p \tag{87}$$

there P_S= peak side-on overpressure of blast-wave [Pa]; t_p= positive phase duration of blast-wave [s].

$$t_p = t_p' \cdot \left(E / p_a\right)^{1/3} / a_a \tag{88}$$

there t_p' = scaled positive phase duration of blast-wave; E = total combustion energy [J]; p_a = ambient pressure [Pa]; a_a = speed of sound in ambient air [m/s].

$$P_S = P_S' \cdot p_a \tag{89}$$

there P_S' = scaled peak side-on overpressure of blast-wave.

For the determination of the scaled peak side-on overpressure of blast-wave and the scaled positive phase duration of blast-wave, the Dutch approach uses the graphs (fig. 57, 58):

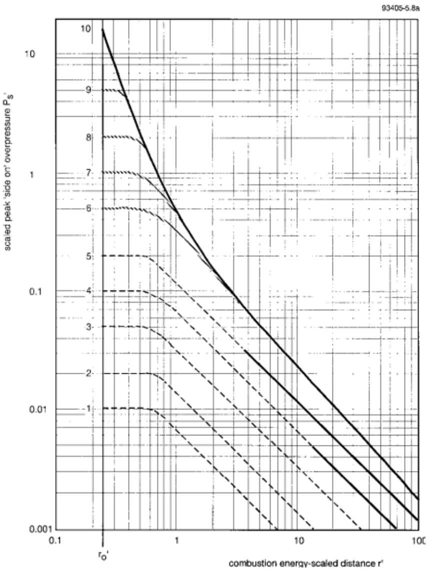


Figure 57. Multi-Energy method blast chart: peak side-on overpressure (CPR14E 2006, p. 5.35).

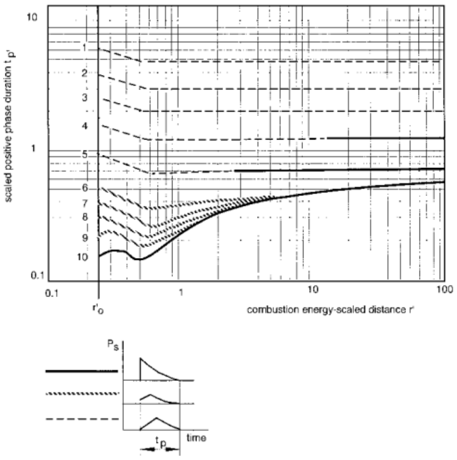


Figure 58. Multi-Energy method blast chart: positive phase duration and blast-wave shape (CPR14E 2006, p. 5.37).

The difference to the Dutch approach is that the Russian approach, which uses the equation (82) to calculate the positive impulse, is supported by equations (80) and equations (84, 85) (depending form the class: mode of combustion of a cloud). Equation (82) (1 class mode of combustion of a cloud – detonation) is based on natural logarithmic function and depends on the dimensionless distance too.

8.5.4 Comparison in the risks calculations

The Dutch approach only evaluates the degree of injury of buildings and not the risks or the probabilities of the injury. It is classified as:

- Damage (general description) for the release distance

Total destruction	Zone A: > 83 kPa
Heavy damage	Zone B: 35 - 83 kPa
Moderate damage	Zone C: 17 - 35 kPa
Minor damage	Zone D: 3.5 - 17 kPa

- Damage to brick houses for the release distance

More than 75% of all outer brick walls have collapsed	70 kPa
The damage is not repairable; 50% to 75% of the outer brick walls are lightly to heavily damaged. The remaining brick walls are unreliable	35 kPa
Not habitable without major repair works. Partial roof failures, 25% of all brick walls have failed, serious damage to the remaining carrying elements. Damage to window frames and doors	7-15 kPa
Habitable after relatively easy repairs. Minor structural damage	3 kPa
Damage to roofs, ceilings, minor crack formation in plastering, more than 1% damage to glass panels	1 - 1.5 kPa

- Damage to typical American-style houses for the release distance

Total collapse of building	70 kPa
Serious damage. Collapse of some walls	30 kPa
Moderate to minor damage. Deformed walls and doors; failure of joints. Doors and window frames have failed. Wall covering has fallen down	15 kPa
Minor damage. Comparable to a damage due to a storm; wooden walls fail, breakage of windows	7 - 10 kPa

- Damage to structures (empirical) for the release distance

The supporting structure of a round storage tank has collapsed	100 kPa
Brickstone walls (20-30 cm) have collapsed	50 kPa
Displacement of a cylindrical storage tank, failure of connecting pipes	50 - 100 kPa
Loaded train carriages turned over	50 kPa
Collapse of a pipe-bridge	40 - 55 kPa
Displacement of a pipe-bridge, rupture of piping	35 - 40 kPa

The Russian approach uses determined criteria to evaluate the injury to personnel, located in buildings or on open air:

Degree of injury	Peak overpressure , kPa
Total collapse of building	100
50 % collapse of building	53
Middle injury of building	28
Moderate damages of buildings (damage of internal partitions, frames, doors, etc.)	12
Lower threshold of injury to the personnel by a pressure wave	5
Minor damage (breakage of windows)	3

For the calculation of the probability (%) of the lethal outcome (probability of fatality to personnel) the Russian approach uses also the probit function Pr, which is related to the destruction of buildings:

$$\mathrm{Pr} = 5.0 - 0.26 \cdot \ln V \tag{90}$$

$$V = \left(\frac{17500}{\Delta P}\right)^{8.4} + \left(\frac{290}{I^{+}}\right)^{9.3} \tag{91}$$

The value of conditional probability of fatality to personnel $Q_{di}(a)$ is calculated depending on the calculated probit function Pr:

$$Q_{di}\left(a\right) = \frac{1}{\sqrt{2 \cdot \pi}} \int_{-\infty}^{\mathrm{Pr}-5} \exp\left(-\frac{U^{2}}{2}\right) \cdot dU \tag{92}$$

Because the integral belongs to special functions, the decision was made to calculate it with the help of the trapezoidal rule (fig. 59):

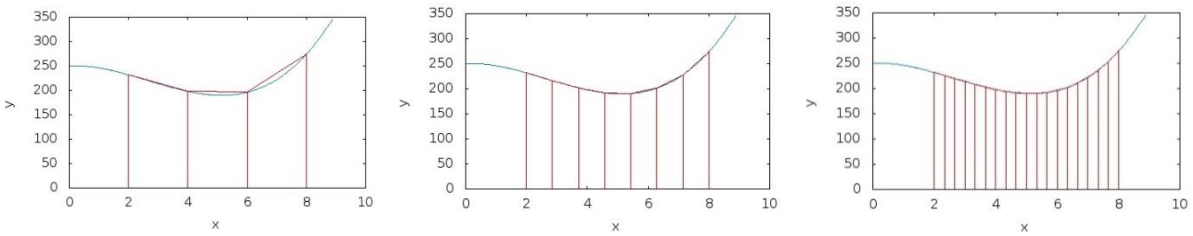


Figure 59: An animation showing how the trapezoidal rule approximation improves with more strips. From (https://en.wikipedia.org/wiki/Trapezoidal_rule#/media/File:Trapezium.gif V.: June, 2016).

The calculation of the conditional probability of fatality to personnel $Q_{di}(a)$ is used for every fire (pool fire, jet fire, fire ball) and explosion (vapour cloud explosion) models.

8.5.5 Prototype tool of the Russian approach

To compare the two tools, the Russian approach was transformed into a tool as in the example with the pool fire model.

Chapter 8.5.1 outlines the Russian approach from the side of the equations and the procedure of the calculated model.

This chapter introduces the method in form of an MS Excel prototype which gives the auditor a simple option to calculate the overpressure of a vapour cloud explosion, positive impulse and injury based on the probit function, depending on the distance. The auditor must enter the next parameters:

- Mass quantity of flammable part of the cloud, M_T
- Class of the combustible substance
- Class of the obstruction
- Correction parameter β (from table 60)
- Extent of expansion of combustion products, σ
- Correction coefficient for the vapour cloud location (1 = if the vapour cloud is located in the air; 2 = if the vapour cloud is located at the earth surface)

As described in chapter 8.5.1 the mass quantity of flammable part of the cloud M_T must by calculated by the auditor separately before it can be entered in the input mask.

After the input of all data, the results are:

for a set of overpressure values in kPa (kilopascal) $\Delta P = \{100,\ 53, 28, 12,\ 5,\ 3\}$ the tool gives the distance from the vapour cloud [m]. The minimum distance, there the overpressure does not change is also given for the calculated corresponding dimensionless distance (R_x). For this distance the exact value of the maximum overpressure is calculated.

For a set of probabilities of fatality to personnel [%] $Q = \{99.9, 90.0, 50.0, 10.0, 1.0\}$ the tool gives the distance from the center of the vapour cloud [m]. At the same time the tool calculates the probit function Pr for the entered distance (table 65) and gives the probability (%) of the lethal outcome (probability of fatality to personnel) as output:

Table 65. Data output table.

Parameter	Output (example)
Pr	10.965
Q, [%]	100.00

8.5.6 Calculation

For the comparison of Dutch and the Russian standards, three different substances (hydrazine, propane and methyl mercaptan) and two kinds of scenarios (in dependence of the type of explosions – detonation and different deflagrations) were chosen. The total mass of explosive range is 1000 [kg] for every scenario.

Dutch approach uses the “Default value” 0.08 by the determination of the fraction of flammable cloud confined. Russian approach uses as a “Default value” 0.1, that corresponds 10%. It means that the fraction of flammable cloud confined is the volume percentage of the explosive cloud (part of the vapour cloud within explosive limits). Therefore, in both tools the fraction of flammable cloud confined is accepted as 0.1.

The results of the comparison are presented in tables 66 to 72:

1st Scenario: 1 class of the substance (Hydrazine) and II Class of the obstruction, the combustion mode is selected as Class 1 – detonation. The Dutch approach determines for such scenario the same explosion type:

Table 66. Comparison of calculated overpressure for hydrazine (high class of obstruction). Curve number – Detonation.

Approach	Overpressure values [kPa]					
	100	53	28	12	5	3
	Distance *m* [m] from the vapour cloud					
Russian	18	26	37	66	147	304
TNO (detonation)	19	26	37	66	141	220

The scenario of detonation in a high class of obstructions shows the same result values in both approaches. The Russian approach calculates the maximum overpressure 289 [kPa] by a distance of 11 meters. However the Dutch approach calculates the maximum overpressure 1363 [kPa] by a distance of 7 [m].

2nd scenario: 1 class of the substance (Hydrazine) and IV Class of the obstruction, the combustion mode is selected as Class 3 – deflagration, flame front speed 200 – 300 [m/s]. The Dutch approach determines the class (curve) number – 5: Medium deflagration – for such a scenario.

Table 67. Comparison of calculated overpressure for hydrazine (low class of obstruction).

Approach	Overpressure values [kPa]					
	100	53	28	12	5	3
	Distance *m* [m] from the vapour cloud					
Russian	-	28	61	151	371	623
TNO (medium deflagration)	-	-	-	26	66	107

The Russian approach calculates the maximum overpressure 83 [kPa] by a distance of 11.1 [m]. The Dutch approach calculates the maximum overpressure 12 [kPa] by a distance of 26 [m].

The results of both methods are completely different. As described in chapter 8.5.1 the Russian approach uses table 61 to define the combustion mode. Thus, an influence of the type of the explosion of the calculated results is observed.

3^{th} *scenario*: change of the class (curve) number of a highest – 7: Strong deflagration

Table 68. Comparison of calculated overpressure for Hydrazine by a strong deflagration (low class of obstruction).

Approach	Overpressure values [kPa]					
	100	53	28	12	5	3
	Distance *m* [m] from the vapour cloud					
Russian	-	28	61	151	371	623
TNO (strong deflagration)	12	25	38	68	140	310

Also by the changing of the class (curve) number of a highest – 7: Strong deflagration – the results are similar only for an overpressure of 53 [kPa]. For overpressure values the distances of the Russian approach are twice as big as the Dutch approaches values.

4^{th} *scenario*: 2 class of the substance (Propane) and II Class of the obstruction, the combustion mode is selected as Class 2 – deflagration, flame front speed 300 – 500 [m/s] (Russian approach).

The Dutch approach determines the class (curve) number – 7 – 10 for such a scenario: (strong deflagration – detonation). There are no differences between the calculated results for the “strong deflagration” and “detonation” in the (TNO EFFECTS 2014).

Table 69. Comparison of calculated overpressure for Propane (high class of obstruction). Curve number – Detonation.

Approach	Overpressure values [kPa]					
	100	53	28	12	5	3
	Distance *m* [m] from the vapour cloud					
Russian	60	122	238	567	1370	2289
TNO (detonation)	25.5	34.5	50.5	92	190	295

By the comparison of the scenarios for Hydrazine and Propane it can be seen, that by the explosion type of a “detonation”, the results in both methods can differ. An influence of the class of the substance plays an important role.

The Russian approach calculates the maximum overpressure 230 [kPa] at a distance of 15 [m]. The Dutch approach calculates the maximum overpressure 1474 [kPa] at a distance of 9 [m].

5th *scenario*: 2 class of the substance (Propane) and IV Class of the obstruction, the combustion mode is selected as Class 4 – deflagration, flame front speed 150 – 200 [m/s] (Russian approach). The Dutch approach determines the class (curve) number – 5: Medium deflagration – for such a scenario

Table 70. Comparison of calculated overpressure for Propane (low class of obstruction).

Approach	Overpressure values [kPa]					
	100	53	28	12	5	3
	Distance *m* [m] from the vapour cloud					
Russian	-	-	29	84	213	360
TNO (medium deflagration)	-	-	-	36	90	143

As in the comparison of the Hydrazine, the results of the Russian approach are twice as big as the Dutch approach values for the similar type of an explosion.

The Russian approach calculates the maximum overpressure 37 [kPa] at a distance of 15 [m]. The Dutch approach calculates the maximum overpressure 20.6 [kPa] at a distance of 20 [m].

6th scenario: 4 class of the substance (Methyl mercaptan) and II Class of the obstruction, the combustion mode is selected as Class 4 – deflagration, flame front speed 150 – 200 m/s (Russian approach). The Dutch approach determines the class (curve) number 7 – 10 for such a scenario.

Table 71. Comparison of calculated overpressure for Methyl mercaptan (high class of obstruction).

Approach	Overpressure values [kPa]					
	100	53	28	12	5	3
	Distance *m* [m] from the vapour cloud					
Russian	-	-	24	68	172	291
TNO (detonation)	20.5	28	40	73	150	239

Such comparison is not expedient as it only compares the different types of an explosion. But the results are similar to each over beginning for least overpressures. The Russian approach calculates the maximum overpressure 37 [kPa] at a distance of 12 [m]. The Dutch approach calculates the maximum overpressure 1584 [kPa] at a distance of 7 [m].

7th scenario: 4 class of the substance (Methyl mercaptan) and IV Class of the obstruction, the combustion mode is selected as Class 6 – deflagration, the flame front speed is calculated as:

$$u = k_2 \cdot M_T^{1/6} \tag{77}$$

where k_2 = constant = 26; M_T = mass quantity of flammable part of the cloud [kg]. The Dutch approach determines for such scenario the class (curve) number – 4 – 5:

Table 72. Comparison of calculated overpressure for Methyl mercaptan (low class of obstruction).

Approach	Overpressure values [kPa]					
	100	53	28	12	5	3
	Distance *m* [m] from the vapour cloud					
Russian	-	-	-	-	-	-
TNO (4 weak deflagration)	-	-	-	-	40	95
TNO (5 medium deflagration)	-	-	-	29	71	115

The Russian approach calculates the maximum overpressure 2.8 [kPa] at a distance of 12.2 [m]. Such result is possible in the Dutch approach if the class (curve) number is 1 – 2: very weak deflagration. It is possible if the ignition strength is low (table 63 of the Dutch approach). But it also has an influence on other scenarios with the same substance.

8.5.7 Conclusions

The deflagration scenarios with higher flame front speed give larger calculated results in the Russian approach. In fact if the overpressure is lower, the variation between both approaches is bigger. The deflagration scenario with weak flame front speed gives lower calculated results in the Russian approach. The determination of the curve number according to the table 63 is rather subjective and makes the selection of the deflagration speed more complicate for an auditor. There is a high probability in a wrong definition of the flame front speed. In contrast to the Dutch approach the Russian approach uses the substance properties, supported by the tables 59, 60 and the class of the obstruction. Thus, the definition of the flame front speed is easier in the Russian approach. The results of the calculated overpressure have automatically an influence on the probit function and as a consequence on the estimated risk. Thus, the potential risk is incredibly higher in the Russian approach.

The differences can pose the question how close the analyzed results of both approaches are to reality. Nevertheless, the Russian and Dutch ordinances refer the developed vapour cloud explosion models on the experimental data tests.

9 Conclusions to the extended quantitative approach for consequence assessment

“The Russian and Dutch ordinances for calculating physical effects of hazardous substances differ in their origin and legal context. For this it is not surprising that the models, [which are compared], are slightly different. The [chapter 8 explains] these varieties. Furthermore both ordinances are industry standards which imply their design for practical oriented purposes and eased feasibility. Again there are differences. The comparison of models [and] results […] gives hints towards methodological improvements and [application] development.

As shown in this dissertation, the Russian approach and the [prototype tool] according MS Excel […] is easier and it requires in most instances less input […] [data], which gives a better chance for the auditor to view the serviceability.

The final version of the MS Excel prototype tool expects to show similar analysis properties as (TNO EFFECTS 2014). This gives auditors the possibility to make an accelerated [progress in] risk analysis of […] scenarios and they will have more detailed output data about the scenarios, risk contours and probit functions. Graphs, e.g. visualized on a site map, supplement this approach” (Leksin et al. 2015).

The advantages of the suggested MS Excel prototype tool, which is based on the Russian approach, is that it considers the probit function in all scenarios in comparison to the Dutch ordinance. It gives a better overview about the risk spectrum and risk limits for the audited enterprise. Another benefit lies in the exact defined risk limit for an individual, e.g. by fire models the heat flux scale $q = \{10.5,\ 7.0, 4.2, 1.4\}$ and by explosion model the overpressure scale $\Delta P = \{100,\ 53, 28, 12,\ 5,\ 3\}$. Such unambiguous limit values make a consequence assessment easier and furthermore the process of deciding for a risk nomination to develop precautions measurements.

The extended quantitative approach for consequence assessment can be also used not only for typical storage facilities but also for processes and plants (e.g. separator, pumps etc.), which gives the assessment another beneficial factor.

10 Results and Outlook

In the context of this dissertation methodological challenges occurred that were discussed in detail in the respective chapters.

On the whole it was observed that the risk analysis in CPI in the field of EFP has to be considered as a complicated and complex system. This dissertation seeks to contribute to the enhancement of the individual risk assessment.

As the literature research showed today's business environment is far more competitive, demanding continuous improvement of financial performance as well as requirement compliance with safety legislation. The reported methodological gaps existing in the process of risk analysis, when duly considered in the development of a new method, strive to be in accordance with the industry's needs. The presented developed method results in a detailed semi-quantitative risk and quantitative consequence assessment in the field of explosion and fire risks.

Such an analysis provides more flexibility due to the detailed risk evaluation, additionally considering the range of the majority of possible scenarios. Possible improvements of the MS Excel prototype tool which is based on the developed method cannot be excluded due to the overall complexity of the system. Nevertheless, the mathematical procedures working in the background of the MS Excel prototype tool rule out possible faults due to their universality.

The presented extended method can be adapted for other kinds of risk analyses, e.g. to assess the financial impact of a risk to which a plant or building is exposed. In other words this also allows a risk estimation concerning material damage, building damage or interruption damage. Although, it is important to consider that the financial risk analysis needs further research and an adaption of the check list, additional parameters for the developed equations and furthermore the acquisition of data in the examined surveyed area of interest.

In general the presented method needs an additional survey to gather further data in order to improve the risk relevant parameters. Under these conditions a more comprehensive risk analysis can be carried out as a medium-term target. Naturally a supplementary examination of explosion and fire accidents in CPI is needed which naturally results in the development of a new database.

The presented extended quantitative approach for consequence assessment has manifold advantages, e.g. simpler application which give the auditor a better chance to view the serviceability based on the reduced amount of input data. As a consequence the MS Excel prototype tool based on this approach does not only need to be used by experts in the area of EFP. In addition to that the numerous output data cannot only be used for the individual risk calculation but also for the estimation of damages. This is possible due to the usage of the probit function which can possibly optimize the presented prototype tool. However as mentioned in the chapters comparing the Russian and Dutch approaches the question on closeness to reality was raised for the presented models (pool fire, fire ball, torch fire and vapour cloud explosion). The MS Excel prototype tool gives information to the auditor concerning hazards, worst case scenarios and based on this the auditor has to come to a conclusion on how the risk can be reduced.

Therefore, the set aims are achieved and the knowledge gaps are bridged. In order to distribute the new approaches among experts the next step will be the realization of the MS Excel prototype tools and its implementation as a commercial tool. Thus, chemical enterprises which have already signaled their interest will have the chance to apply the new method in practice.

References

AGENA (2012). *AgenaRisk*. Cambridge, United Kingdom: Agena. *www.agenarisk.com/products/desktop.shtml*. V.: June, 2016.

Apostolakis, G. (1990). The concept of probability in safety assessments of technological systems. *Science*, 250: 1359 - 1364. 1990.

AssessNET. *Fire Risk Assessment Module* (2012). Delo, M. Riskex Ltd., United Kingdom. www.assessnet.co.uk/fire_risk_assessment.aspx. V.: June, 2013.

Atallah, S. & J. Shah (1990). LNGFIRE: A Thermal Radiation Model for LNG Fires. *GRI-89/0176*. Gas Research Institute.1990.

Boot, H. (2016). Personal communication. 2016.

BS-62502 (2011). *Analysis techniques for dependability. Event tree analysis (ETA)* (BS EN 62502:2011-06-30: 2011). London: BSI Buntine, V. (1998). *Learning with Bayesian models (Report 94 - 04 - 13)*. NASA Ames Research Center. 2011.

Beerens, H.I. & J.G. Post (2006). The use of generic failure frequencies in QRA: the quality and use of failure frequencies and how to bring them up-to-date. *Journal of hazardous materials*. 130: 265 - 270. 2006.

Benichou, N., A.H. Kashef, I. Reid, et al. (2005). FIERAsystem: a fire risk assessment tool to evaluate fire safety in industrial buildings and large spaces. *Journal of Fire Protection Engineering*. 15: 145 - 172. 2005.

Boot, H. (2013). Quantifying safety with a QRA: To agree on the results, the method should be explicit. *Chemical Engineering Transactions*. 31: 7 - 12. TNO, Dep. Urban Environment and Safety. 2013.

Björkmann, J. & E. Mikkola (2011). Risk assessment of a timber frame building by using CRISP simulation. *Fire and Materials 2011*. 25: 185 - 192, John wiley & Sons, Ltd.. 2011.

Chamberlain, G.A. (1987). Development in design methods for predicting thermal radiation from flares. *Chem. Eng. Res. Des. Vol. 65*. 299 - 309. July 1987.

Chemical exposure index (2006). A Summary of the Dow Chemical Company's quick method to calculate toxic vapour dispersion. https://mimihassim.files.wordpress.com/2013/04/s2s_chemical_exposure_index.pdf. V.: June, 2016.

Christensen, F., O. Andersen, N. Duijm, & P. Harremoes (2003). Risk terminology – a platform for common understanding and better communication. *Journal of Hazardous Materials. 103*(3), 181 - 203.

Cluzel, D. & P. Sarrat (1979). Methode ERIC. Evaluation du Risque Incendie par le Calcul. In: *Proc. CIB Symposium on Systems Approach to Fire Safety in Buildings, Vol. I*. II/37 - II/58. 1979.

Coburn, A.W., R.J.S. Spence & A. Pomonis (1992). Factors determining human casualty levels in earthquakes: mortality prediction in building collapse. In: *Proc. 10th World Conf. Earthquake Eng*.. Madrid, Spain. 1992.

Compes, P.C. (1974). Modell zur Bestimmung des Sicherheitsgrades. In: Bundesanstalt für Arbeitsschutz und Unfallforschung. Literaturexpertise über theoretische Grundlagen des Arbeitsschutzes. *Forschungsbericht Nr. 111*. Dortmund. 1974.

Cook, D.K., M. Fairweather, J. Hammonds & D.J. Hughes (1987). Size and radiative Characteristics of Natural Gas Flares, Part 2: Empirical Model. *Chem. Eng. Res. Des. Vol. 65*. 318 - 325. July, 1987.

COSSH Assessment Software. Weir, B. Perspective CMMS Company, Scotland. www.pemms.co.uk/risk_assessment_software.html. V.: June, 2013.

COVO (1981). COVO Commision. Risk analysis of six potentially hazardous industrial objectes in the Rijnmond area. A pilot study. *A report to the Public Authority. Schiedam: Central Environment Control.* Agency Rijnmond. 1981.

CPR14E (2006). Committee for the Prevention of Disasters (CPR) publication CPR 14E. *The Yellow book*. Methods for the calculation of physical effects due to releases of hazardous materials, third edition second revised print 2005, republished as PGS2. 2006.

CPR16E (2005). Committee for the Prevention of Disasters (CPR) publication CPR16E, *The Green book*, Methods for the determination of possible damage to people and objects resulting from release of hazardous materials, 1992, republished as PGS1. 2005.

CPR18E (2005). Committee for the Prevention of Disasters (CPR) publication CPR 18. *The Purple book*. Guidelines for Quantitative Risk Assessment, 1999, republished as PGS 3. 2005.

Dic. Academic (2013). *Academic Dictionaries and Encyclopedias*. http://dic.academic.ru/dic.nsf/enc_chemistry/769/%D0%92%D0%97%D0%A0%D0%AB%D0%92%D0%9E%D0%9E%D0%9F%D0%90%D0%A1%D0%9D%D0%9E%D0%A1%D0%A2%D0%AC#sel=20:4,20:5. V.: June, 2016.

DIN EN ISO 13943 (2010). *Fire safety – Vocabulary. German and English version.* (ISO 13943:2010). Berlin: DIN Deutsches Institut für Normung e.V. 2010.

DNV (2012). *Synergi Life Risk Management*. Det Norske Veritas (DNV GL), Norway. www.dnv.com/services/software/products/synergi/synergilife/synergiliferiskmanagement.asp. V.: June, 2016.

DNV GL (2016). Det Norske Veritas (DNV GL), Norway. http://www.dnv.com/services/software/publications/2013/no_1/safeti_offshore_the_new_standard_for_offshore_qra_modelling.asp. V.: June, 2015.

Dow Chemical Method (2013). *S2S. The European Web Portal for Process Safety.* http://www.safetys2s.eu/modules.php?name=s2s_wp4&idpart=2&op=v&idm=34. V.: June, 2016.

Druzdzel, M. & L. Gaag (2000). Building probabilistic networks: where do the numbers come from? *IEEE Transactions on Knowledge and Data Engineering*. Vol.12, No.4. 2000.

Duijm, N. (2009). Acceptance criteria in Denmark and the EU. *Environmental Project No. 1269 2009 (Miljøprojekt),* Danish Ministery of the Environment - Environmental Protection Agency.

Dutcher, C. R., D. T. Yung & G.V. Hadjisophocleous (1996). FiRECAM System Model Documentation. *Internal Report 732*. Institute for Research in Construction, National Research Council of Canada, Ottawa, ON. 1996.

Eggen, J.B.M.M. (1998). GAME: Development of Guidance for the Application of the Multi-energy Method, TNO Prins Maurits Laboratory, Rijswijk, The Netherlands. 1998.

Eisenberg, N.A., C.J. Lynch & R.J. Breeding (1975). Vulnerability Model: A Simulation System for Assessing Damage Resulting from marine Spills (VM1). *US Coast Guard, AD/A-015 245*, NTIS rapport no. CG-D-137-75.

ETANKFIRE (2015). Experimental results of large ethanol fuel pool fires. SP Technical Research Institute of Sweden. Johan Sjöström, Glenn Appel, Francine Amon, Henry Persson et al. file:///U:/Projekt%20Schweiz%20Brandrisikobeurteilung/ESREL%202015/Literatur/ETANKFIRE%20%E2%80%93%20Experimental%20results%20of%20large.pdf , file:///U:/Projekt%20Schweiz%20Brandrisikobeurteilung/ESREL%202015/Literatur/Thermal%20exposure%20from%20large%20scale%20ethanol%20fuel%20pool%20fires.pdf. V.: December, 2015.

Firesafetysearch (2015). Fire Safety Search Marcus Media Ltd. United Kingdom. http://www.firesafetysearch.com/news/large-ethanol-fires-release-more-radiation-than-petrol/. V.: June, 2016.

FRAME. Fire Risk Assessment Method (for) Engineering www.framemethod.net; www.framemethod.net/indexen_2.html. V.: June, 2013.

Fraser-Mitchell, JN & BB Pigott (1993). Modelling Human Behaviour in the Fire Risk Assessment Model CRISP 2. C*IB W14: Fire Safety Engineering, part 3*. Proc. Int. Symp.. 1993.

Friedman, N., I. Nachman & D. Peer (1999). Learning Bayesian network structure from massive datasets: The "sparse candidate" algorithm. In *Proc. Uncertainty in Artificial Intelligence*, 206 - 215. 1999.

FZ (1994). *About fire safety (No. 69 - FZ)*. Federal Law of the Russian Federation. Moscow, Russia: Dec. 21, 1994.

Giannini, F. M., M.S. Monti, S.P. Ansaldi & P. Bragatto (2006). P.L.M., to support hazard identification in chemical plant design. In *D. Brissaud, et al. (Eds.), Innovation in life cycle engineering and sustainable development*. 349 - 362. Springer. 2006.

GOST 12.1.004-91 (1992). Occupational safety standards system. Fire safety. General requirements. *Safety standarts*. Moscow: IPK State committee of standards.

GOST 12.1.033-81 (1982). Occupational safety standards system. Fire safety. Terms and definitions. *Safety standarts*. Moscow: State committee of standards USSR.

GOST 12.3.047-2012 (2012). Occupational safety standards system. Fire safety of technological processes. General requirements. Methods of control. *Safety standarts*. Moscow: IPK State committee of standards.

Hadjisophocleous, G.V. & Z. Fu (2004). Literature Review of Fire Risk Assessment Methodologies. *International Journal on Engineering Performance-Based Fire Codes 6(1)*. 28 - 45. 2004.

Hall, J. R. (2006). Overview of Standards for Fire Risk Assessment. *Fire Science and Technology*. 2006.

Hall, J. R. & J. M. Watts (2008). Fire Risk Analysis. In *Fire Protection Handbook, Cote, A. E. (ed.)*. NFPA. 2008.

Hasofer, A. M., V. R. Beck & I.D. Bennetts (2007). Risk Assessment in Building Fire Safety Engineering. Oxford: Butterworth-Heinemann. 2007.

Hauptmanns, U. (2003). Reliability data for process plants. R*eprot No. IAUT-AS 0103*. 2003.

Heckerman, D. & J. Breeze (1995). Causal independence for probability assessment and inference using Bayesian networks. *Technical report MSR-TR-94-08*. Microsoft Research, Redmond, WA (USA). 1995.

Hottel, H.C. & A.F Saforim (1967). Radiative transfer, *McGraw Hill*, New York. 1967.

HSE (1989). Risk criteria for land-use planning in the vicinity of major industrial hazards. *HMSO*. ISBN 0 11 885491 7. 1989.

HSE (2004). Guidance on ‘as low as reasonably practicable’ (ALARP) Decision in Control Of major Accident Hazards (COMAH). *SPC/Permissioning/12*. Issue: Jul 2002, Review: Jul 2004.

HSE-REPORT (1978). Canvey: an investigation of potential hazards from operations in the Canvey Island/ Thurrock Area. 1978.

https://en.wikipedia.org/wiki/68%E2%80%9395%E2%80%9399.7_rule (2016).
Wikipedia (2016). 68 - 95 - 99.7 rule. V.: June, 2016.

Hucke, M. (2016). Personal communication. 2016.

Hurley, M. J. & R.W. Bukowski (2008). Fire Hazard Analysis Techniques. In: *Fire Protection Handbook*. Cote, A. E. (ed.), NFPA, Ch. 7. 3 - 121 - 3 - 134. 2008.

I.Chem.E (1992). Nomenclature for Hazard and Risk Assessment in the Process Industries, Institution on Chemical Engineers, UK. 1992.

IEC/FDIS 31010 (2009). *Risk management – Risk assessment techniques* (IEC/FDIS 31010:2009). Geneva: International Electrotechnical Commission. 2009.

IPCS (2004). *IPCS risk assessment terminology - Part 1 and Part 2*. Geneva, Switzerland: World Health Organization. 2004.

IRGC (International Risk Governance Council) (2005). Risk Governance – Towards an Integrative Approach. *White Paper No 1*. O. Renn with an Annex by P. Graham. IRGC, Geneva. 2005.

ISO 31000 (2009). *Risk management – Principles and guide lines* (ISO 31000:2009). Geneva: International Standards Organisation. 2009.

ISO-GUIDE 51 (1999). *Safety aspects -- Guidelines for their inclusion in standards* (ISO/IEC Guide 51:1999). Geneva: International Standards Organisation. 1999.

ISO-GUIDE 73 (2009). ISO/IEC. *Risk Management – Vocabulary –Guidelines for Use in Standards* (ISO GUIDE 73:2009(E/F). Geneva: International Standards Organisation. 2009.

ISO/TS 16732 (2005). *Fire safety engineering - Guidance on fire risk assessment*. (ISO/TS 16732:2005). Geneva: International Standards Organisation. 2005.

Kauer, R., F. Luciano, R. Giribone & J. Heerings (2002). Risk Acceptance Criteria and Regulatory Aspects. In *OMMI Vol. 1*. Issue, Dezember 2002.

Karlsson, B. (2002). Fire Risk Index Method - Multi Storey Apartment Buildings. *FRIM-MAB. Version 2.0*. Trätek, Rapport 0212053. 2002.

Kinsella, K.G. (1993). A rapid assessment methodology for the prediction of vapour cloud explosion overpressure, proceedings of the International Conference and Exhibition on Safety. Health and Loss Prevention in the Oil, Chemical and Process Industries. Singapore. 1993.

K. van Windergen, H.C. Salvesen & R. Perbal (1995). Simulation of an accidental vapour cloud explosion. *Process Safety Prog. 14 (3)*.173 - 181. 1995.

Mercx, W.P.M., A.C. van den Berg, C.J. Hayhurst, N.J. Robertson & K.C. Moran, (2000). Developments in vapour cloud explosion blast modelling. *J. Hazard. Mater. 71*. 301 - 319. 2000.

Kaplan, A. & B. John Garrick (1980). On the quantitative definition of risk. *Risk Analysis, I.* 1980.

Koseki, H. (1989). Combustion Properties of Large Liquid Pool Fires. *FireTechnology*. 241 - 255. August 1989.

Kustosz, A. (2013). Entwicklung einer Methodik zur monetären Bewertung von Schadensereignissen. *Dissertation*. Bergische Universität Wuppertal. 2013.

Kustosz, A. & U. Barth (2010). Bewertung der wirtschaftlichen Folgen von Explosionsereignissen. *TÜ Bd. 51. Nr. 11/12*. 2010.

Lauritzen, S. & D. Spiegelhalter (1988). Local computations with probabilities on graphical structures and their application to expert systems. *Journal Royal Statistics Society B.* 50(2). 1988.

Larsson, D. (2000). Developing the Structure of a Fire Risk Index Method for Timber-frame Multistorey Apartment Buildings. In: *Report 5026.* Lund University: Department of Fire Safety Engineering. 2000.

Lawley, G. (1974). Operability studies and hazards analysis, loss prevention. CEP. 1974.

Leksin, A., R. Mock & U. Barth (2013). The Potential of QRA Audit Tools in Industrial Fire and Explosion Protection. In *Proc. of European Safety and Reliability Conference (ESREL 2013)*. In: *Safety, Reliability and Risk Analysis: Beyond the Horizon,* Amsterdam, the Netherlands : 1895 - 1901. Peer reviewed. 2013.

Leksin, A., U. Barth, D. Adeulov & R. Mock (2014). The Use of the Combination of Indexing and Semi-quantitative Methods in Audits for Individual Risk Assessment in the Field of Fire and Explosion Protection. In *Proc. of European Safety and Reliability Conference (ESREL 2014)*. In: *Safety and Reliability. Methodology and Applications,* Wrosalw, Poland: 1369 - 1376. Peer reviewed. 2014.

Leksin, A., U. Barth, D. Adeulov & R. Mock (2015). Comparison of Dutch and Russian standards for calculating physical effects of hazardous substances. In *Proc. of European Safety and Reliability Conference (ESREL 2015).* In: *Safety and Reliability of Complex Engineering Systems,* Zurich, Switzerland: 69-78. Peer reviewed. 2015.

Lees, F.P. (1986). Loss Prevention in the Process Industries. ISBN 0-0408-10604-2. 1986.

Lewis, S. (2005). An Overview of Leading Software Tools for QRA. *American Society of Safety Engineers – Middle East Chapter (161)*. 7th Professional Development Conference & Exhibition, Kingdom of Bahrain, www.asse-mec.org, March 18 - 22, 2005.

Lottermann, J. (2012). Ansätze zur integrierten Brand- und Explosionssicherheit Entwicklung, Validierung und normative Verankerung einer bilateralen, kohärenten Beurteilungssystematik am Beispiel staubführender Anlagen. *Berlin Pro Business 2012. Dissertation*. Bergische Universität Wuppertal. 2012.

Magdeburg (2015). Personal communication with Prof. Dr.-Ing. Habil. Ulrich Krause within the scope of the projet TIBRO, University Magdeburg, Germany. 2015.

Mahadevan, S., R. Zhang & N. Smith (2001). Bayesian Networks for System Reliability Reassessment*. Structural Safety, 23*. 231 - 251. 2001.

Mannan, S. & F. P Lees (2005). Lee's loss prevention in the process industries: hazard identification, assessment and control. *3rd ed. Amsterdam, Boston: Elsevier Butterworth-Heinemann*. 2005.

Marszal, E. (2001). Tolerable Risk Guidelines. *ISA Transactions 40*. 391 - 399. 2001.

Meacham, B. J. (2008). A Risk-Informed Performance-Based Approach to Building Regulation. *7th International Conference on Performance-Based Codes and Fire Safety Design Methods*. 1 - 13. 2008.

Mock, R., U. Barth, A. Franz, S. Brunner & A. Leksin (2012). Computer-assisted risk assessment audit on operational level. In *Proc. PSAM 11 & ESREL 12 Vol. 5,* Helsinki, Finland: 4093 - 4102. 2012.

Mudan, K.S. (1984). Thermal Radiation Hazards from Hydrocarbon Pool Fires. *Progress Energy Combustion Science, 10*. 59 - 80. 1984.

Mudan, K.S. (1987). Geometric View Factors for Thermal Radiation Hazard Assessment. *Fire Safety Journal 12*. 89 - 96. 1987.

Murphy, K. (1998). Brief introduction to graphical models and Bayesian networks. Univ. of British Columbia, Canada. *www.cs.ubc.ca/~murphyk/Bayes/bnintro.html.* V.: June, 2013.

NFPA (2003). *NFPA Glossary of Terms.* The National Fire Protection Association (NFPA). USA. 289. *www.nfpa.org/assets/files/pdf/definitions.pdf*. V.: June, 2013.

NFPA 101A (2001). *Alternative Approaches to Life Safety* (2001). Quincy, MA: National Fire Protection Association. 2001.

NFPA 551. (2007). *Guide for the Evaluation of Fire Risk Assessments*. National Fire Protection Association. 2007.

NUREG/CR-2815 Nuclear Regulatory Commission. (1983). USA, *PRA procedure guide*. 1983.

Offshore hydrocarbon (2001). Offshore hydrocarbon releases statistics. *HID Statistics* Report. HSR 2001 002. 2001.

Order No. 404 (2009). The Method to define the computed value of fire risks in industrial facilities. *Order of the Russian Ministry of Emergency Situations (EMERCOM), № 404, 10 July* 2009.

Order No. 649 (2010). *Addition to [3], 14 December* 2010.

OREDA (2002). *Offshore Realiability Data, 4th Edition*. DNV 2002.

Pahl, G. & W. Beitz (2007). Konstruktionslehre : Grundlagen erfolgreicher Produktentwicklung ; Methoden und Anwendung. *Berlin [u.a.]: Springer, 2007.*

PAS 79 (2011). *Fire risk assessment – Guidance and a recommended methodology*. (PAS 79:2011). British Standards Institution. 2011.

Paté-Cornell, E. (2002). Risk and uncertainty analysis in government safety decisions. *Risk Analysis. Volume 22, Issue 3.* 633 - 646. 2002.

Pearl, J. (2000). *Causality*. Cambridge: Cambridge University. 2000.

Peterjohann, H. (2013). Projektmanagement: Checklisten. http://www.peterjohann-consulting.de/_pdf/peco-pm-checklisten.pdf. V.: June, 2016.

Press, S. J. (1989). Bayesian statistics: principles, models, and applications, New York: John Wiley & Sons. 1989.

Rasbash, D., G. Ramachandran, B. Kandola, J. Watts & M. Law (2004). Evaluation of Fire Safety. N.Y.: J. Wiley & Sons. 2004.

RD-03-26-2007 (2008). Методические указания по оценке последствий аварийных выбросов опасных веществ. *Regulatory document*. Moscow: Federal environmental, industrial and nuclear supervision service of Russia. 2008.

Rew, P. J. & W. G. Hulbert (1996). Development of Pool Fire Thermal Radiation Model. *HSE Contract Research Report 96/1996.*

Ridder, A. (2015). Risikologische Betrachtungen zur strategischen Planung von Feuerwehren – Empirische Befunde und Systematisierung von Zielsystemen. *Dissertation*.109 - 111. Bergische Universität Wuppertal. 2015.

Risk assessment data directory. OGP. International Association of Oil & Gas Producers. *Report No. 434 - 3*. *http://www.ogp.org.uk/pubs/434-03.pdf*. V.: June, 2016.

RISKPLOT GRAPHIC (2006). Davies, P.A, D.A. Carter & D. Quinn. ViewRisk: Risk calculation software. Proc. *Hazards XIX, IChemE.* 901 - 909. 27 - 30 March 2006, Manchester, UK.

Roberts, A.F. (1982). Thermal radiation hazard from releases of LPG from pressurised storage. *Fire Safety Journal, 4*.197 - 212.1982.

SAFETI (2015). Onshore Quantitative Risk Assessment. Industry standard software package for onshore QRA. *https://www.dnvgl.com/services/onshore-quantitative-risk-assessment-safeti--1715*. V.: June, 2016.

Salvi, O. & D. Gaston (2004). Risk assessment and risk decision-making process related to hazardous installation in France. *Journal of Risk Research: 7 (6)*. 599 - 608. September 2004.

Schönbucher, A. (2002). Sicherheitstechnische Aspekte, in: „Thermische Verfahrenstechnik". *Grundlagen und Berechnungsmethoden für Ausrüstungen und Prozesse*. Springer-Verlag. Berlin (2002).

SFK-GS-41 (2004). *Leitfaden „Risikomanagement im Rahmen der Störfall-Verordnung"*. April, 2004.

SFPE (2002). Fire Risk Analysis. *SFPE Handbook of Fire Protection Engineering Section 5*. Quincy, MA: Nat. Fire Protection Association. 2002.

Siegel, J. & R. Howell (2001). Thermal radiation heat transfer. New York: *Taylor & Francis, Inc.*. xix – xxvi *list of symbols for thermal radiation formulas*. ISBN 978-1-56032-839-1. Retrieved 2009-07-23.

SITIS (2015). SITIS Software tools. Russia. *http://www.sitis.ru/*. V.: June, 2016.

Spouge, J. (2006). Leak frequencies from the hydrocarbon release database. *Symposium Series No. 151*. ICHEME 2006.

Stephen, M., Olenick & Douglas J. Carpenter (2003). An Updated International Survey of Computer Models for Fire and Smoke. *SFPE Journal of Fire Protection Engineering, v. 13*. n. 2. 2003.

TAA-GS-03 (1994). *Abschlußbericht des Arbeitskreises: Novellierung der 2. Störfall-VWV*. 1994.

TAM Software Ltd. (2007). The Action Manager Company, United Kingdom. *www.theactionmanager.com*. V.: June, 2016.

Thomas, P.H. (1963). The size of flames from natural fires. In: *Proceedings of the Ninth Symposium (International) on Combustion*. 27 August - 1 September 1962, Ithaca, NY. 844 - 859. The Combustion Institute: Pittsburgh, PA. 1963.

TNO EFFECTS (2014). Version 9.0.19.8723, YAWS Database. 2014.

TNO (2015). TNO Innovation for life. EFFECTS – software for safety- and hazard analysis. *https://www.tno.nl/en/focus-area/urbanisation/environment-sustainability/public-safety/effects-software-for-safety-and-hazard-analysis/*. V.: June, 2016.

TOXI (2015). TOXI Software tools. Russia. http://toxi.ru/. V.: June, 2016.

Trebojevic, V. M. (2005). Risk criteria in EU*. ESREL European safety and reliability conference*. 2005. Risk Support Limited. London. 2005.

Tsao, C.K. & W.W. Perry (1979). Modifications to the Vulnerability Model: A Simulation System for Assessing Damage Resulting from Marine Spills (VM4). ADA 075 231. *US Coast Guard NTIS Report No. CG-D-38-79*. 1979.

UN/ISDR (2009). UN Office for DRR. *https://www.unisdr.org/we/inform/terminology*. V.: August, 2014.

Watts, J. M. (2002). Fire Risk Indexing. In: *SFPE Handbook of Fire Protection Engineering, Ch. 10. Section 5, Fire Risk Analysi*s. 5 - 125 - 5 - 142. Quincy, MA: National Fire Protection Association. 2002.

Weber, P., G. Medina-Oliva, C. Simon & B. Iung (2012). Overview on Bayesian networks applications for dependability, risk analysis and maintenance areas. *Engineering Applications of Artificial Intelligence 25 (4)*. 671 - 682. 2012.

Worthington, D. & H. Witlox (2007). DNV, 2007: QRA 's for Dutch Installations. II. Overview of Risk Tools SAFETI-NL Selected by the Dutch Government. *Loss Prevention and Safety Performance in the Process Industries 2007*. IChemE Symposium Series No. 153. IChemE. 2007.

Yung, D. (2008). Principles of Fire Risk Assessment in Buildings. N.Y.: J. Wiley & Sons. 2008.

Белько, И.В. & Свирид Г.П. (2004). *Теория вероятностей и математическая статистика*. 2004.

Ниворожкина, Л.И. & З.А. Морозова (2005). *Математическая статистика с элементами теории вероятностей в задачах с решениями*. 2005.

Кремер, Н.Ш. (2006). *Теория вероятностей и математическая статистика*. 2006.

Молчанов, В., П. Болодьян, Ю. И. Дешевых и др. (2001). Концепция объектно-ориентированного нормирования промышленных предприятий по пожарной безопасности. *Пожарная безопасность, № 4*. 94 - 106. 2001.

ППБ 01-03 (2003). *Правила пожарной безопасности в Российской Федерации*.
(ППБ 01-03. *Fire prevention rules in the Russian Federation*). 2003.

РД 03-418-01 (2001). *Методические указания по проведению анализа риска опасных производственных объектов. Methodical instructions on carry out of the analysis of risk of dangerous industrial objects*. 2001.

Руководство по оценке пожарного риска для промышленных предприятий 2006. Москва. 2006*. The management according to fire for the industrial enterprises.* Moscow. 2006*.*

Федеральный закон № 184 (2004). *Федеральный закон от 27 декабря 2002 № 184-ФЗ «О техническом регулировании». Federal law from December, 27th, 2002 № 184-FZ „On Technical regulation“*. 2004.

1nd Guidelines (1989). *Guidelines for process equipment reliability data with data tables. Center for Chemical Process Safety of the American Institute of Chemical Engineers*. 1989.

2nd Guidelines (1989). *Guidelines for chemical process quantitative risk analysis. 2nd Edition. Center for Chemical Process Safety of the American Institute of Chemical Engineers*. 2000.

Attachment: Possible role of the Bayesian network in the determined weighting factors

The Bayesian framework can be most useful (Paté-Cornell 2002) for the reliability check of the offered weighting factors, whose conditional probabilities are actually presented in a graph (fig. 16). The introduction of the Bayesian framework in the dissertation mainly follows (Friedman et al. 1999). A Bayesian network for random variables $\boldsymbol{X} = \{X_1, X_2, \ldots, X_n\}$ is a pair $G = \langle G, \Theta \rangle$. G is a directed acyclic graph whose vertices are associated with $\boldsymbol{X}$. Θ " … represents the set of parameters that quantifies the network". "It contains a parameter $\Theta_{x_i|\mathbf{Pa}(X_i)} = P(x_i \mid \mathbf{Pa}(X_i))$ for each possible value x_i of X_i, and $\mathbf{pa}(X_i)$ of $\mathbf{Pa}(X_i)$". Then, "a Bayesian network B specifies a unique joint probability distribution over $\boldsymbol{X}$" (Leksin et al. 2013) given by:

$$P_B = \left(X_1,\ldots,X_n\right) = \prod_{i=1}^{n} P_B\left(X_i \middle| \mathbf{Pa}\left(X_i\right)\right) \qquad \text{(I)}$$

In the graphical representation of a Bayesian network, nodes represent Bayesian random variables and are associated with a probability function. Edges show conditional dependencies. The variables interconnected with each node can be discrete or continuous. The causal relations between variables are expressed in terms of conditional probabilities.

An example of three nodes is presented in (fig. Example of Bayesian net), where the graphical structure shows that the variable C is influenced by variables A and B, and the variables A and B are independent. Each node has two possible values, corresponding to the working (true function) and failure (false function) states of the components of an assessed system, e.g. a fire protection system.

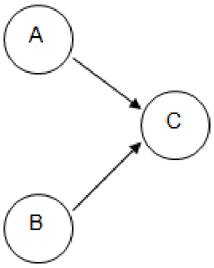


Figure. Example of Bayesian net.

For complex engineering constructions and structures the revaluation of the reliability on the basis of the Bayesian network has to be carried out with the simultaneous accounting of two important features of structural systems: existence of various options of sequence of multiple damages and correlation of limit states (Mahadevan et al. 2001).The Bayesian approach gives a chance to identify and structure a set of possible hypotheses, examining all existing data of the conditional probabilities of every node and presenting the risk analysis results along with the quantification of uncertainties (Apostolakis 1990, Press 1989). “Some of these benefits are the capability to model complex systems, […], to compute exactly the occurrence probability of an event [or scenario], […], to represent multimodal variables and to help modelling user-friendly by a graphical and compact approach” (Weber et al. 2012).

Further information about Bayesian networks and inference can be found in literature, e.g. (Pearl 2000, Druzdzel et al. 2000, Heckerman et al. 1995).

The Bayesian network approach enables the model developer to check input data and model factors against operational experience, e.g. from auditors of engineering companies. This formalisation will also increase the confidence into procedures and results. This and the comprehension of scenarios into the QRA approach can increase the potential of the audit tool.

The weighting factors can be assessed for more complex scenarios by means of the Bayesian tools. However this was not the objective target of this dissertation. As a means of help Bayesian tools are made available under the link (http://www.cs.iit.edu/~mbilgic/classes/fall10/cs595/tools.html). Some recommended of them are:

- Bayesialab (http://www.bayesia.com/en/products/bayesialab)
- Bayesian Knowledge Discoverer (http://kmi.open.ac.uk/projects/bkd/)
- Bayesian Network tools in Java (BNJ) (http://bnj.sourceforge.net/)
- Bayes Net Toolbox for Matlab (http://code.google.com/p/bnt/)

The last one, the Bayes Net Toolbox for Matlab, is auspicious because of the spreading and recognition of the Matlab in the R & D world. Moreover, they simplify the handling with a such tool, e.g. allowing liberties to visualize the results. Many instructions and examples for this tool can be found in the internet.

For simpler graphs the training expenditure probably keeps to a certain extent. However it is necessary to consider that for more complicated graphs with a larger number of nodes and, as a possible result, a larger possibility of their interconnection, the assessment procedure of the weighting factors becomes complicated repeatedly.

Bayesian network Application

The practical application of the Bayesian network modelling approach in the context of this dissertation needs a link to EFP scenarios as relevant for, e.g. audited enterprises. The application is shown by the text book example of (Murphy 1998) well known in the area of Bayesian inference. The notation is slightly adapted. Similar examples are, e.g. given in (Lauritzen et al. 1988).

The starting point of modelling is similar to ETA in (fig. 14) and the resulting Bayesian graph and variables are shown in (fig. I):

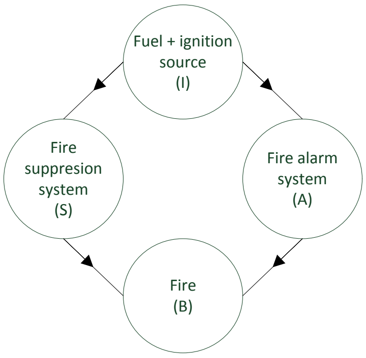


Figure I: Bayesian network “Fire Spreads”

The nodes and variables X_i are

- I: Fuel and ignition source (start)
- S: Fire suppression system (technical equipment; barrier)
- A: Fire alarm system (technical equipment; barrier)
- B: Fire (“blaze”; endpoint)

Supposed, an auditor evaluates the compliance of alarming system *A* as “acceptable” and suppression system *S* as “accepted”. Following a table I with determined weighting factors this is associated with unreliability’s 0.2 and 0.1:

Table I. Weighting factors for safety parameters

Compliance	Weighting Factors
Irrelevant	1.00
Unacceptable	0.50
Acceptable	0.20
Accepted	0.10

The nodes in (fig. I) are binary denoted by true (*T*) or false (*F*). The variable states are associated with probabilities according to compliance levels.

The Bayesian network quantification of this audit example needs a further assumption: as there is no a priori information about the presence of source *I* at the audited enterprises, the probabilities are set as $P(I = T) = \mathrm{P}(I = F) = 0.5$. Table II summarises these probabilities.

Table II: (Conditional) probabilities of *I*, *A*, *and S*

P(*S*=*F*)	*P*(*S*=*T*)	*P*(*I*=*F*)	*P*(*I*=*T*)	*P*(*A*=*F*)	*P*(*A*=*T*)
0.5	0.5	0.5	0.5	0.8	0.2
0.1	0.9			0.2	0.8

Table II considers the audit evaluation results whereas the adaption of Murphy's example needs a careful adaption of binary states.

The true states of node variables are associated with "success" as far as possible:

- Ignition source present ⇒ *T*
- EFP equipment operable ⇒ *T*
- No fire ⇒ *T*

Then, the probability of an inoperable suppression system *S* is expected to be low, e.g. $P(S = F) = 0.1$ ($P(A = F) = 0.2$, resp.). As there is no information about the reaction of suppression system *S* in dependency of *I*, the probability $P = 0.5$ is used. With this, the joint probability function is

$$P(B, S, A, I)= P(B|S, A)\cdot P(S|I)\cdot P(A|I)\cdot P(I)$$

Table III shows the estimated conditional probabilities for the "final" *B* node, i.e.:

- $P(B = T)$: Prob. of no fire (fire extinguished)
- $P(B = F)$: Prob. of fire (not extinguished).

Table III: Conditional Probabilities

P(*B*=*F*)	*P*(*B*=*T*)
1.0	0.0
0.1	0.9
0.1	0.9
0.01	0.99

For instance, if *S* and *A* are operable, then probability of no fire (true state) is 0.99. Using a Bayesian network, the conditional probabilities are computed as follows:

$$P\left(S=T\,|B=1\right)=\frac{P\left(S=T,\ B=T\right)}{P\left(B=T\right)}=\frac{\sum_{i,a}P\left(I=i,\ S=T,A=a,B=T\right)}{P(B=1)},$$

$$P\left(A=T\,|B=T\right)=\frac{P\left(A=T,B=T\right)}{P\left(B=T\right)}=\frac{\sum_{i,s}P\left(I=i,S=\mathrm{s},A=T,B=T\right)}{P\left(B=T\right)},$$

where

$$P\left(S=T,B=T\right)=$$
$$\begin{bmatrix} I=T & S=T & A=T & B=T \\ I=T & S=T & A=F & B=T \\ I=F & S=T & A=T & B=T \\ I=F & S=T & A=F & B=T \end{bmatrix}=\begin{bmatrix} 0.5 & 0.9 & 0.8 & 0.99 \\ 0.5 & 0.9 & 0.2 & 0.9 \\ 0.5 & 0.5 & 0.2 & 0.99 \\ 0.5 & 0.5 & 0.8 & 0.9 \end{bmatrix}=0.70$$

and

$$P\left(A=T,\ B=T\right)=$$
$$\begin{bmatrix} I=T & S=T & A=T & B=T \\ I=T & S=F & A=T & B=T \\ I=F & S=T & A=T & B=T \\ I=F & S=F & A=T & B=T \end{bmatrix}=\begin{bmatrix} 0.5 & 0.9 & 0.8 & 0.99 \\ 0.5 & 0.1 & 0.8 & 0.9 \\ 0.5 & 0.5 & 0.2 & 0.99 \\ 0.5 & 0.5 & 0.8 & 0.9 \end{bmatrix}=0.49$$

The probability of no fire, which is computed by the same procedure, is $P(B=T)$ = 0.75, and is the normalising constant. The final conditional probabilities are

- $P(S = T|B = T) = 0.89$
- $P(A = T|B = T) = 0.65$.

Thus, it is more likely of extinguished fire because of an operating suppression system. The probabilities looks reasonable for a fully compliant suppression and a weakening alarm system as found by the auditor. This was an example with a combination to the ETA. The ETA is linked with a check list, as described in chapters 7.1 – 7.2.2. The practical application of the Bayesian network modelling approach in the field of EFP QRA development needs a link to a typical check list. Next example shows a more complex application, which is exemplified by (Magdeburg, 2015) who calculates the probability of fatality to personnel by a fire (Fig.II).

Within an QRA audit, the auditor determines the basic elements, which have to be evaluated. The proposed Bayesian network uses the already given elements of the check list (as mentioned above) and calculates the likelihoods of those events which might have several independent causes.

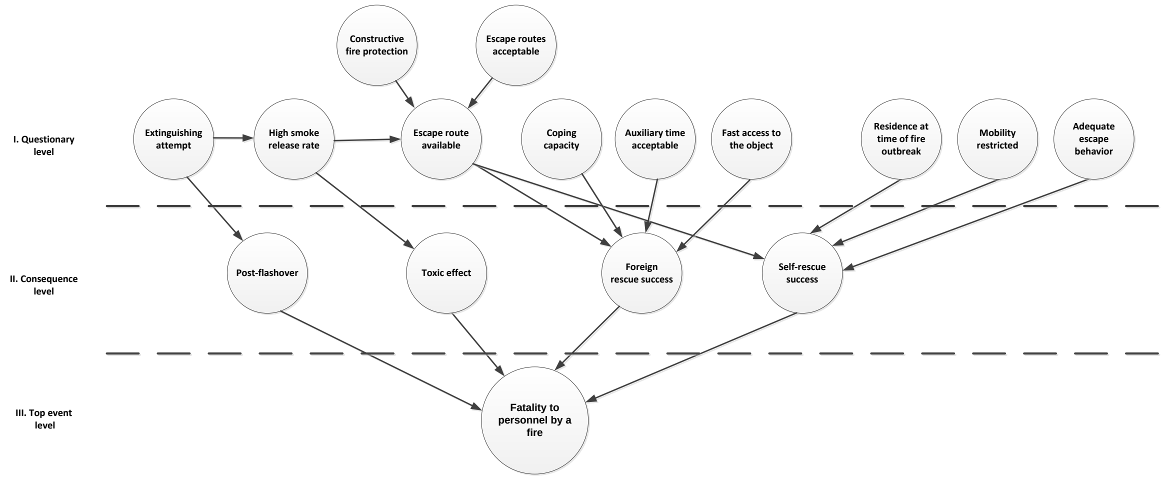


Figure II: Example of the calculation of the probability of fatality to personnel by a fire by Bayesian network

As re-using basic elements of given check lists, the approach semi-automatically supports the auditor who has to follow three steps:

- I. Questionary level – evaluation of the relevant elements for the risk audited area (enterprise, plant processes, escape routes which are relevant for the individual risk of personnel).
- II. Consequence level – evaluation of the consequences which are appropriable from the negative or positive side (determination of the linking with each other nodes and there dependences).
- III. Top event level – calculation of the probability of the top event supported by the Bayesian approach.

This Bayesian network allows calculating the final conditional probabilities for scenarios as given in table VII.

Following step I, the relevant elements are already evaluated. In this example the auditor evaluates the compliance of the estimated conditional probability of the "*Adequate escape behavior*" (table IV). One task in step II is the evaluation of the consequence, e.g. of "*Post-flashover*" (table V), which has one predecessor node (also determined by the auditor).

Table IV: Adequate escape behavior (Node without predecessor nodes)

Yes	0.65
No	0.35

Table V: Post-flashover (Node with 1 predecessor node)

Extinguishing attempt	Yes	No
Yes	0.3	0.9
No	0.7	0.1

If there are more predecessor nodes, the auditor has to evaluate them too.

Table VI: Fatality to personnel by a fire (Node with 4 predecessor nodes)

Foreign rescue	Yes								No	
Self-rescue	Yes				No				Yes	
Toxic effect	Yes		No		Yes		No		Yes	
Post-flashover	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Dead	0.1	0.65	0	0	0.6	0	0	0	0.1	0.65
Alive	0.9	0.35	1	1	0.4	1	1	1	0.9	0.35

Finally, step III gives an overview about the top event, the dependences of the linked nodes and the probabilities the scenarios:

Table VII: Evidence of the event

Evidence	Probability of fatality to personnel by a fire
None	11,45%
Mobility restricted	13,03%
Mobility not restricted	9,87%
Self-recue successful	8,97%
Self-recue unsuccessful	19,23%
Without a Post-Flashover	9,93%

With a Bayesian approach, the already available knowledge in the auditor's' check list can be used and enriched with additional information about the determined weighting factors, which actually represent the conditionally probabilities.

The results can be checked against generic data of operating EFP systems in order to improve the input data and weighting factors of the QRA model, if necessary.

Attachment: Example of an check list survey

The use of the semi-quantitative part of the approach requires a backbone of safety and hazard aspects and their evaluation. A check list example of questions and requests is given in table VIII and IX. These will be evaluated by the auditor based on the weighting factors (table 9).

Table VIII. Check list of hazard parameters.

1. Further factors
1.1 Substance temperature
1.2 Amount of dangerous substance / fire loading
1.3 Technological process
1.4 Room category
…
…
1.x Ambient temperature
2.Fire hazards
2.1 Ignition temperature
2.2 Dispersion of substance (Unintentional surface expansion by mechanical means)
2.3 Sedimented Dust
2.4 Potential of ignition source
2.5 Potential quantity of a smoke by fire
2.6 Potential amount of toxic substances by burning
2.7 Potential speed of distribution of a flame
2.8 Amount of combustible substances
2.9 Combustibility
2.10 Availability of an oxidizer
2.11 Interaction with other substances
2.12 Oxidising solids
…
…
2.y Spontaneously combustible solids
3. Explosion hazards
3.1 Instability/Reactivity
3.2 Classification of combustible substances
3.3 Flash point
3.4 Dispersed Dust
3.5 Capable of detonation or explosive decomposition at normal temperatures and pressures (e.g. according to NFPA 780)
3.6 Undergoes violent chemical change at elevated temperatures and pressures, reacts violently with water, or may form explosive mixtures with water (e.g. white phosphorus, potassium, sodium) (e.g. according to NFPA 780)
3.7 Upper explosive limit
3.8 Potential of ignition source

3.9 Potential amount of toxic substances by explosion
…
…
3.z Maximum explosion pressure

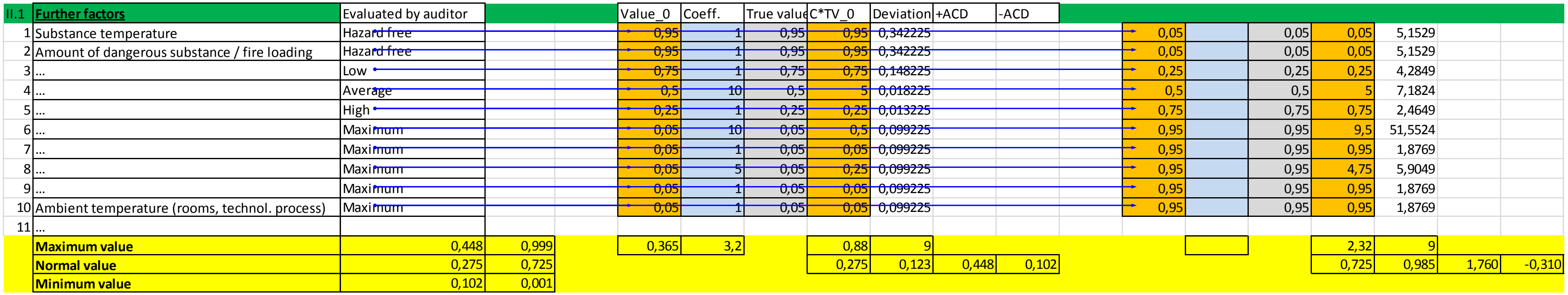
An example of indicative list for safety measures and parameters is given as an example in the table IX. These will be evaluated by the auditor based on the weighting factors (table 8).

Table IX. Check list of safety measures.

I. Architects measures
I.1 Evacuation routes
I.2 Amount of dangerous substance / fire loading
I.n …
II. Technical measures
II.1 Gas detection system
II.2 Lightning protection
II.3 Fire alarm system
II.4 Fire suppression system
II.5 Emergency control systems
II.6 Fire extinguisher, Fire hydrant etc.
II.7 Electrical installations and systems
II.8 Emergency light
II.9 Heat and Smoke Vents / Positive Pressure Ventilation
II.10 Emergency Power Supply
II.11 Special extinguishing systems and equipment
II.12 Air-technical systems
II.13 Automatic interruption of processes
II.14 Constructive explosion protection measures
II.m …
III. Organization measures
III.1 Safety officer
III.2 Emergency organisation
III.3 Instructors for the protection of health and safety
III.4 Evacuation plans
III.5 Safety briefings
III.6 Maintenance of safety-related equipment
III.7 Intervention group (fire fighters)
III.8 General requirements for fire protection
III.9 Fire protection self-monitoring
III.10 Safety signposting
III.11 Fire protection plans
III.12 Change of technologycal processes and documentation of these
III.13 Hazard prevention plan
III.14 Determination and announcement of evacuation assistants
III.15 Marking of explosive zones
III.16 Explosion-proof designed work equipment in explosive zones

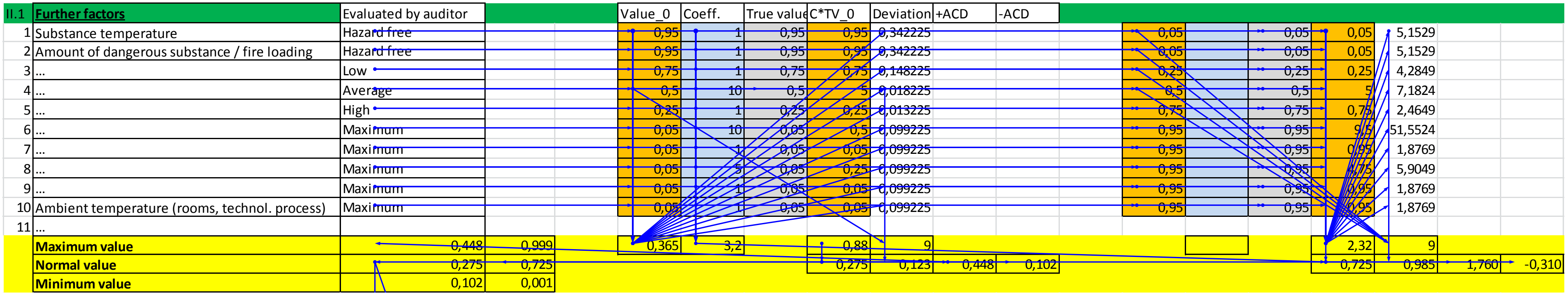
A check list serves as a means for the determination of the actual state of a situation as well as the systematic detection of vulnerabilities. Such check lists are a well-used method. However it is often the case that there is only sparse knowledge about the audited situation. A certain preknowledge of the auditor concerning the topic in question should not be renounced. Furthermore the temporal documentation is to be stressed positively as it can be consulted as a source of argumentation in assessing meetings. This might be the danger that the check list provides a false feeling of safety which could obscure possible deficiencies and problems. In such cases the check list cannot be extended and the necessity of the addition of important contents is neglected. The best-case scenario would be to describe the single contents in detail as well as the thematic design has to be mentioned (Peterjohann 2013) (e.g. a check list can be extended based on the hazard and operability study (HAZOP analysis) if carried out (Hucke 2016)). Therefore, a check list has to be set up for every enterprise and its individual needs. The problem of the universality is that a check list has to comprise all factors to be assessed.

Attachment: Correlations between the Excel cells for II step



II.1	**Further factors**	Evaluated by auditor			Value_0	Coeff.	True valu	C*TV_0	Deviation	+ACD	-ACD								
1	Substance temperature	Hazard free			0,95	1	0,95	0,95	0,342225				0,05		0,05	0,05	5,1529		
2	Amount of dangerous substance / fire loading	Hazard free			0,95	1	0,95	0,95	0,342225				0,05		0,05	0,05	5,1529		
3	...	Low			0,75	1	0,75	0,75	0,148225				0,25		0,25	0,25	4,2849		
4	...	Average			0,5	10	0,5	5	0,018225				0,5		0,5	5	7,1824		
5	...	High			0,25	1	0,25	0,25	0,013225				0,75		0,75	0,75	2,4649		
6	...	Maximum			0,05	10	0,05	0,5	0,099225				0,95		0,95	9,5	51,5524		
7	...	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
8	...	Maximum			0,05	5	0,05	0,25	0,099225				0,95		0,95	4,75	5,9049		
9	...	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
10	Ambient temperature (rooms, technol. process)	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
11	...																		
	Maximum value	0,448	0,999		0,365	3,2		0,88	9							2,32	9		
	Normal value	0,275	0,725					0,275	0,123	0,448	0,102					0,725	0,985	1,760	-0,310
	Minimum value	0,102	0,001																

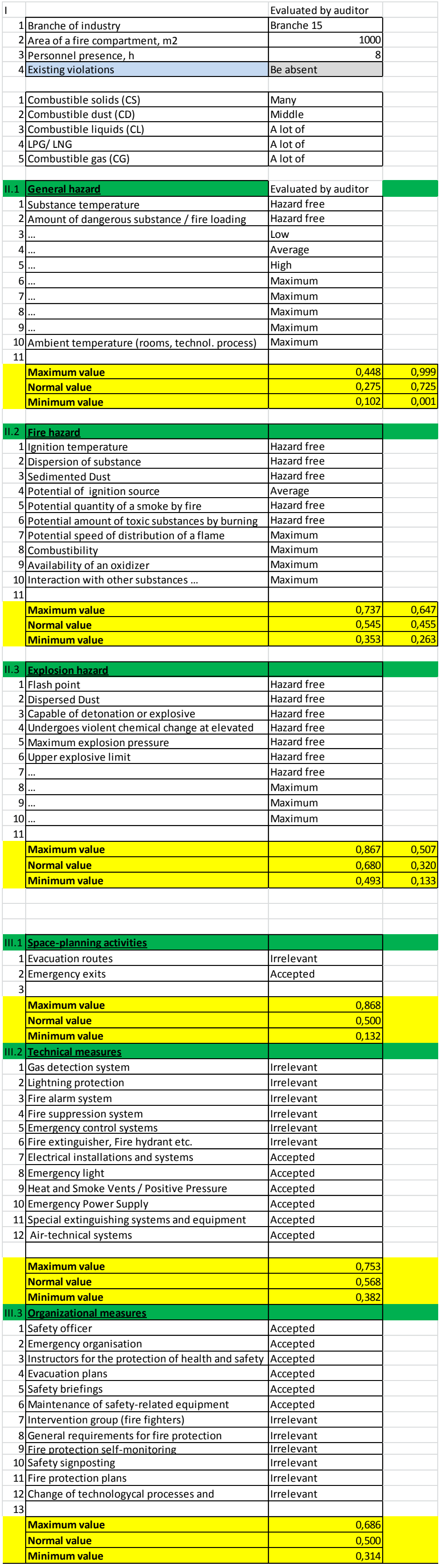
Attachment: Overview of the interconnections and function of the II step



II.1	**Further factors**	Evaluated by auditor			Value_0	Coeff.	True valu	C*TV_0	Deviation	+ACD	-ACD								
1	Substance temperature	Hazard free			0,95	1	0,95	0,95	0,342225				0,05		0,05	0,05	5,1529		
2	Amount of dangerous substance / fire loading	Hazard free			0,95	1	0,95	0,95	0,342225				0,05		0,05	0,05	5,1529		
3	...	Low			0,75	1	0,75	0,75	0,148225				0,25		0,25	0,25	4,2849		
4	...	Average			0,5	10	0,5	5	0,018225				0,5		0,5	5	7,1824		
5	...	High			0,25	1	0,25	0,25	0,013225				0,75		0,75	0,75	2,4649		
6	...	Maximum			0,05	10	0,05	0,5	0,099225				0,95		0,95	9,5	51,5524		
7	...	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
8	...	Maximum			0,05	5	0,05	0,25	0,099225				0,95		0,95	4,75	5,9049		
9	...	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
10	Ambient temperature (rooms, technol. process)	Maximum			0,05	1	0,05	0,05	0,099225				0,95		0,95	0,95	1,8769		
11	...																		
	Maximum value	0,448	0,999		0,365	3,2		0,88	9							2,32	9		
	Normal value	0,275	0,725					0,275	0,123	0,448	0,102					0,725	0,985	1,760	-0,310
	Minimum value	0,102	0,001																

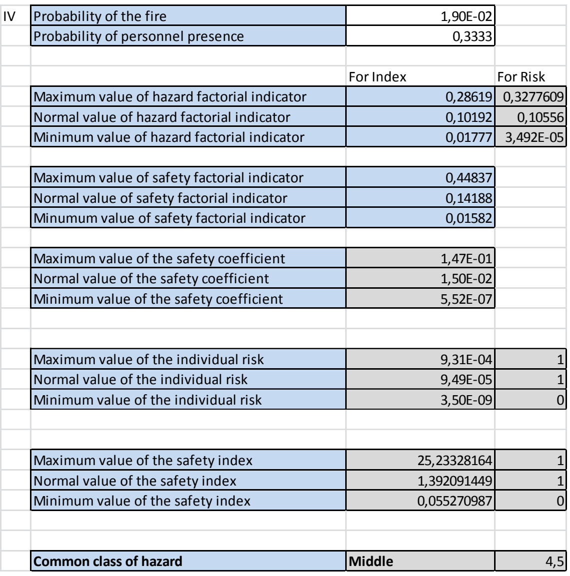
Attachment: MS Excel prototype tools

Table X. Extended semi-quantitative approach for individual risk assessment. Input data



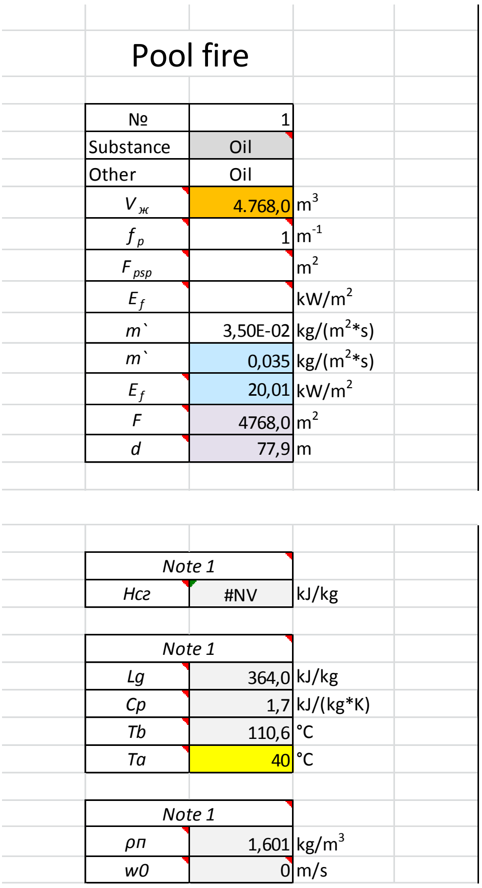
I		Evaluated by auditor	
1	Branche of industry	Branche 15	
2	Area of a fire compartment, m2	1000	
3	Personnel presence, h	8	
4	Existing violations	Be absent	
1	Combustible solids (CS)	Many	
2	Combustible dust (CD)	Middle	
3	Combustible liquids (CL)	A lot of	
4	LPG/ LNG	A lot of	
5	Combustible gas (CG)	A lot of	
II.1	**General hazard**	Evaluated by auditor	
1	Substance temperature	Hazard free	
2	Amount of dangerous substance / fire loading	Hazard free	
3	…	Low	
4	…	Average	
5	…	High	
6	…	Maximum	
7	…	Maximum	
8	…	Maximum	
9	…	Maximum	
10	Ambient temperature (rooms, technol. process)	Maximum	
11			
	Maximum value	0,448	0,999
	Normal value	0,275	0,725
	Minimum value	0,102	0,001
II.2	**Fire hazard**		
1	Ignition temperature	Hazard free	
2	Dispersion of substance	Hazard free	
3	Sedimented Dust	Hazard free	
4	Potential of ignition source	Average	
5	Potential quantity of a smoke by fire	Hazard free	
6	Potential amount of toxic substances by burning	Hazard free	
7	Potential speed of distribution of a flame	Maximum	
8	Combustibility	Maximum	
9	Availability of an oxidizer	Maximum	
10	Interaction with other substances …	Maximum	
11			
	Maximum value	0,737	0,647
	Normal value	0,545	0,455
	Minimum value	0,353	0,263
II.3	**Explosion hazard**		
1	Flash point	Hazard free	
2	Dispersed Dust	Hazard free	
3	Capable of detonation or explosive	Hazard free	
4	Undergoes violent chemical change at elevated	Hazard free	
5	Maximum explosion pressure	Hazard free	
6	Upper explosive limit	Hazard free	
7	…	Hazard free	
8	…	Maximum	
9	…	Maximum	
10	…	Maximum	
11			
	Maximum value	0,867	0,507
	Normal value	0,680	0,320
	Minimum value	0,493	0,133
III.1	**Space-planning activities**		
1	Evacuation routes	Irrelevant	
2	Emergency exits	Accepted	
3			
	Maximum value	0,868	
	Normal value	0,500	
	Minimum value	0,132	
III.2	**Technical measures**		
1	Gas detection system	Irrelevant	
2	Lightning protection	Irrelevant	
3	Fire alarm system	Irrelevant	
4	Fire suppression system	Irrelevant	
5	Emergency control systems	Irrelevant	
6	Fire extinguisher, Fire hydrant etc.	Irrelevant	
7	Electrical installations and systems	Accepted	
8	Emergency light	Accepted	
9	Heat and Smoke Vents / Positive Pressure	Accepted	
10	Emergency Power Supply	Accepted	
11	Special extinguishing systems and equipment	Accepted	
12	Air-technical systems	Accepted	
	Maximum value	0,753	
	Normal value	0,568	
	Minimum value	0,382	
III.3	**Organizational measures**		
1	Safety officer	Accepted	
2	Emergency organisation	Accepted	
3	Instructors for the protection of health and safety	Accepted	
4	Evacuation plans	Accepted	
5	Safety briefings	Accepted	
6	Maintenance of safety-related equipment	Accepted	
7	Intervention group (fire fighters)	Irrelevant	
8	General requirements for fire protection	Irrelevant	
9	Fire protection self-monitoring	Irrelevant	
10	Safety signposting	Irrelevant	
11	Fire protection plans	Irrelevant	
12	Change of technologycal processes and	Irrelevant	
13			
	Maximum value	0,686	
	Normal value	0,500	
	Minimum value	0,314	

Table XI. Extended semi-quantitative approach for individual risk assessment. Output data



IV	Probability of the fire	1,90E-02	
	Probability of personnel presence	0,3333	
		For Index	For Risk
	Maximum value of hazard factorial indicator	0,28619	0,3277609
	Normal value of hazard factorial indicator	0,10192	0,10556
	Minimum value of hazard factorial indicator	0,01777	3,492E-05
	Maximum value of safety factorial indicator	0,44837	
	Normal value of safety factorial indicator	0,14188	
	Minumum value of safety factorial indicator	0,01582	
	Maximum value of the safety coefficient	1,47E-01	
	Normal value of the safety coefficient	1,50E-02	
	Minimum value of the safety coefficient	5,52E-07	
	Maximum value of the individual risk	9,31E-04	1
	Normal value of the individual risk	9,49E-05	1
	Minimum value of the individual risk	3,50E-09	0
	Maximum value of the safety index	25,23328164	1
	Normal value of the safety index	1,392091449	1
	Minimum value of the safety index	0,055270987	0
	Common class of hazard	**Middle**	4,5

Table XII. Extended quantitative approach for consequence assessment. Input data.



Pool fire

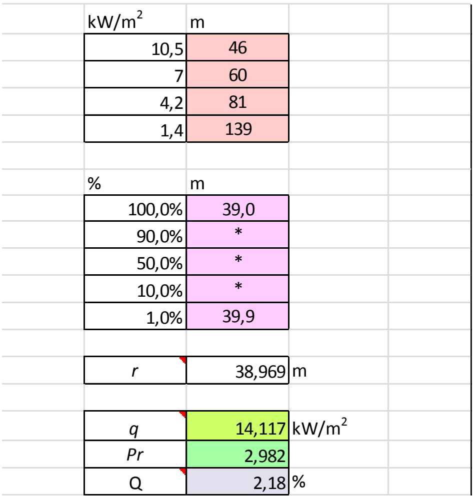
№	1	
Substance	Oil	
Other	Oil	
$V_ж$	4.768,0	m^3
f_p	1	m^{-1}
F_{psp}		m^2
E_f		kW/m^2
m`	3,50E-02	$kg/(m^2*s)$
m`	0,035	$kg/(m^2*s)$
E_f	20,01	kW/m^2
F	4768,0	m^2
d	77,9	m

Note 1		
Нсг	#NV	kJ/kg

Note 1		
Lg	364,0	kJ/kg
Cp	1,7	kJ/(kg*K)
Tb	110,6	°C
Ta	40	°C

Note 1		
ρп	1,601	kg/m^3
w0	0	m/s

Table XIII. Extended quantitative approach for consequence assessment. Output data.

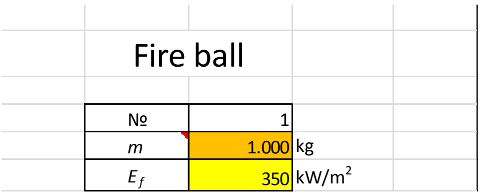


kW/m^2	m
10,5	46
7	60
4,2	81
1,4	139

%	m
100,0%	39,0
90,0%	*
50,0%	*
10,0%	*
1,0%	39,9

r	38,969	m
q	14,117	kW/m^2
Pr	2,982	
Q	2,18	%

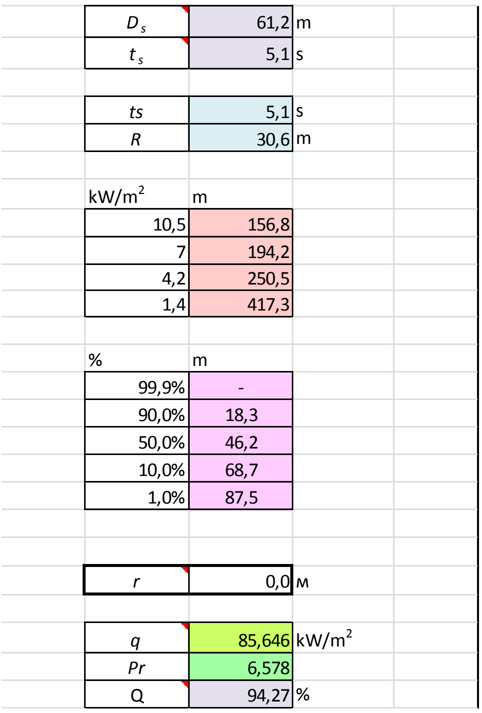
Table XIV. Extended quantitative approach for consequence assessment. Input data.



Fire ball

№	1	
m	1.000	kg
E_f	350	kW/m^2

Table XV. Extended quantitative approach for consequence assessment. Output data.



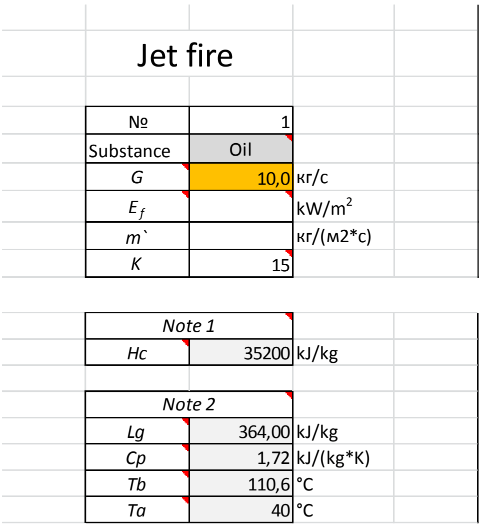
D_s	61,2	m
t_s	5,1	s
ts	5,1	s
R	30,6	m

kW/m^2	m
10,5	156,8
7	194,2
4,2	250,5
1,4	417,3

%	m
99,9%	-
90,0%	18,3
50,0%	46,2
10,0%	68,7
1,0%	87,5

r	0,0	м
q	85,646	kW/m^2
Pr	6,578	
Q	94,27	%

Table XVI. Extended quantitative approach for consequence assessment. Input data.



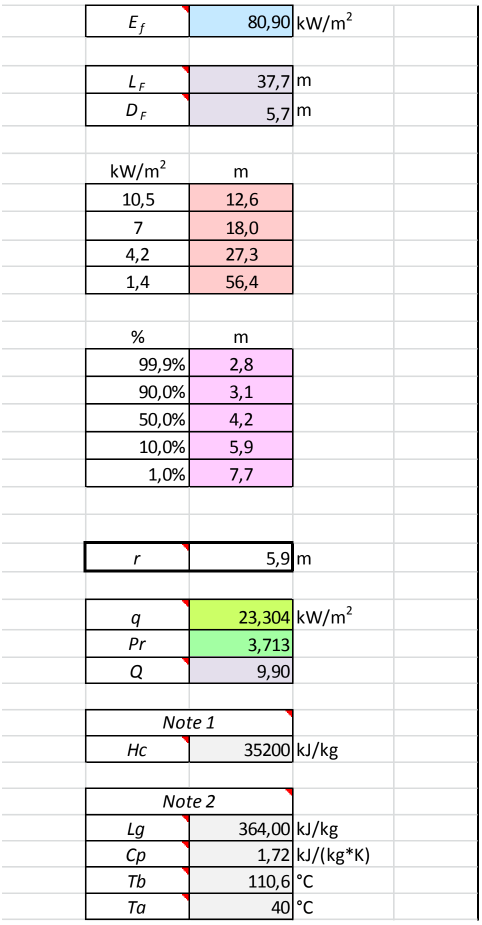
Jet fire

№	1	
Substance	Oil	
G	10,0	кг/с
E$_f$		kW/m^2
m`		кг/(м2*с)
K	15	

Note 1		
Hc	35200	kJ/kg

Note 2		
Lg	364,00	kJ/kg
Cp	1,72	kJ/(kg*K)
Tb	110,6	°C
Ta	40	°C

Table XVII. Extended quantitative approach for consequence assessment. Output data.



E$_f$	80,90	kW/m^2

L$_F$	37,7	m
D$_F$	5,7	m

kW/m^2	m
10,5	12,6
7	18,0
4,2	27,3
1,4	56,4

%	m
99,9%	2,8
90,0%	3,1
50,0%	4,2
10,0%	5,9
1,0%	7,7

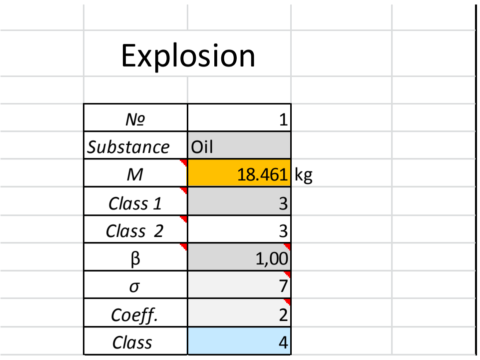
r	5,9	m

q	23,304	kW/m^2
Pr	3,713	
Q	9,90	

Note 1		
Hc	35200	kJ/kg

Note 2		
Lg	364,00	kJ/kg
Cp	1,72	kJ/(kg*K)
Tb	110,6	°C
Ta	40	°C

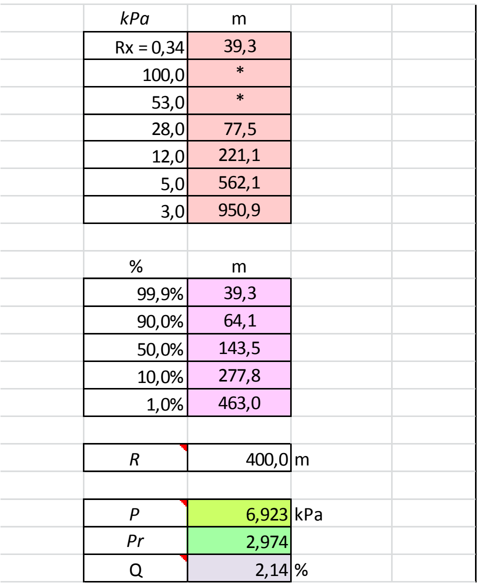
Table XVIII. Extended quantitative approach for consequence assessment. Input data.



Explosion

№	1	
Substance	Oil	
M	18.461	kg
Class 1	3	
Class 2	3	
β	1,00	
σ	7	
Coeff.	2	
Class	4	

Table XIX. Extended quantitative approach for consequence assessment. Output data.



kPa	m
Rx = 0,34	39,3
100,0	*
53,0	*
28,0	77,5
12,0	221,1
5,0	562,1
3,0	950,9

%	m
99,9%	39,3
90,0%	64,1
50,0%	143,5
10,0%	277,8
1,0%	463,0

R	400,0	m

P	6,923	kPa
Pr	2,974	
Q	2,14	%

Attachment: Symbols for extended semi-quantitative approach for individual risk assessment

R_{Ind}	individual risk [1/a]
F_F	frequency of a fire at the enterprise [m^2/a]
P_τ	probability of presence of the personnel [-]
C_S	safety coefficient [-]
τ	working time of a person [h]
F_S	factorial indicator of safety, which depends on the safety measures [-]
F_{Hrisk}	factorial indicator of hazard, which is dependent on the worst case path of an event tree (relative to indexing factor, which is dependent on the hazard measures) [-]
$\overline{M}_{arch}$	arithmetic mean of safety architectural measures [-]
$\overline{M}_{tech}$	arithmetic mean of safety technical measures [-]
$\overline{M}_{org}$	arithmetic mean of safety organizational measures [-]
$\overline{H}_{fut}$	arithmetic mean of further (general) hazards (e.g. amount of dangerous substance, room category, technological process etc.) [-]
$\overline{H}_f$	arithmetic mean of fire hazards [-]
$\overline{H}_{ex}$	arithmetic mean of explosion hazards [-]
F_{HInd}	factorial indicator of hazard, which is dependent on the best case path of ETA (relative to indexing factor, which is dependent on the hazard measures) [-]
V_E	existing violations [-]
R_{AC}	risk acceptance criteria [-]
AC	acceptance criteria for the safety index [-]
I_S	safety index [-]

Attachment: Symbols for pool fire models

E_f	actual surface emissive power (SEP) of the flame [kW/m^2]
F_q	view factor [-]
τ	atmospheric transmissivity [-]
d	pool fire diameter [m]
m'	burning flux at still weather conditions [kg/m^2·s]
H_{SG}	heat of combustion [kJ/kg] (in the Russian original $H_{СГ}$)
L	average height of the flame (flame length) [m]
L_g	vaporization heat of the flammable material at its boiling point [kJ/kg]
C_p	specific heat capacity at constant pressure [kJ/kg·K]
T_b	liquid boiling temperature [K]
T_a	ambient temperature [K]
F_V^2 , F_H^2	factors of irradiancy for vertical and horizontal platforms [-]
X	distance from the geometrical center source to the receiver [m]
θ	flame tilt angle [-]
ρ_a	density of air [kg/m^3]
$\rho_П$	vapour density of the flammable materials by boiling point [kg/m^3]
w_0	wind velocity [m/s]
g	gravitational acceleration [9.81 m/s^2]
Pr	probit function [-]
$Y(r)$	percentage of vulnerable resources which sustain injury or damage [-]
k_1, k_2	parameters to specify accidents [-]
V	thermal radiation [(kW/m^2)$^{4/3}$·s]
α_W, α_C	absorption factors [-]
q	heat radiation level in [W/m^2]
t	exposure duration in seconds [s]
$V_ж$	total mass released [m^3]
f_p	coefficient of the released mass [-]
F_{psp}	pool surface pool fire [m^2]
Q	probabilities of fatality to personnel [%]
t_0	time in which the person finds the fire and makes the decision about further actions (can be accepted as 5 seconds) [s]
χ	distance from the location of the person to a safety zone [m]

Attachment: Symbols for fire ball models

E_f	actual surface emissive power (SEP) of the flame [kW/m^2]
F_q	view factor [-]
τ	atmospheric transmissivity [-]
H	height from the center of the fire ball [m]
D_S	effective diameter of the fire ball [m]
r	distance measured over the ground of the projected centre of the fire ball on the ground under the fire ball, and the object [m]
m	total mass released [kg]
F_S	fraction of the generated heat which is radiated from the flame surface [-]
m'	burning rate [kg/m^2 s]
ΔH_C	heat of combustion [J/kg]
L	average height of the flame [m]
P_{SV}	saturated vapour pressure before the release [N/m^2]
c_6	0.00325 [(N/m^2)$^{-0.32}$]
r_{fb}	radius of the fire ball [m]
X	distance from the centre of the fire ball to the radiated object [m]
q	heat radiation level in [W/m^2]
Pr	probit function [-]
Q	probabilities of fatality to personnel [%]

Attachment: Symbols for jet fire models

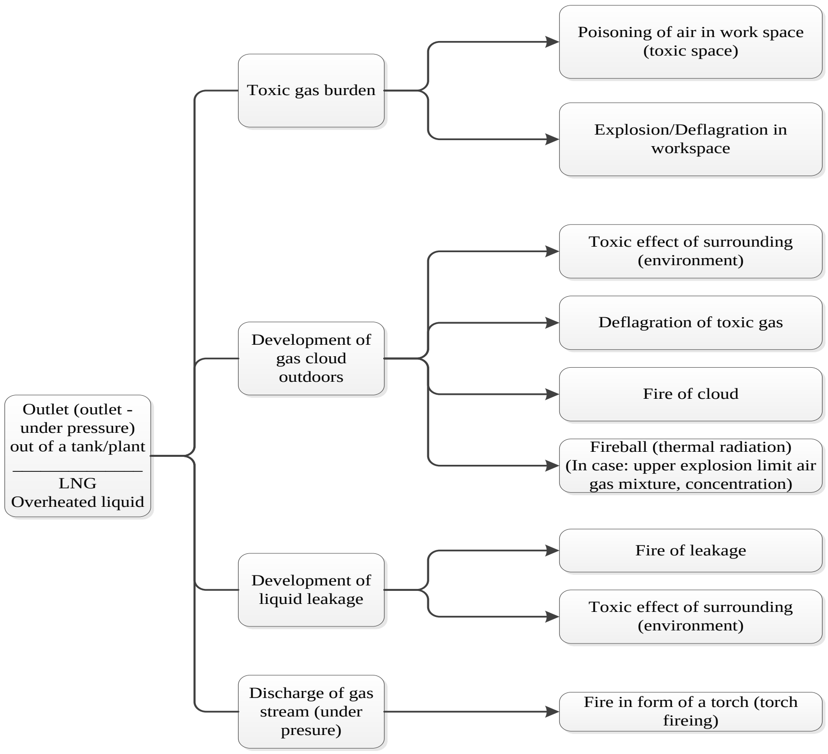
E_f	actual surface emissive power (SEP) of the flame [kW/m^2]
F_q	view factor [-]
τ	atmospheric transmissivity [-]
L_F	flame length (length of frustum) [m]
L_g	vaporization heat of the flammable material at its boiling point [kJ/kg]
G	mass flow rate [kg/s]
K	empirical coefficient [-]
D_F	width of a torch [m]
F_S	fraction of the combustion energy radiated from the flame surface [-]
Q'	combustion energy per second [J/s]
A	surface area of the flame [m^2]
u_j	jet velocity [m/s]
m'	mass flow rate [kg/s]
ΔH_c	heat of combustion [J/kg]
X'	distance from the centre of the bottom plane of a lifted-off flame to the object [m]
X	distance from the centre of the flame without lift-off to the object [m]
Θ'	angle between the centreline of a lifted-off flame and the plane between the centre of bottom of the lifted-off flame and the object [^{0}]
b	frustum lift-off height [m]
Θ_j	angle between hole axis and the horizontal in the vertical plane [^{0}]
α	angle between hole axis and the flame axis [^{0}]
W_1	width of frustum base [m]
W_2	width of frustum tip [m]
R	radius of the flame [m]
L_b	flame length, flame tip to centre of exit plane [m]
C_p	specific heat capacity at constant pressure [kJ/kg·K]
T_b	liquid boiling temperature [K]
T_a	ambient temperature [K]
m'	burning flux at still weather conditions [kg/m^2·s]
H_{SG}	heat of combustion [kJ/kg] (in the Russian original $H_{\text{СГ}}$)
ρ_a	density of air [kg/m^3]

ρ_{Π}	vapour density of the flammable materials by boiling point [kg/m^3]
w_0	wind velocity [m/s]
A_{hol}	area of the hole [m^2]
P_V	initial pressure in the pipeline [Pa]
γ	heat capacity ratio of the gas [-]
μ	flow coefficient 0.8 [-]
ρ_V	density of gas at the initial pressure in the pipeline [kg/m^3]
q	heat radiation level in [W/m^2]
Q	probabilities of fatality to personnel [%]
Pr	probit function [-]

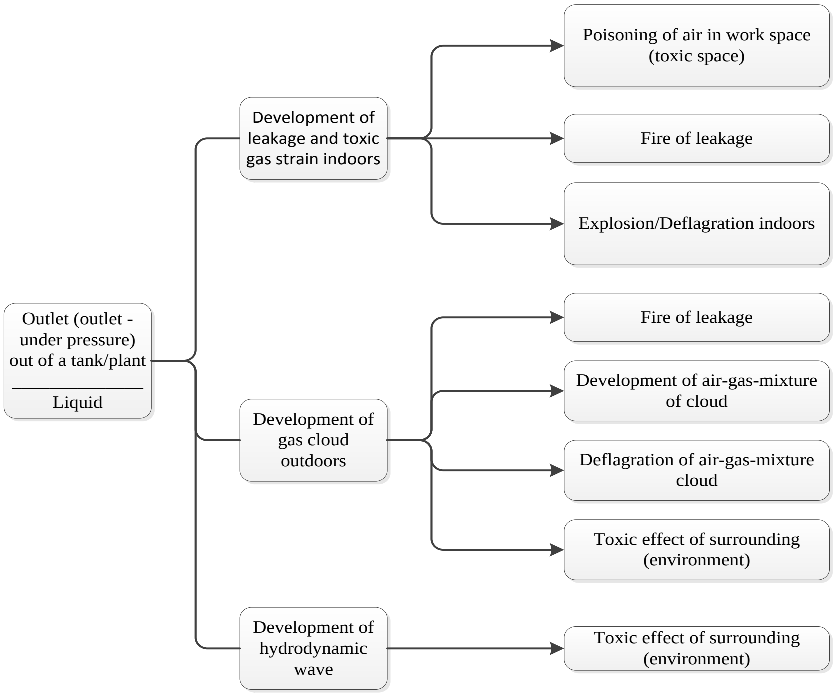
Attachment: Symbols for vapour cloud explosion models

k_1	constant = 43 [-]
k_2	constant = 26 [-]
M_T	mass quantity of flammable part of the cloud [kg]
u	visible speed of the flame front [m/s]
R	distance from the center of the cloud [m]
P_0	atmospheric pressure [Pa]
E	total combustion energy [J]
P_x	dimensionless pressure [-]
I_x	dimensionless impulse I_x
σ	extent of expansion of combustion products [-]
p_{dyn}	peak dynamic pressure in blast-wave [Pa], in Russian version ΔP)
p_{dyn}'	scaled dynamic pressure in blast-wave (in Russian version P_x) [-]
i_S	positive side-on impulse of blast-wave [-]
P_S	peak side-on overpressure of blast-wave [Pa]
t_p	positive phase duration of blast-wave [s]
t_p'	scaled positive phase duration of blast-wave [-]
p_a	ambient pressure [Pa]
a_a	speed of sound in ambient air [m/s]
P_S'	scaled peak side-on overpressure of blast-wave [-]
Q	probabilities of fatality to personnel [%]
Pr	probit function [-]
β	correction parameter [-]
σ	extent of expansion of combustion products [-]

Attachment: Event trees

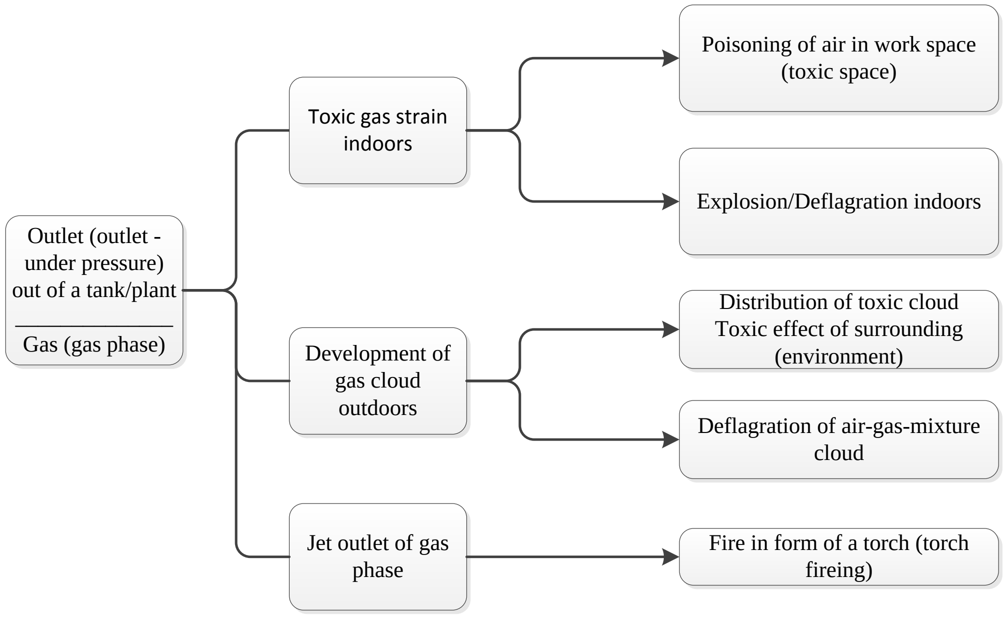


ETA – outlet of LNG or overheated liquids out of a tank/plant.

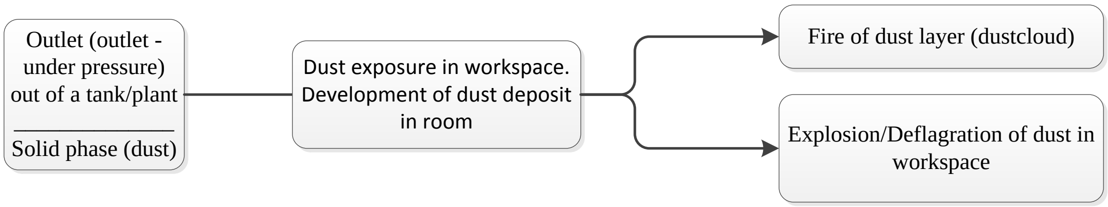


ETA – outlet of liquid out of a tank/plant.

Attachment: Event trees

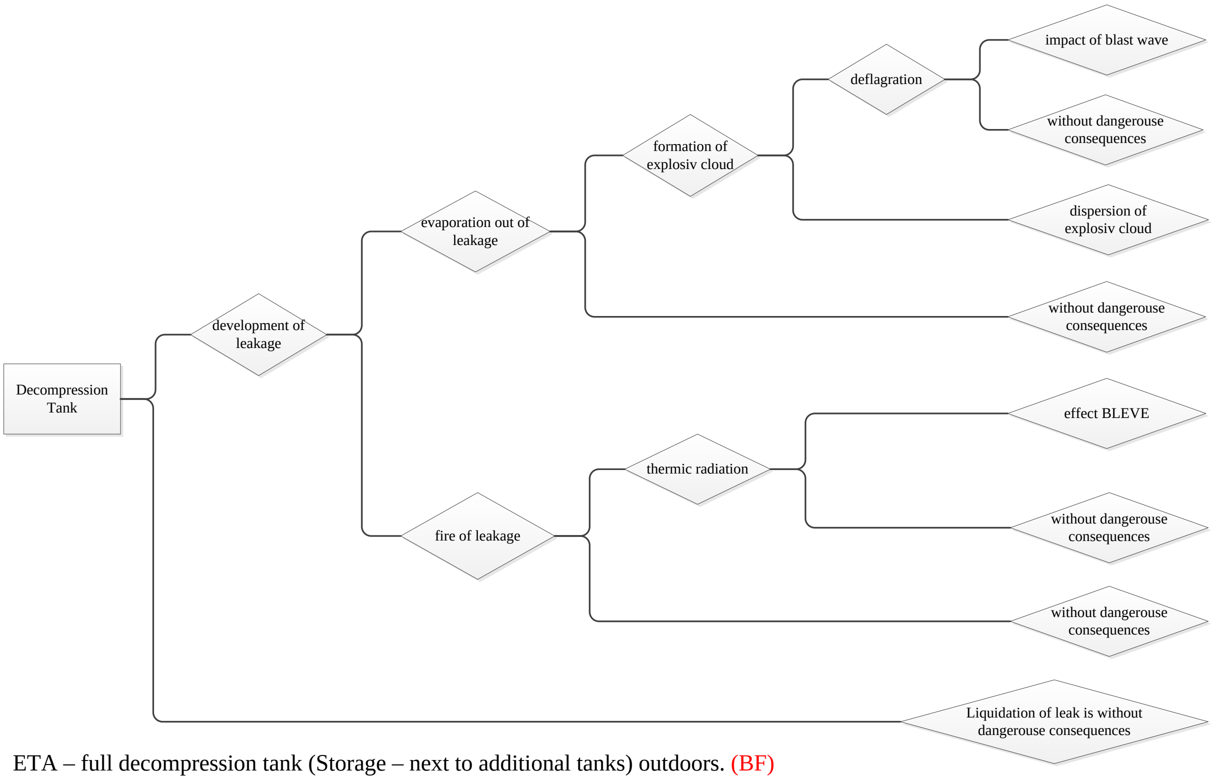


ETA – outlet of gas out of a tank/plant.

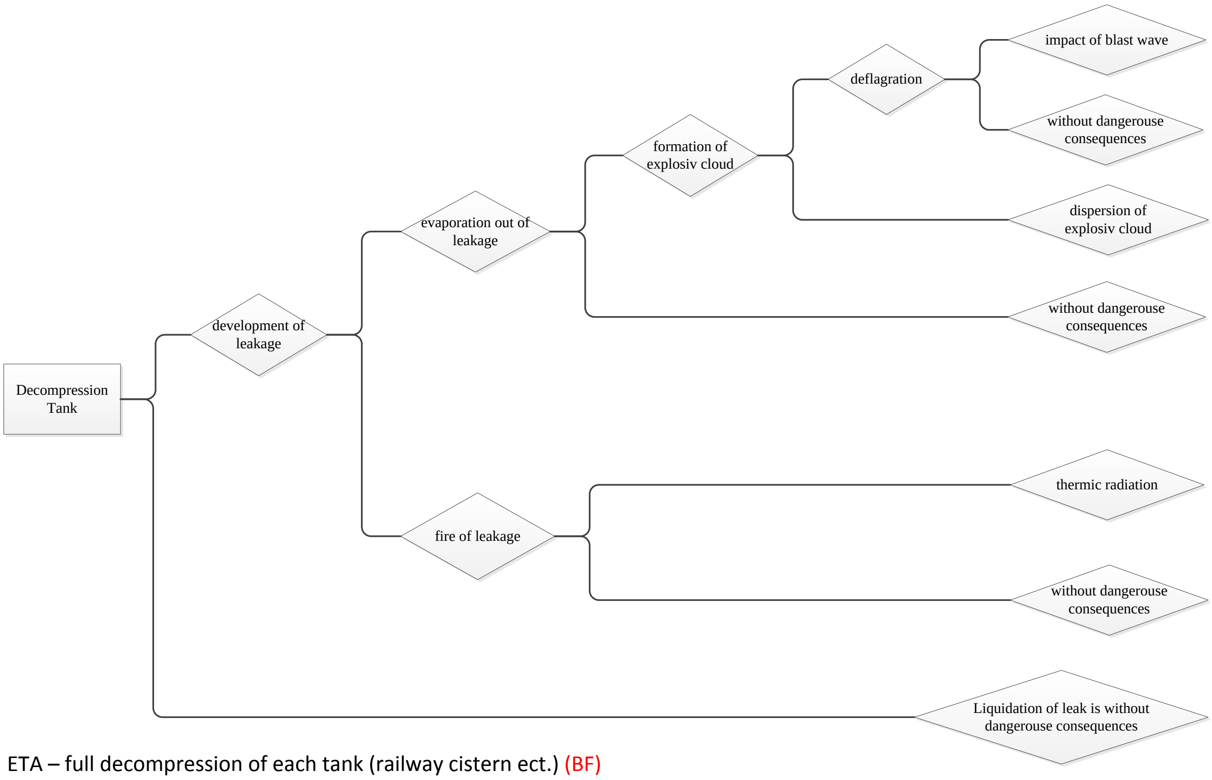


ETA – outlet of solid phase (dust) out of a tank/plant.

Attachment: Event trees

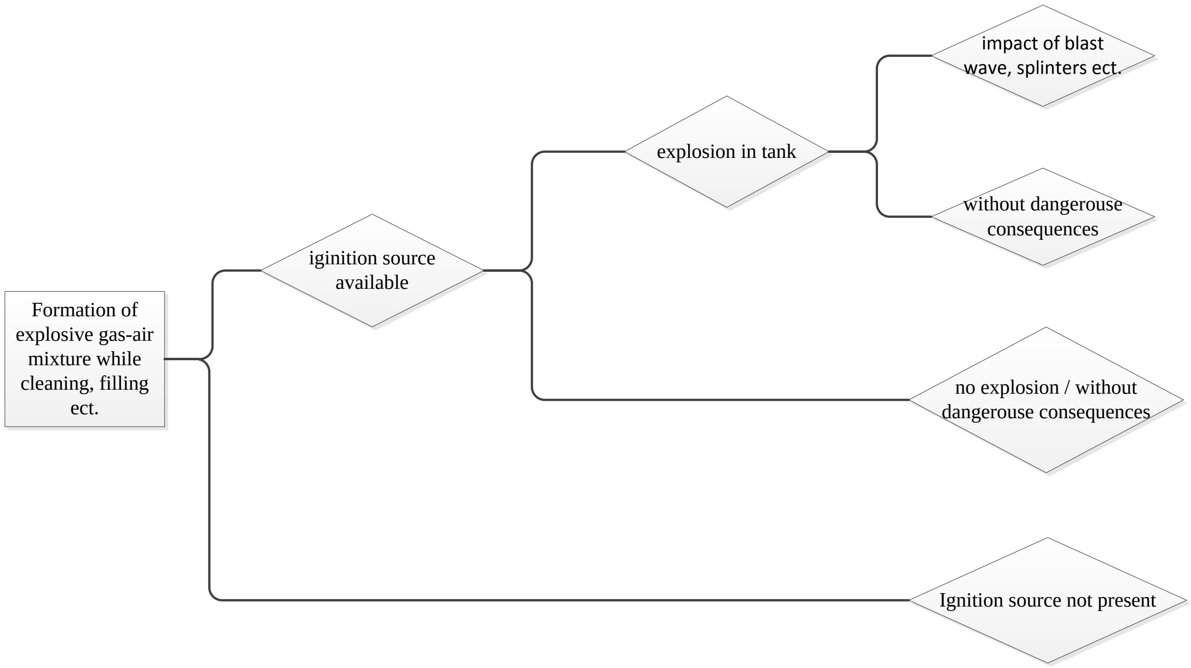


ETA – full decompression tank (Storage – next to additional tanks) outdoors. (BF)

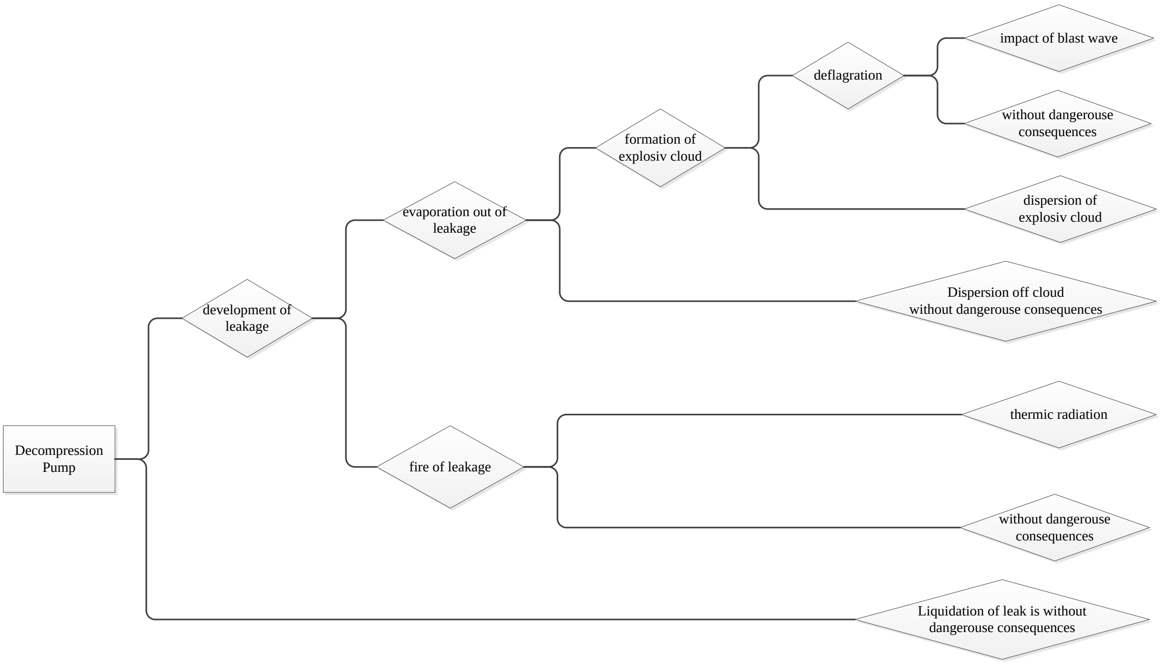


ETA – full decompression of each tank (railway cistern ect.) (BF)

Attachment: Event trees

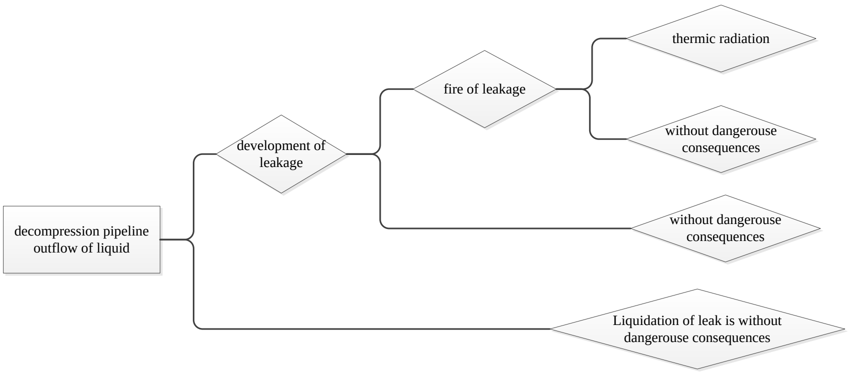


ETA – explosion in tank/plant. (BF)

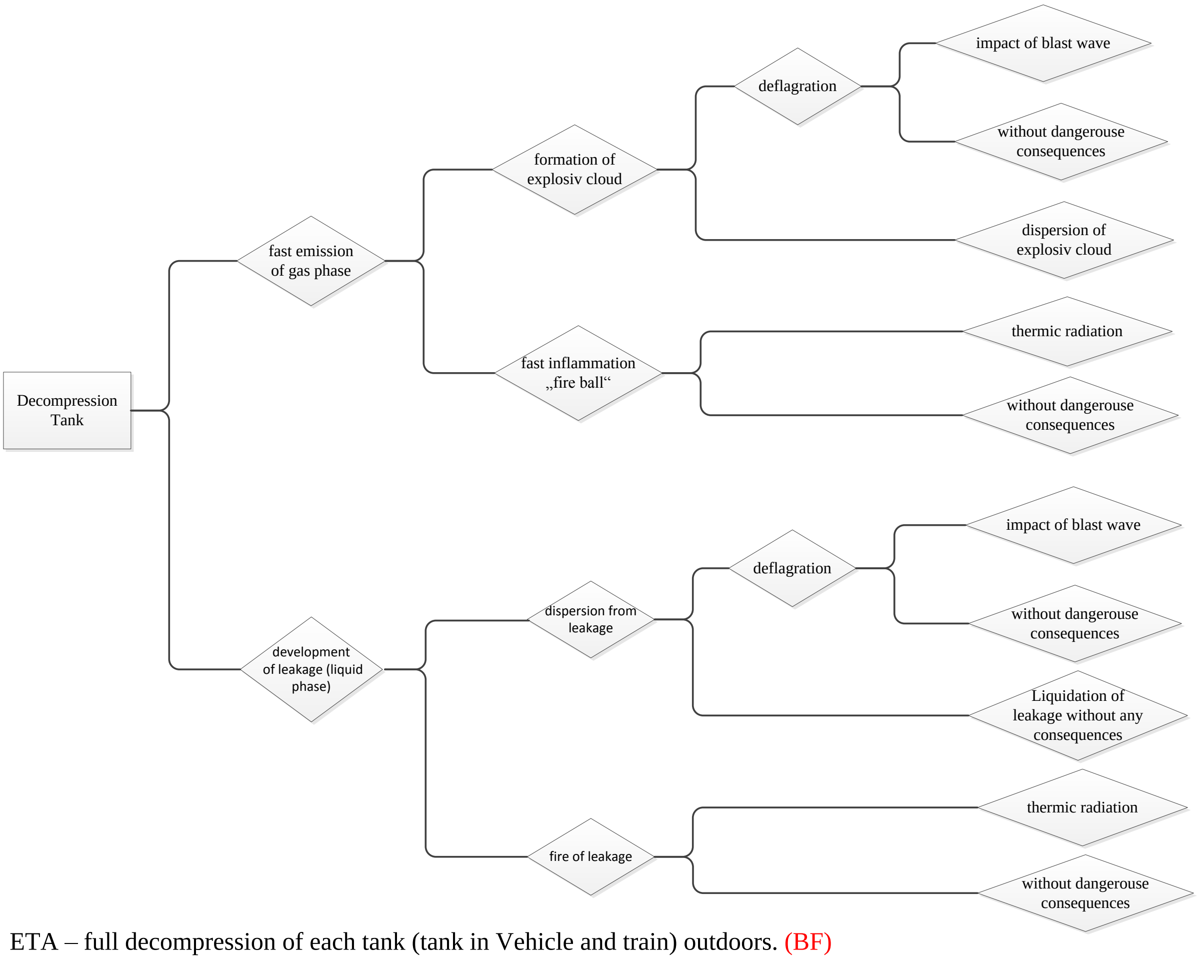


ETA – decompression of pump indoors/outdoorsank (the probability for indoors is less then i.e. during evaporation out of leakage

Attachment: Event trees

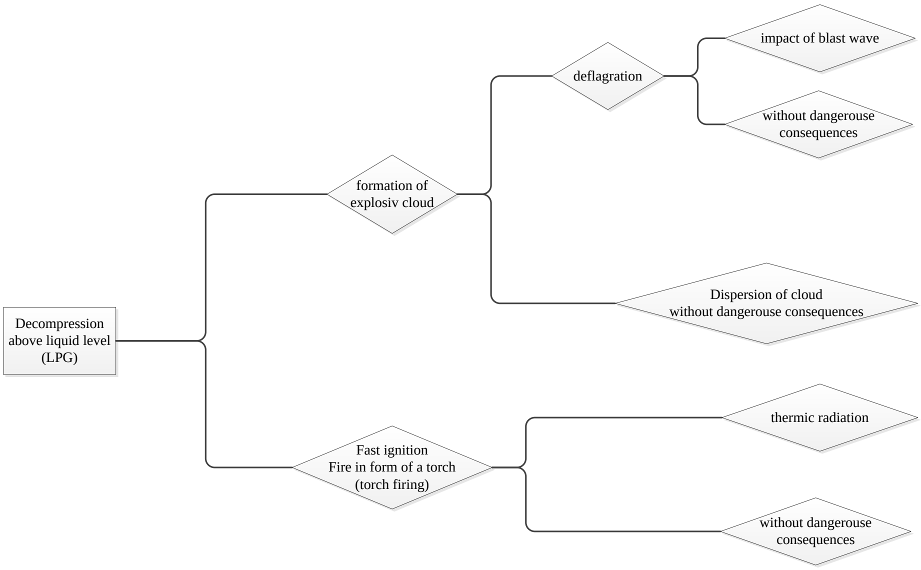


ETA – decompression of pipline indoors/outdoorsank (the probability for outdoor fire is less then an indoor fire

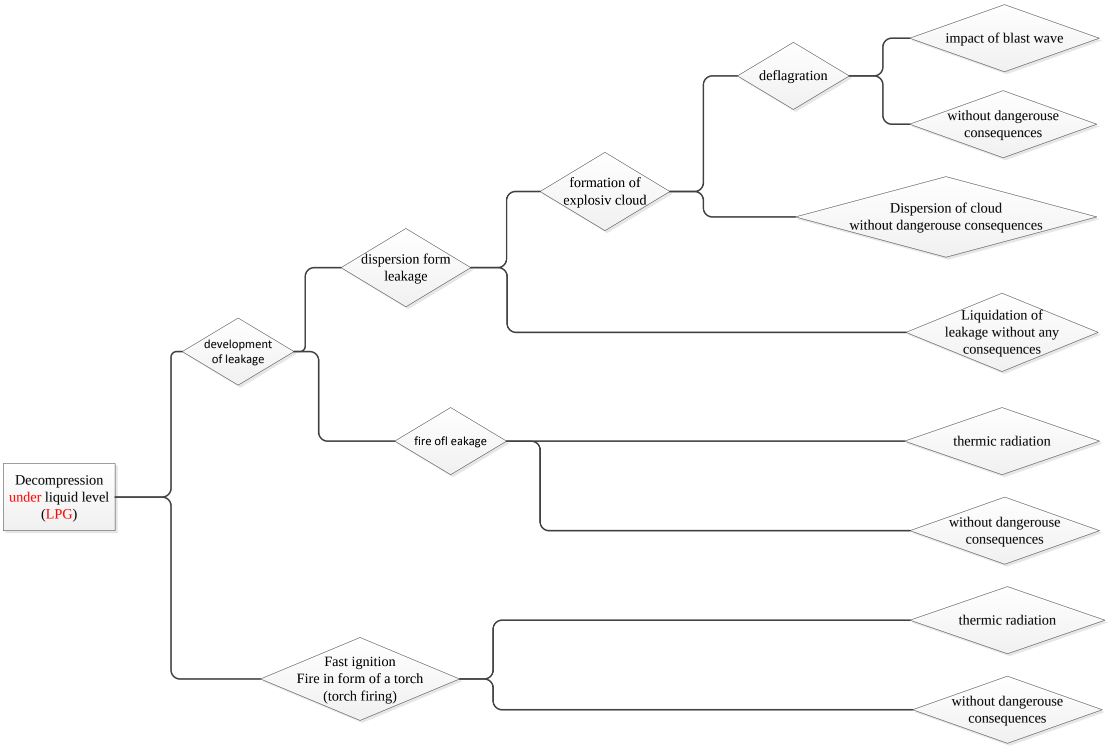


ETA – full decompression of each tank (tank in Vehicle and train) outdoors. (BF)

Attachment: Event trees

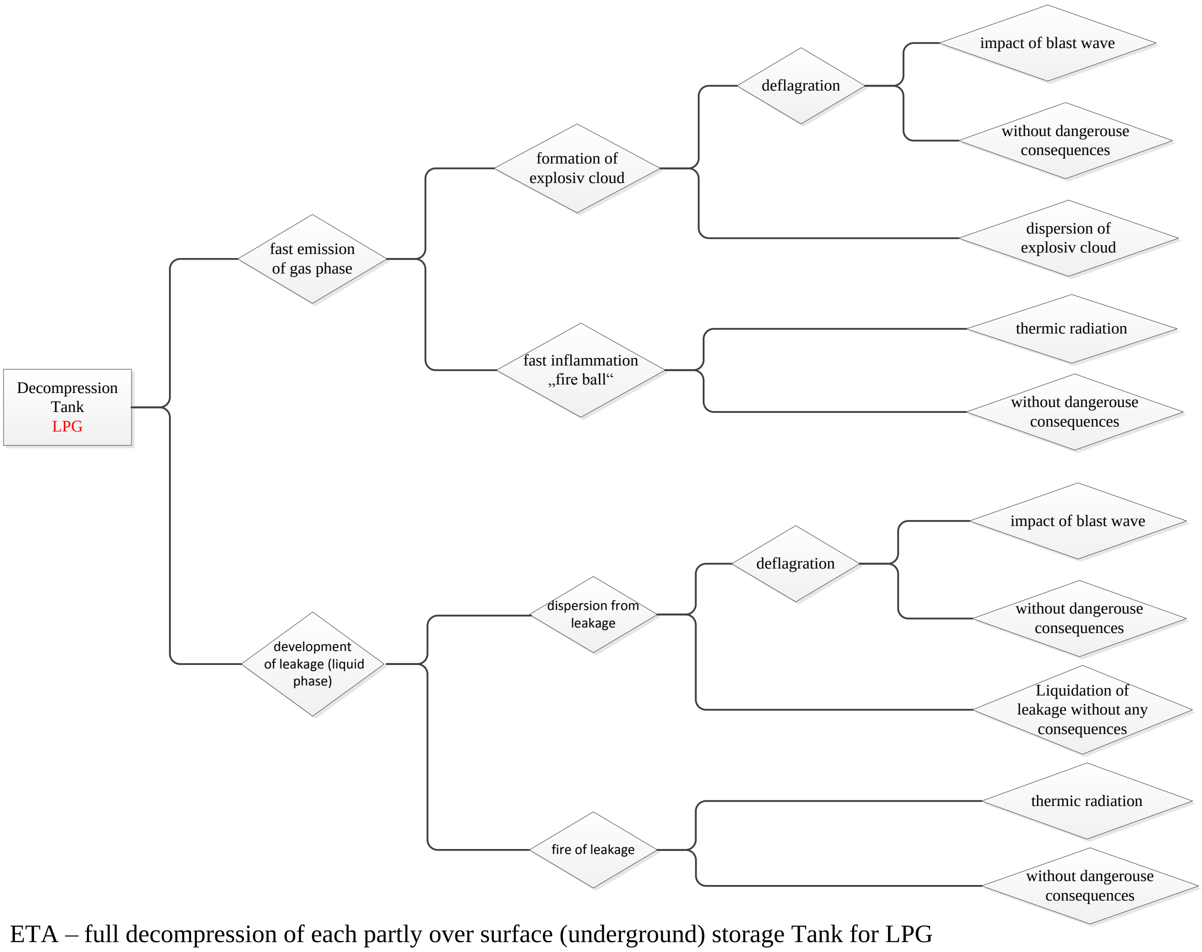


ETA – decompression part of stand alone tank above liquid level (tank of vehicel and train) outdoor (LPG)

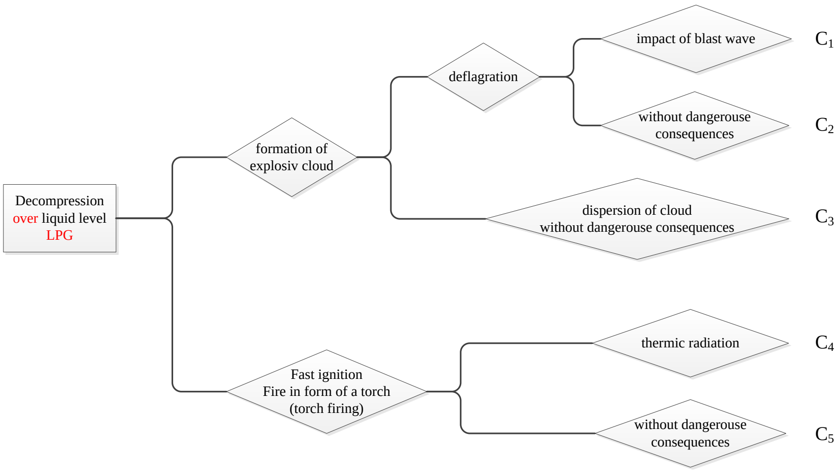


ETA – decompression part of stand alone tank under liquid level (tank of vehicel and train) outdoor (LPG)

Attachment: Event trees

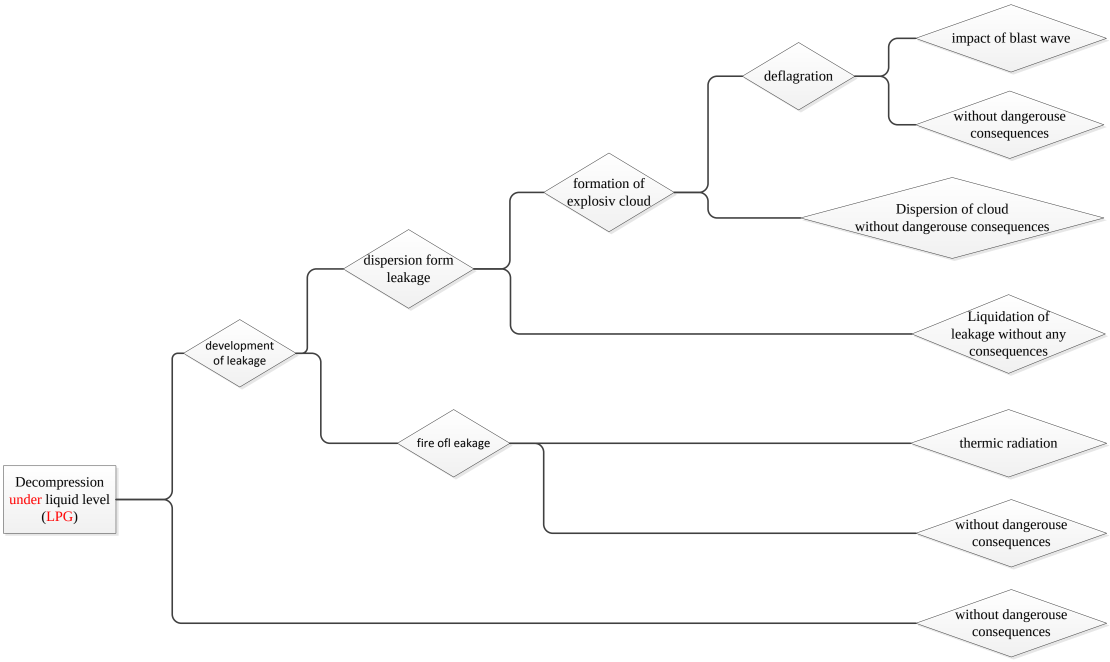


ETA – full decompression of each partly over surface (underground) storage Tank for LPG

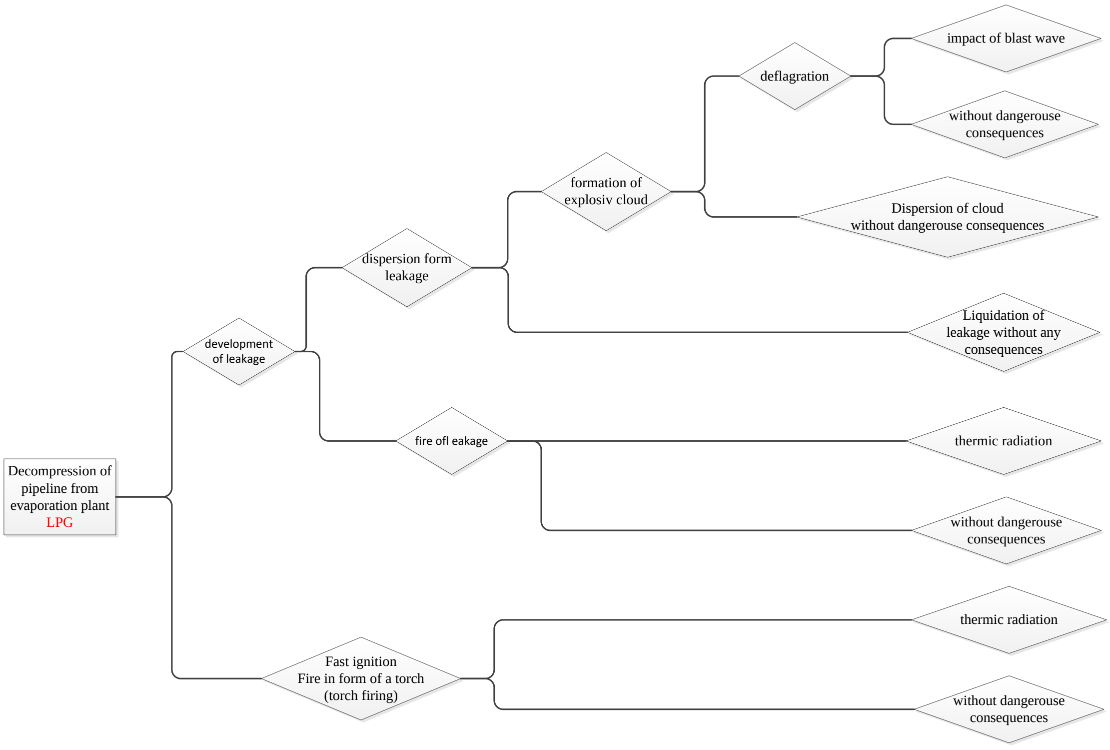


ETA – decompression part of partly over surface (underground) storage tank for LPG over surface level (LPG)

Attachment: Event trees

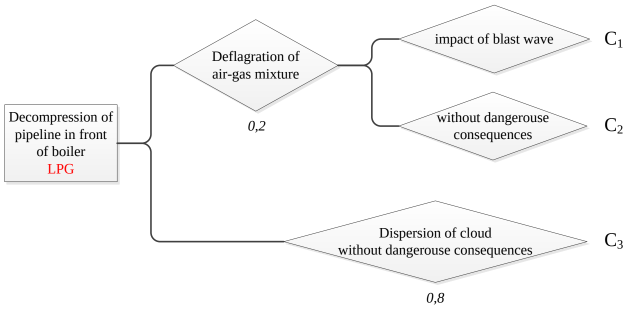


ETA – decompression part of partly over surface (underground) storage tank for LPG under surface level (LPG)



ETA – decompression of a pipeline in front of an evaporation plant (LPG)

Attachment: Event trees



ETA – decompression of a pipeline in a heating plant (in front of the boiler, steam boiler ect.) (LPG)

Curriculum Vitae

Personal Information	Name	Alexey Leksin
	Nationality	Russian
	Date of birth	30. January 1987
	Place of birth	Leningrad, USSR
Education	Since 10/2009	Ph.D. Student at the Chair Methods of Safety Engineering/Incident research Univ.-Prof. Dr.-Ing. Uli Barth University of Wuppertal
	09/2004-07/2009	Dipl.-Ing. Student at the Chair Energy Technology St. Petersburg State Technological Institute (TU) Diploma: Assessment of industrial safety of processes of acceptance, transportation and storage of gasoline on JSC „Henkel-ERA”.
	01/2009	Intermediate diploma at JSC ”Henkel-ERA” Tosno, Russia Developing explosion protection concept
	09/2008	Training Intership Primorsk, Russia Training to deal with explosive materials in order to receive an explosion certificate
	07/2008	Practical Training at JSC ”Henkel-ERA” Tosno, Russia Supporting engineer in industrial safety who are reviewing safety measures (explosion & fire protection)
	1997-2004	Primary School Nº 418, Kronstadt, Russia
	1994-1997	Elementary School, Ober-Olm, Germany
Career	Since 05/2010	Research Associate at the Chair Methods of Safety Engineering/Incident research Univ.-Prof. Dr.-Ing. Uli Barth University of Wuppertal
	11/2009-03/2010	Research Assistant at the Chair Methods of Safety Engineering/Incident research Univ.-Prof. Dr.-Ing. Uli Barth University of Wuppertal

	04/2011-12/2013	REMBE® GMBH SAFETY+CONTROL Brilon, Germany Explosion Safety and Business Development Russia
	05/2010-12/2010	DMT GmbH & Co. KG Dortmund, Germany Department of Fire and Explosion Protection
Committee Work	Since 06/2016	Guideline committee of VDI 2263 Part 1 “Dust fires and dust explosions; Hazards – Assessment – Protective Measures; Test Methods for the Determination of the Safety Characteristic of Dust”
	Since 01/2015	Guideline committee of VDI 2263 “Dust fires and dust explosions; Hazards – Assessment – Protective Measures”