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Safety risk management in University laboratories

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A – Acceptability
AHP – Analytical Hierarchy Process
AIAG – Automotive Industry Action Group
ALARA – As Low as Reasonably Acceptable
ALARP – As Low as Reasonably Practicable
BSL – Biosafety levels
CE – Compatibility with the environment
CFA – Confirmatory Factor Analysis
CI – Consistency Index
CLD – Causal Loop Diagram
CLP – Classification, Labelling, and Packing
CMR – Carcinogenic, Mutagenic or Toxic for Reproduction
CP – Process compatibility
CSE – Cognitive System Engineering
EFA – Exploratory Factor Analysis
ELECTRE – ELimination Et Choix TRaduisant la REalité (Elimination and Choice Translating Reality)
ETA – Event Tree Analysis
FAHP – Fuzzy Analytical Hierarchy Process
FCF – Failure Contributing Factor
FMEA – Failure Modes and Effects Analysis
FMECA – Failure Modes, Effects, and Criticality Analysis
FP – Failure Probability
FTA – Fault Tree Analysis
FTOPSIS – Fuzzy Technique for Order of Preferences by Similarity to Ideal Solution
GFI – Goodness of Fit Index
GHS – Globally Harmonized System, Labeling and Packaging of Chemicals
GRF – General Reliability Factor
GRR – General Risk Reduction
HAZOP – Hazard and Operability Analysis
HEP – Human Error Probability
HCR – Human Cognitive Reliability
HR – Human Reliability
ICI – Imperial Chemical Industry
KA – Knowledge-based Activity
Lab-HIRA – Laboratory Hazard Identification and Risk Analysis
LARA – Laboratory Assessment and Risk Analysis
LARA+D – Laboratory Assessment and Risk Analysis + Decision-Making
LTM – Long-term Memory
MCDM – Multicriteria Decision-Making
MMS – Man-Machine System
NFI – Normal Fit Index
OHS – Occupational Health Services
PDCA – Plan-Do-Check-Act
RA – Rule-based Activity

RI – Random Index
RiCS – Risk Criticality Score
RPN – Risk Priority Number
S – Simplicity
SA – Skilled-based Activity
SAE – Society of Automotive Engineers
SC – Safety Climate
SEM – Structural Equation Modeling
SHF – Sensitivity to Human Factors
STOT SE – Specific Target Organ Toxicity (Single Exposure)
TEAM – The Egg Aggregated Model
TOPSIS – Technique for Order of Preferences by Similarity to Ideal Solution
TR – Technical Reliability
WE – Working Environment

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Abstract

Risk management has become an essential element in the functioning of modern society. Correct risk identification and assessment are undoubtedly crucial to improving overall safety; nevertheless, often, it is accompanied by the wrong selection of corrective actions. To ensure that safety intentions reach their final objective – making the working environment safe for people both inside and outside, nature and organization, the whole process of safety management must be set correctly. It includes three main stages: risk analysis, decision-making, and follow-up. While the two first steps are closely connected in the time frame, the last step can be significantly extended and represented by a continuous process. University laboratories are often mistakenly considered a safe place; however, frequent accidents demonstrate otherwise. There are plenty of different efficient risk management methods. However, they are not applicable in the academic environment or require significant modifications. Different limitations: not standardized and modified processes, diversified laboratory hazard pool, limited budget planning, organizational decentralization, other specific characteristics of the university setting require a different approach.

This dissertation aims to investigate existing approaches further and propose a solution suitable for the mentioned environment. It involves reviewing further risk analysis and decision-making methods and setting a list of objectives for the required safety management method ideal for academic laboratories. These objectives are met by designing LARA+D (Laboratory Assessment and Risk Analysis + Decision-Making), a method that enhances previously applied in Swiss Universities LARA tool.

The application of the LARA+D for process risk analysis and decision-making illustrates that it is a helpful tool for process risk assessment and decision-making. It is sufficiently flexible for a diverse multi-hazardous environment of the research laboratories and precise to the extent possible in the environment with no historical data. Integrated decision-making tool assists involved stakeholders with selecting optimal safety solutions, considering various objectives. This tool considers different types of human involvement in the risk analysis and decision-making stages, diminishing the harmful effects and designing a proper safety environment.

Keywords: Hazard, risk, occupational safety, risk analysis, risk assessment, risk management, academia, risk mitigation, decision-making.

Résumé

La gestion du risque est aujourd'hui un élément essentiel au bon fonctionnement de la société moderne. Une identification et une évaluation correcte du risque est sans aucun doute crucial pour améliorer la sécurité. Néanmoins, cela est souvent accompagné par une mauvaise sélection de mesures correctives. Afin de s'assurer que l'intention initiale atteigne l'objectif final, à savoir rendre l'environnement de travail sécurisé pour les intervenants externes et internes, le processus de gestion des risques doit être adéquat. Cela inclut 3 étapes cruciales : L'analyse du risque, la prise de décision et le suivi des mesures. Bien que les 2 premières étapes sont temporellement proches, la dernière peux être significativement éloignée et donc représentée par un processus continu. Les laboratoires dans les universités sont souvent considérés à tort comme des environnements de travails sécurisés. Cette hypothèse est malheureusement réfutée par les accidents graves s'y passant chaque année. Il y a de nombreuses méthodes efficaces pour gérer les risques. Néanmoins, elles ne sont pas toutes applicables aux environnements académiques spécifiques ou alors elles nécessitent de gros ajustements. Parmi les limitations peuvent être cités : Des processus non standardisés, des risques diversifiés dans les laboratoires, des ressources non clairement définies ou encore une organisation décentralisée. Cela implique la nécessité d'une approche différente.

Cette thèse a pour but d'investiguer en détail les approches de gestion du risque existantes et de proposer des solutions adaptées aux environnements particuliers décrits ci-dessus. Cela implique la revue approfondie des outils d'analyse de risque et la mise en œuvre d'une liste précise d'objectifs pour que la méthode sélectionnée soit adaptée à l'environnement académique. Ces objectifs sont atteints par la création de LARA+D (Laboratory Assessment and Risk Analysis + Decison-Making), une méthode qui améliore la méthode actuellement utilisée dans les universités Suisses ; LARA.

L'application concrète du processus par LARA+D démontre son utilité dans l'analyse et sa capacité à évaluer les risques et la pise de décision subséquente. LARA+D est suffisamment flexible pour considérer un environnement multi-dangers tel que les laboratoires de recherche et suffisamment précis considérant le manque de données historiques. L'outil décisionnel assiste les différentes parties prenantes au processus en sélectionnant les solutions optimales d'amélioration de la sécurité tout en considérant les objectifs variés. Cette outil prend en compte les différents types d'implications humaines dans le processus d'analyse des risques et de prise de décision afin de diminuer les effets néfastes de certaines de ces dernières. LARA+D permet, en finalité, de créer un environnement de travail sécurisé pour tous.

Mots clefs: Danger, risque, sécurité, analyse de risque, prioritisation des risques, gestion des risque, academia, analyse de risque, la prise de décision.

Chapter 1. Introduction

This chapter aims to illustrate the importance of process risk analysis and decision-making in research laboratories. It covers the problem statement, research purpose, and contribution of the current research.

1.1 Background

The flowchart in the Figure 1 is aimed to visualize the logic of the chapter for the reader.

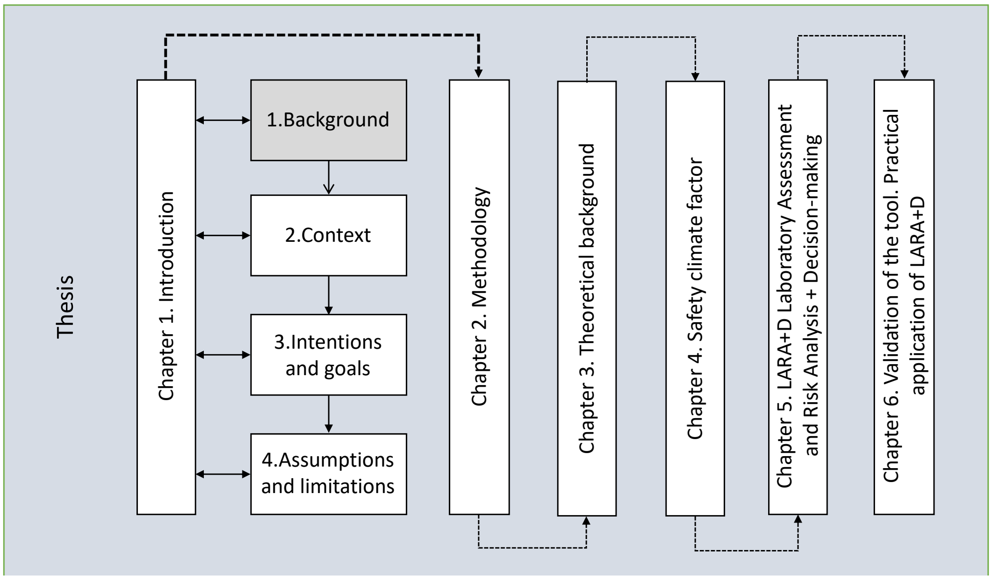


Figure 1. Structure of the thesis. Background.

Risk analysis and decision-making are closely connected subjects and rarely practically treated separately. The main goal of any risk analysis is a decision. It can be a decision to take or not any actions, and if yes, then which objectives to consider first and how to select the correct action or measure (Roy, 1981). There is no clear distinction and separation between these two processes, as the decision-making process starts when we select those risks that we consider essential to assess and act upon.

Risk analysis has a long historical trace. One of the first historical proofs of such can be Asipu groups living in 3200 B.C., whose primary function was to consult on risky and uncertain decisions (Covello and Mumpower, 1985). Later, a tradition continued in the middle centuries, and Arnoubius created the first historically known decision-making matrix. This 2*2 matrix proposes alternative solutions: "accept Christianity" and "remain a pagan," considering possible scenarios "God exists" and "God does not exist". Not long after, probabilistic theories for risk analysis emerged from the church debates over interest rates. However, not only did probabilistic theories emerge, but tracing back to the Romans, the causation approach for identifying links between health effects and hazardous activities reappeared in the 16th-18th centuries (Bernstein, 2013). With the acceleration of life due to industrialization, the invention of the internet, and social media, more complex approaches to risk assessment with new risks emerged. Risk analysis has become an essential element in all fields of our life (Aven, 2017). With an upcoming fourth industrial revolution, new risks connected with cybersecurity emerge that require new risk assessment and decision-making methods (Waslo *et al.*, 2017).

Any decision-making process can meet various obstacles, such as different types of uncertainties, contradicting objectives among decision-makers, human biases, etc., and would be challenged to make good decisions. Meanwhile, inadequate risk analysis methods create insufficient information for decision-making and impact the quality of safety decisions and an organization's general well-being. Management often has financial and time constraints and tries to manage operational risk to As Low as Reasonably Practicable (ALARP) or Acceptable (ALARA). To reach this objective, a reliable risk analysis method should be applied to generate reliable, accurate, relevant, and exhaustive (as possible) data for further decision-making. Meanwhile, a reliable and verifiable decision-making process shall be established in order to guarantee not biased (to the possible extent) evaluation. It needs to be accurate and consider existing uncertainties, which will be known to the decision-maker. Different methods lay the basis for the construction of reliable decision-making tools. They can be divided into three categories: quantitative, semi-quantitative, and qualitative. Depending on the environment, available information and decision tool types will vary.

1.2. Context

The flowchart in the Figure 2 demonstrates the place of the current chapter in the thesis.

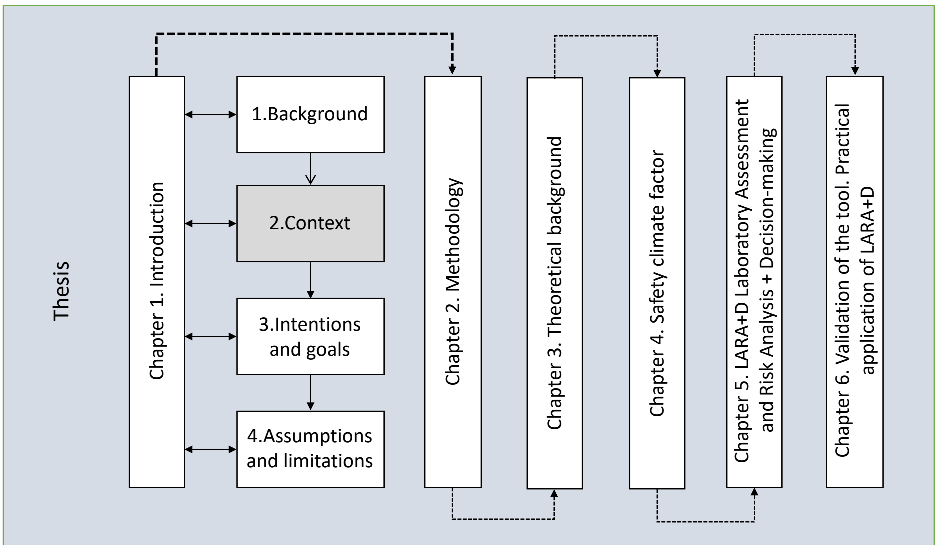


Figure 2. Structure of the thesis. Context of the project.

Safety is a crucial factor for all industries and the duty of all organizations to ensure the well-being of all employees and employers, protect population and nature. Comparing industrial and academic sectors, it is evident that there is a massive disparity between safety culture and practices in these two fields and that academia is where more efforts need to be spent. Safety in academia was first discussed in 1991 (Commision Health and Safety, 1991), but little effort has been spent in this area. Academia is often perceived as a safe environment. However, accidents in the last five years demonstrate that they occur and that they are not related to the country of origin or level and strictness of regulations. Accidents are a common trend worldwide, as expressed in Figure 3 (bigger version ca be found in Attachment A1.).

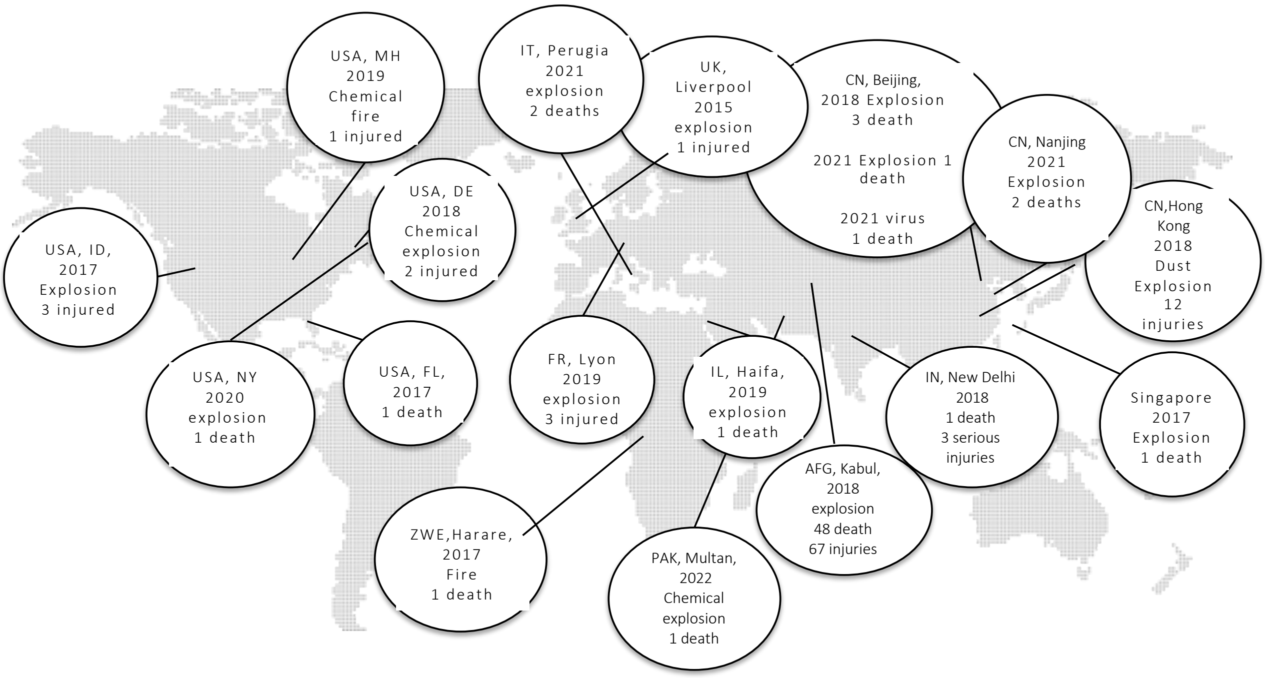


Figure 3. Universities accidents map for the period from 2015 to 2022

Even though accidents are not a direct indicator of safety level, it is a factor that requires some attention. As stated by Bahnolzer et al. (Banholzer, Calabrese and Confalone, 2013), Occupational Safety & Health Organization statistics highlighted that researchers are 11 times more likely to get hurt in an academic than in an industrial lab.

Academic research is an engine of economic growth and is a focal point of policy and geopolitical interests. Highly ranked institutions drive successful economies. On the other hand, the university management is strongly determined by research objectives, including alumni and staff winning awards, frequent citations, and publication in highly ranked scientific journals. University's financial aspect depends on the national R&D priorities and hired professors. Professors are given a lot of working and research freedom as the primary asset. As one of the organization's main pillars, they shape this environment's working and studying culture. Their intermediate role between university administration and research staff/students is crucial in transferring information between these levels. However, individuals' judgments can be very biased when their objectives are different from others. It can result in disinformation and misjudgment and lead to severe consequences.

Meanwhile, either in the monetary unit or in time, safety investments are often considered a burden on necessary compliance rather than beneficial investment. Particular attitude toward accidents in academia worsens safety situation. Even top-ranking universities cannot be considered safe.

Occupational health laws are mainly focused on employees and not on students, making safety a top priority for industrial laboratories where personnel bear personal responsibility for accidents, which are also traceable. The situation in the academic environment is different and varies from country to country. While university management and professors have to deal with various risks present daily in their working routine, safety is often not the first on the list of priorities.

Traditional techniques used for the process risk assessment and safety decision-making in the industry require clearly defined processes and resources. The academic setting rarely has such, and it differs significantly from the industrial. One of the aspects that differ two sectors is the management style. Most industries operate in traditional hierarchal or flatter management models, with a rare exclusion (Mazal, 2014). In contrast, European universities are flatarchies or "leaderless" (MacBeath, 2012). Flatarchies are challenging for superior management to impose and control how it is done in hierarchal structures. The second reason is significantly higher personal turnover, which cannot be compared with industry (Towns, 2019). Statistical information about causes of incidents and accidents is absent since often they are either not reported or not appropriately investigated. While the industry uses approved equipment and processes, due to various existing standards and pressure applied by audit companies, the primary goal of academia is scientific progress, and a significant percentage of equipment is custom-made to suit the purposes of the process. The state of this equipment can have some safety issues, as the responsibilities for maintenance and checking the equipment state can be shared among the laboratory, unit, and safety center. Degradation of the equipment is also more possible in the case of academia due to several reasons:

- The delay between the start of the work and training (sometimes more than 30 days)
- High turnover of individuals working with particular equipment

- Specific equipment can be shared among different administrative units without transparent monitoring of the use and maintenance schedule.

The last and possibly the most critical reason why hierarchal control-based methods are not applicable in Academia settings is that "In many cases, academic freedom is more important than safety" (Sarkar, 2014). Tremendous performance pressure and research goals result in frequent choices in favor of research or academic performance goals rather than personal safety. While, in the industry, these choices happen, are usually made on the management level, are less frequent, and thus can be easier controlled to keep system resilience. In Higher Education, decisions not to follow safety protocols or safety measures are made on an individual level and can hardly be controlled, especially when individual works alone.

Limited resources of the labs are often one of the reasons (Benderky, 2016) why laboratory managers/professors are not willing to invest more than required by regulations on safety. Compliance level is often even not reached (Witonsky, 2011). While industry labs would be shut down in case of severe non-compliance and consequences causing severe harm or death to an individual, academic laboratories will continue performing. Safety incentives are undoubtedly are extremely important as they demonstrate management commitment and care for the employees. But as well as use of nudges it cannot be the ultimate solution to improve safety and reduce violations, if major issues that push employees to violate rules are not addressed (i.e. not installed air-conditioning in the laboratories, common office and laboratory zones without separations etc.).

One of the ways to change this negative trend is to illustrate that implementing specific safety measures or improvement of their safety culture not only will not negatively impact their scientific performance but, in the long run, will result in financial benefits. Thus, one of the dimensions important for this type of decision-maker is the efficiency of the measures in terms of their suitability for the working environment, processes, acceptance by the employees, and simplicity of their use. Another dimension is financial, which probably shall be compared with the scenario without investment (higher accident probability/severity and lost time for the research work, due to investigation, etc.).

Similar information can be transferred to the higher management when necessary safety implementations or changes in the safety culture in the laboratory are essential but not made. The main argument to influence the behavior of lab managers with known malpractice can be forecasted reputational losses in case of an accident.

Discussion and raise of awareness are crucial. It requires transfer of relevant information freely and at any moment of the time. To improve safety in laboratories and university in general, information workflow needs to exist on three levels. On the micro level, the knowledge on the process safety, equipment, organization, concerns and safety needs shall be transferred between head of the laboratory and employees in both directions. Effective communication on this level will not only raise awareness, but improve overall safety. Different actions can be done in order to ensure high quality of communication: group meetings, journal of recommendations and concerns, individual discussions with PI etc. The intermediate level represents transfer of information between OHS service, infrastructure and labs, representing operational part of information transfer. The macro level is the communication between various university stakeholders and management.

1.3. Intention and goals of this dissertation

The flowchart in the Figure 4 is aimed to ease the follow-up of the thesis for the reader.

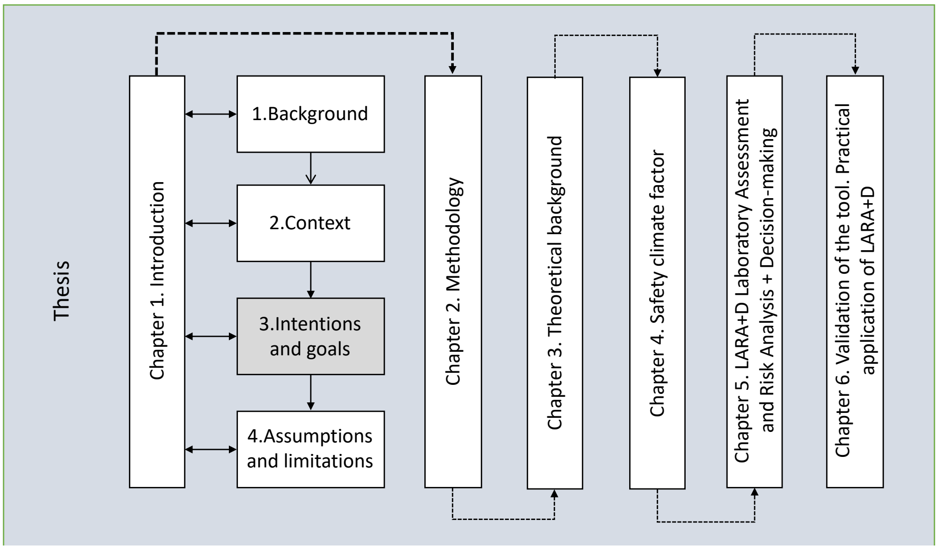


Figure 4. Structure of the thesis. Intentions and goals.

To improve the safety situation in the university laboratories, there is a need for an effective safety management tool that will consider all features of the research environment. This research aims to develop a process risk analysis method with an integrated decision-aiding tool. To achieve this project was divided into two stages, see Figure 5.

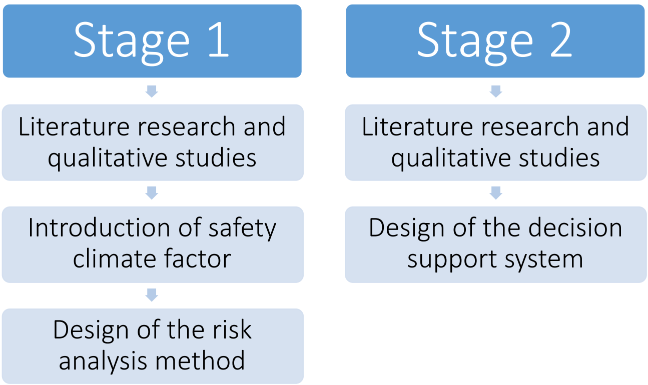


Figure 5. Project structure. Two steps.

Different risk analysis methods were investigated during the first stage, and risk analysis optimal for the discussed environment was proposed. During the project's second stage, different decision-making methods were investigated and compared to propose a decision-aiding tool that will serve as an additional block to the proposed risk analysis tool.

Research questions were developed to study which kind of information and presented in which way is essential for decision-makers to ensure optimal selection of safety alternatives during the safety decision-making process in university laboratories. Several questions were formulated during this research.

1. What are the factors contributing the risk level in the laboratory?
2. How can these factors be included in the existing risk analysis methods?
3. How to consider effect of the human contribution in the risk level during the assessment?
4. How does the safety climate affect risk and safety levels in the laboratory?
5. How to estimate probability of unwanted event, with a low availability of historical data and the least biased manner?
6. Which other factors, except risk index, are essential for decision-maker?
7. How do we obtain objective results in the decision-making process with various decision-makers?

1.4. Assumptions and Limitations

As it is depicted in Figure 6 assumptions and limitations of the thesis constitute the last subchapter.

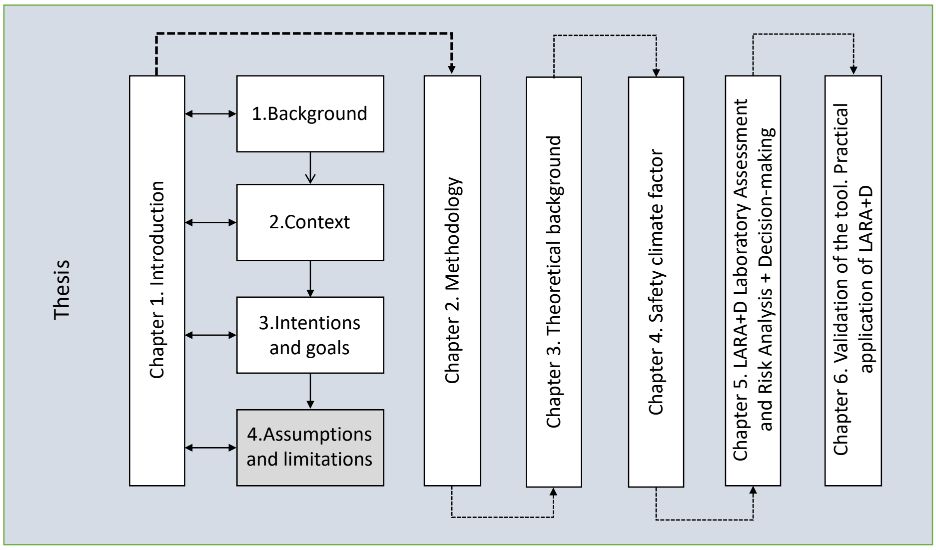


Figure 6. Structure of the thesis. Assumptions and limitations.

The decision support block is an integral and essential part of the safety management tool proposed in this work. The primary assumption made in the beginning that defined the whole design of the work is the nature of the decision-making process. In this work, we assume that the preferences structure of decision-makers, set of alternatives suitable for each case, and set of criteria are relatively fixed and "static". Possible deviations in preferences and suddenly appearing new criteria are not discussed in this work as they are deemed extremely rare, if possible. This study was designed based on one institution's safety regulations, directives, protocols, and management structure. The LARA (Laboratory Analytical Risk Analysis) method was the initial laboratory process risk assessment framework. This method was significantly modified; however, the methodology was kept similar enough to the old one to ensure familiarity for university staff with a new methodology.

This research can be used in any other university, with or without complete integration in its safety management system. However, a significant limitation will be the classification of the hazards and safety solutions proposed by the method.

Chapter 2. Methodology

This section provides an overview of the methodological approach taken to achieve the objective of this research. To achieve the aim of this research, a mixed methodological approach was adopted. An existential literature review and qualitative and quantitative methods were used to develop a safety decision-making tool for the university's laboratory processes.

The research was conducted in iterative manner, meaning that exploration and development of the method was done not in the linear manner, see Figure 7. Various discussions and interviews were conducted simultaneously in order to identify:

- What is feasible to identify during process risk assessment?
- Which information can be accurately evaluated?
- Which information is relevant for decision-making?
- Which other information is neccessary for decision-making?
- How to consider neccessary information, which is complicated to assess?
- What were the applicational and model limitations of previous method?

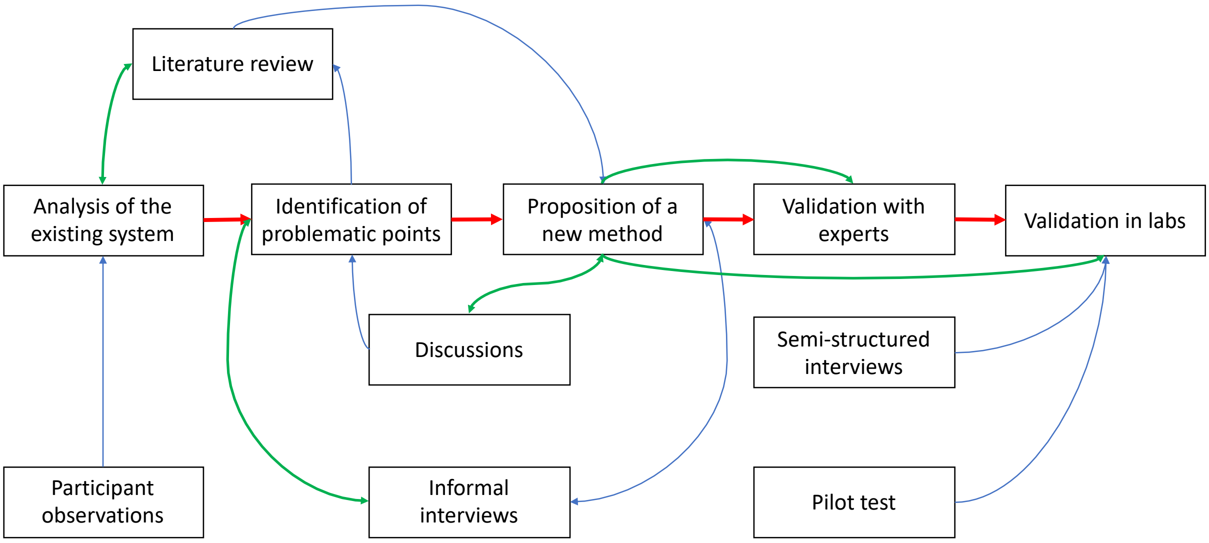


Figure 7. The flowchart of the research process.

2.1. Theoretical frame and grounding of the proposed methodology

Theoretical frame and grounding of this thesis constitute the first and the most crucial part of this chapter, see Figure 8.

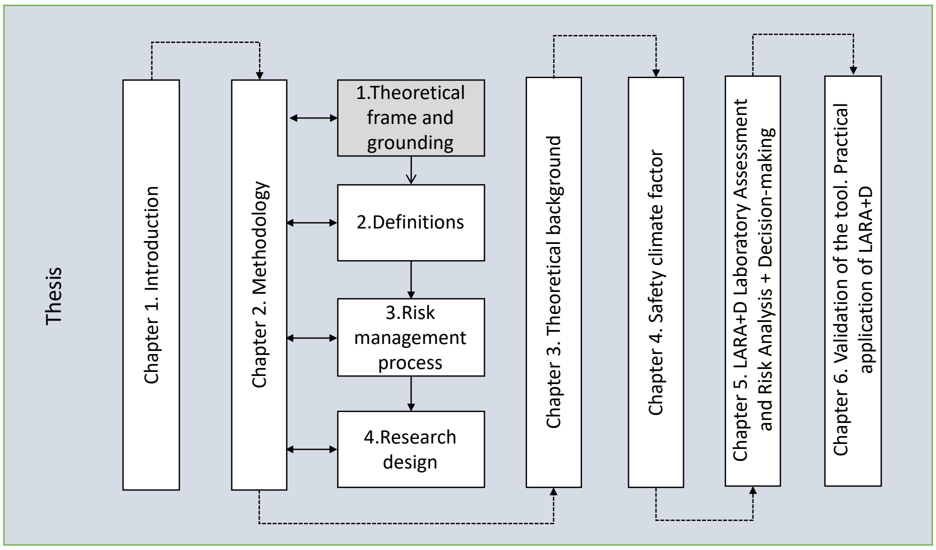


Figure 8. Structure of the thesis. Theoretical frame and grounding.

The way a researcher perceives the world is affected by his/her ontological assumptions. Epistemology derives from ontology and discusses the theory of knowledge, nature, and its limit (Blackburn, 1996), as well as how people acquire knowledge. Therefore, the ontological viewpoints of the researcher affect and determine his/her epistemological beliefs and therefore affects the subject of study. Positivism suggests that human behavior can be reduced to the state of generalized laws when an individual becomes not significant (nomothetic) (Bisman, 2010). Research structured in this scientific way is theoretically based. It explores the nature of relationships and causes and effects. Empirical validation and statistical analyses are the primary tools used to test and confirm theories.

Contrary to positivism, postpositivism assumes that not everything is entirely knowable (Krauss, 2015). The main assumptions of postpositivism are:

1. Absolute truth can never be found, as all knowledge is speculative and antifoundational. Any established evidence has limitations. Thus, a hypothesis can not be proved, but the researcher can accept them.

2. Any research is a continuous process when weaker claims and hypotheses are abandoned for stronger ones.
3. Available data, collected evidence, and rational researcher consideration shape the knowledge.
4. The research aims to develop relevant and accurate statements explaining explored situations or relationships.
5. Objectivity is essential for the research; it needs to be examined for bias (Creswell, 2014).

Postpositivism emerged from positivism. While the second studies evidence-based reality that can be mathematically interpreted, postpositivism explores subjective reality. As objectivity is unattainable for any individual, we can talk about it only as a social phenomenon due to our biases. We can only approach objectivity. Modified objectivity assumes that complete control or elimination of external influences on social objects is impossible; thus, the focus is shifted to controlling factors that are "controllable" and becoming aware and accepting of others (Sinead Ryan, 2019). Triangulation is one of the ways to increase objectivity; another is a comparison of opposite opinions from various individuals.

This study is designed from a postpositivism worldview. Any outcome of this research is not claimed to be definite or general. The model, built based on the conducted research, is most likely partially based on the subjective beliefs of the researcher. The adopted postpositivist approach refers to the attitude adapted to the understanding of safety and the decision-making process that is associated with it.

2.2 Definitions

Based on the epistemology and ontology, the terminology and interpretation derive, Figure 9.

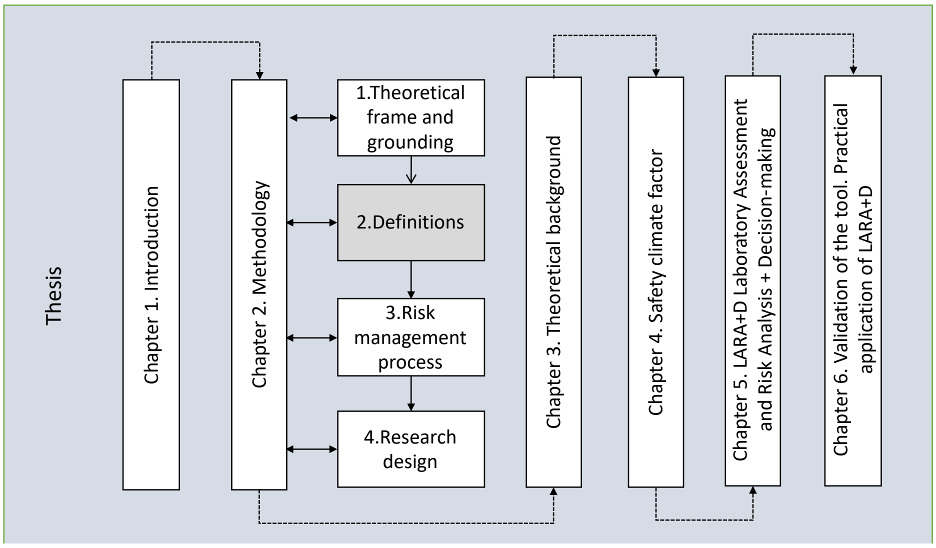


Figure 9. Structure of the thesis. Definitions

Risk management and decision-making are complex topics, the theory of which varies depending on the application filed. Thus, selecting suitable definitions, concepts, and terms is crucial before constructing any model.

2.2.1 Decision-making

Decision-makers getting information from the safety expert perceive risk through the lenses of critical realism. Solidly established criteria of the risk assessment diminish the perceptual bias of decision-maker. On the other hand, people whose actions contribute to increasing or decreasing have their specifically constructed realities of the risk. Such risk perceptions of people potentially involved in the construction of relatively objective reality will impact either positive or negative way the risk level. As the underlying reason for decision-making is solving practical problems in real situations, pragmatism accepts philosophically that there are singular and multiple realities and understandings (Dewey, 1940; Rorty, 1999; Creswell and Plano Clark, 2017). This approach allows decomposing problems on several layers with different elements, some of which can be subjective, objective, or a mixture of both.

Decision-making is sometimes considered a broader process, including problem definition, alternative discovery, alternative selection, and decision evaluation (Frisk, Lindgren and Mathiassen, 2014). The main challenges met during this process are complexity, uncertainty, and multiple, sometimes conflicting, objectives. There are different approaches based on the assumptions about decision-makers and available information:

- Deterministic. Data is known with certainty.
- Stochastic. Data are not known with certainty but can be represented as a probability distribution.
- Uncertain. Data is not available (Kaya, Kahraman and Çebi, 2012). The behavior of individuals in the presence of uncertainty will often be influenced by their attitude to risk (Radford, no date)

Most models assume that a decision-maker is an economic man making rational decisions (Askari, Gordji and Park, 2019). Rational decision-making mainly focuses on decisions made under risk (Endris, 2008). However, not only one's attitude but information overload, existing cognitive heuristics, and miserliness may affect a person's decision-making process (Perry, 2014).

Several critical assumptions are made in this work that determine the methods used during this thesis and theoretically supports the proposed decision-making model. First, we assume that the decision-maker has access to some information, which has a different degree of uncertainty. This information is received from a previously conducted risk analysis. Secondly, this decision-maker is rational; however, it can be influenced by different factors and thus is not objective. Then, risk analysis is conducted by the experts, who do not have access to any historical data and base their assessment on their knowledge, experience, and intuition. When we talk about objectivity and subjectivity of decision, we do not mean absolute objectivity, which is impossible (Wierzbicki, 2010).

2.2.2 Risk

There are many definitions of risk; however, « there is no approach in sight that could integrate the variety and concepts and offer a common conceptual denominator » (Renn, 1992). The increasing complexity of the world and the increase of trans-scientific questions (Weinberg,

1972) and especially the merge of social and natural sciences (Florio, 2020) requires a new way of understanding the risk.

Safety is frequently considered as opposed to the risk (Aven, 2009), and in the man-machine environment often related to the human (Möller, 2005). In the context of the system, where a human can be harmed, risks have to be viewed initially from this perspective. Aven defined risk through probabilities and uncertainties. In the first case, consequences and associated probabilities are used. In contrast, the second is uncertainty about the severity of the consequences or outcomes of activity for something humans' value(Aven, 2011).

According to ISO 31000, « risk is the effect of uncertainty on the objectives » (IRM, 2018). Which means that risks can have both negative and positive aspects, thus the risk appetite will differ depending on the organization. Meanwhile, paraphrasing it in the context of safety management, we can say « risk is the effect of uncertainty on the desired safety ». Risk is defined through the lenses of medicine and science as an objective reality that can be measured, controlled, and measured (Matthews, 2000). According to Weinberg (Weinberg, 1972), most socially associated risk issues can be raised but not answered by science. Being a function of human-made systems, risk can not be perceived and understood using the traditional approach of focusing on the safety and physical aspect of risk (Schwing and Albers, 1980).

2.2.3 Hazard

Hazard is an important term in risk management. It can be defined as the risk source (Fishkin, 2006) or potential source of harm((ISO), 2019). According to Ericson, hazards are prerequisites for an accident, where risk is a possible path from one to another (C. A. Ericson, 2005).

2.2.4 Exposure

Exposure of subject: person, material, etc., to a particular hazard is necessary to create a risk situation. When there is no exposure, there is no risk for the subject. For example, there is a laser in room A, but the person who works in room B is located in another corner of the building; thus, this person is not exposed to the laser, and there is no associated risk.

2.2.5 Uncertainty

There are different uncertainties present during risk analysis and decision-making. As was already mentioned, this research is constructed from the perspective of decision-making under uncertainty. However, when we talk about uncertainties, several kinds and classifications must be considered (Rogers, 2003).

1. Risk-associated uncertainties :
    i) Uncertainty of the cause. Several causal relationships can lead to the known adverse effect. Using various carcinogenic products aligned with constant exposure to a source of non-ionizing radiation can result in cancer (McElroy *et al.*, 2007). However, it is difficult to say with certainty what exactly the cause was.
    ii) Uncertainty in effect. In this case, a hazard is known, and a possible adverse effect is known; however, the probability of this adverse effect is uncertain due to its stochastic nature. « Russian roulette » is an example that demonstrates this situation. Gun as known harm and known adverse effects from pulling the trigger known nevertheless, it might happen or not due to various factors.
    iii) Uncertainty in the cause-effect relationship. This uncertainty is connected to the fact that the degree of correlation between cause and effect is unclear. Some hazards include the description « suspected to cause cancer » or « may cause cancer ». This uncertainty is explained by the fact that existing scientific knowledge is not conclusive enough to state a particular causal relationship.
    iv) Uncertainty about actual exposure level. When toxicological exposure thresholds are determined, the exposure needs to exceed this threshold to discuss risk (Jansen *et al.*, 2018).
2. Using statistics context, uncertainty can be classified as follows:
    i) Aleatoric uncertainty (irreducible). Random processes determine the relative probability of future events. It is not possible to reduce this uncertainty.

ii) Epistemic uncertainty. Limited data and knowledge are typical for any studied or described phenomenon. This type of uncertainty is reducible(Zio, 2014).

Several main causes of uncertainties can be listed:

- Lack of knowledge. It can be both qualitative and quantitative. In the first case, probabilities of events are known, but existing knowledge does not allow a deterministic description of the problem.
- An abundance of knowledge. Different types of heuristics, so valuable for everyday life during the risk analysis result, generate this type of uncertainty. It can be palliated to a certain extent by different aiding tools and systematization of knowledge.
- Conflicting pieces of knowledge. In some instances, an increase in available information does not decrease the uncertainty but increases it, as some knowledge is the rigor with mistakes.
- Measurement error. Physical measurement is always subject to the imperfection of tools and methods.
- Linguistic ambiguity. Different understanding of expression by individuals.
- The subjectivity of analyst opinion. Subjective interpretation of information by the analyst can result in different outcomes (Armacosta and Pet-Edwards, 1999).

2.2.6 Heuristics

During decision-making, our brain uses different shortcuts to facilitate the process. Usually, not all the information is processed due to the human's brain incapacity to process too much information simultaneously. Different types of heuristics affect risk perception (Kahneman, Slovic and Tversky, 1982)

- Availability heuristics. Probability is estimated based on remembered by analyst examples of events. Often, it results in an underestimation of negative consequences (Lichtenstein *et al.*, 1978).
- Anchoring and adjustment effects. New evidence is underestimated, while there is anchoring on already known information.
- Overconfidence and optimism bias. Often probability of positive outcomes or events is overestimated (and negative underestimated) (Oskamp, 1965)

- The illusion of control. People tend to underestimate the probability of adverse events when they have specific control over them (e.i, driving vs. flying in an airplane) (Langer, 1975).

2.2.7 Accident

An undesired event that causes damage: health, material, ecological or reputational. It is difficult to make a distinction between near misses and accidents. Pyramid structure where a less severe level is a prerequisite for the higher level (Reniers, Ponnet and Kempeneers, 2014). It is crucial to remember that frequently occurring near misses, if ignored, will one day lead to an accident.

2.2.8 Failure

However, this term is widely used in different methods depending on the field of application; ISO website gives more than ten definitions. According to the definition used in FMEA, the failure mode is a particular way an item fails to perform its intended function (NASA, 03.05.2022). This definition can be extended to how the process fails to perform its required function (Wang *et al.*, 2009). Performance of the process as intended can be considered a success, while deviations occur during the process as failures, which does not mean that the process as a whole will not be successful. However, a micro process that can be split as steps of an analyzed process can meet different failures.

2.3 Risk Management Process

Apart from common parts of any research, methodology of the risk management is a field specific and requires detailed consideration, see Figure 10.

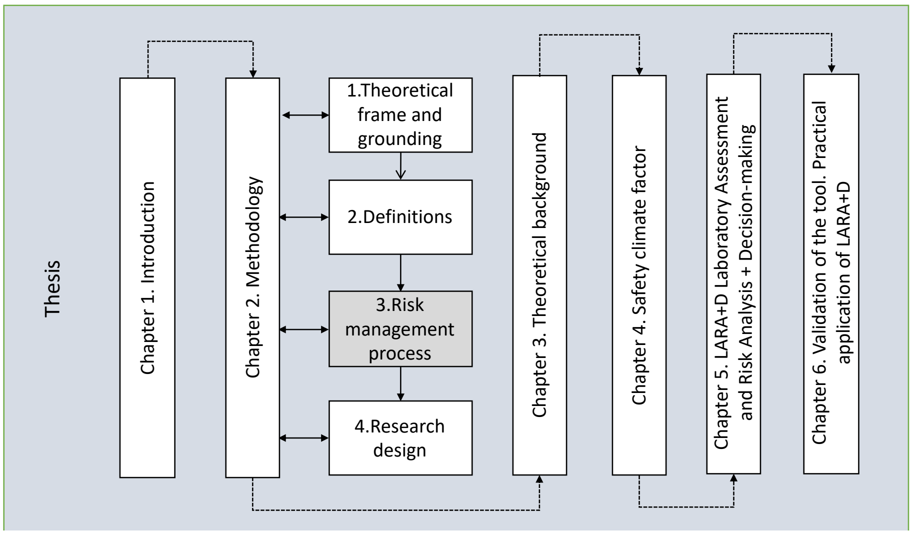


Figure 10. Structure of the thesis. Risk management process.

A Risk Analysis methodology is a methodical and systemic process. It is both iterative and interactive and aims to prepare the most appropriate decisions for managing the risks faced by a company, industry, or any environment where research activities are conducted. On a global scale, three prominent organizations are responsible for standardizing risk standards: The ISO-International Organization for Standardization, the IEC-International Electrotechnical Commission, and ITU-International Telecommunication Union (Rouhiainen and Gunnerhed, 2002). Among the standards governing the different methodologies of risk analysis today are the following:

- ISO 45001 process-based international standard for occupational health and safety. Intended for certification
- IEC 31010:2009 generic risk management standard related to technological systems. Not intended for certification, not specifically focused on safety. It is considered as complimentary standard for risk assessment.
- ISO: 14001 (2018) environmental management standard. Guideline for environmental risk management.
- BS EN ISO 12100 (2010) concerns the safety of machines and the assessment of their risks.
- EN: 1441 (1998) regulates the risk analysis of medical devices.
- CEI EN: 50126 (2000) governs the operational safety of railway networks.
- ISO: 17776 (2016) is a standard for oil and gas industry facilities and a guide and tool for hazard identification and assessment.

- ISO: 31000 (2018) sets out the principles and guidelines for risk management. It is the reference standard that generalizes all other standards related to risk management at the international level. It contains three chapters: principles, framework and process.
- COSO ERM (2017) sets of 20 principles of enterprise risk management which are organized in 5 main chapters: governance and culture; structure and objective-setting; performance; review and revisions; information, communication and reporting.

Often, COSO is compared to ISO 31000 :2018 as. They both have similar goal – implementation of effective risk management strategies in organizations. However, there are some differences that need to be considered, see Table 1.

	ISO 31000 :2018	COSO
Development	International Organization for Standards; reviewed by more than 5'000 people from 70 countries	Committee of Sponsoring Organizations; reviewed by PwC and limited number of external advisors
Focus	Provides guidance on how to implement ERM in organization; focuses on role of ERM in strategic planning	Corporate governance and auditing; serves as standard for evaluation of company's ERM activities
Format	Generic, 16 pages, uses supplementary vocabulary guide IEC 31010.	Detailed, more than 100 pages, provided with « Compedium of Examples »
Audience	Broad	Accounting and auditing
Framework, principles and process	Three elements are distinguished	Combines, incorporating ERM into other management practices and organizational governance.
Appetite vs criteria	Risk criteria is used to describe the amount and type of risk that organization is willing to take.	Is based on the notion of risk appetite which is discussed together with risk tolerance and capacity.
Reduction vs success	Risk management is used to generate business value	Centered on the risk reduction and avoidance.

Table 1. Differences between COSO ERM and ISO 31000:2018.

Standards are set at different times by different authorities. Whatever the standards, they contribute to accident prevention and emergency response preparedness. In all the standards and methodologies of Risk Analysis, the following structure is generally found in a simplified way: determination of the boundary of the work system/context definition, identification of hazards, risk estimation, risk assessment, risk prioritization, risk treatment, audits, and follow-ups. ISO 31000:2018 suggests a risk management workflow (International Organization for Standardization, 2018). The workflow consists of three main parts: definition of context and monitoring, risk assessment, and risk treatment.

2.3.1 Context definition

During the first step, a context for the risk management process needs to be defined, see Figure 11 (International Organization for Standardization, 2018). It includes a description of the process framework, available resources, and identification of responsibilities. Other stakeholders' objectives and expectations must be considered; legal requirements must be formalized.

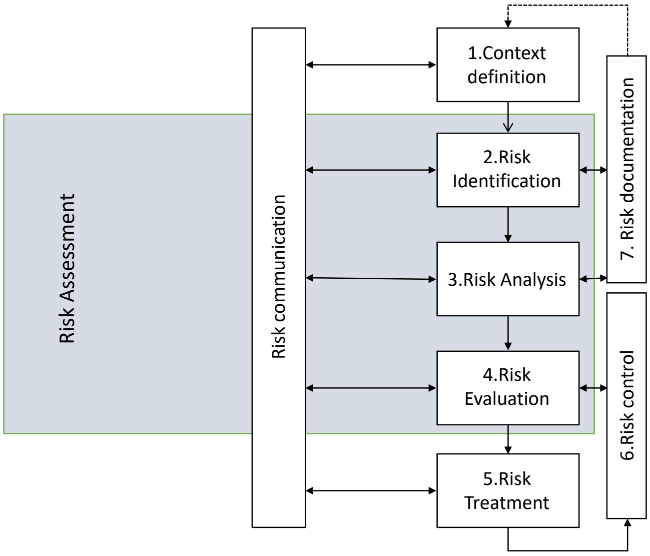


Figure 11. Risk management workflow.

Process performance can be measured using various types of KPI (key performance indicators); quantitative or semi-quantitative approaches to risk analysis can be used to achieve this. Any system for its effective performance requires a clear division of responsibilities. The absence of such can lead to poor risk identification and mitigation. To prioritize objectives, different risks need to be comparable; this clear evaluation mechanism with criteria shall be established. Different sectors need to define appropriate scales for them. For example, severity in the food industry will have different dimensions than in nuclear power plants. To be able to operate efficiently, and remain safe, limits of risk acceptability are set. These limits need to be respected during safety decision-making.

2.3.2 Hazard Identification

The first step of the risk assessment is hazard identification. The main difference between existing methods is the primary focus: activities or components of the process. The technique indicates that most quantitative methods rely on historical information on possible failures or accident frequency rates. Identification of all existing hazards is impossible due to limited available time and aleatoric and epistemic uncertainties following any risk analysis.

2.3.3 Risk Analysis

At this step, the magnitude of the risk is estimated; it includes quantification or qualification of different defined criteria, such as severity, probability, etc. This step also involves f uncertainty; severity, for example, can be determined differently, depending on the type of consequences. From the beginning, it is also essential to define which kind of consequences are accessed: the worst-case scenarios or the most probable one. Established rules shall be applicable for further assessment to ensure comparability of different risks. It can be done in a quantitative, semi-qualitative, or qualitative way. It is also essential to define whether an assessment is made assuming no measures are in place or such are known and thus need to be considered.

2.3.4 Risk Evaluation

The last step of risk assessment is risk evaluation. During this step, the analyst decides how to address different risks. The first question that needs to be addressed: "Is it necessary to treat this risk?". A risk is not always treated; sometimes, it can be accepted when the level is not too high. Decisions on whether a particular risk can be accepted are not made solely by the analyst. Acceptability levels are set prior to allowing experts to make these decisions. These levels are determined by different decision-makers involved in the safety management of the institution.

These acceptability levels can have different levels, depending on the context and type of the hazards. Different risk analysis techniques use as low as reasonably practical (ALARP) principles to establish different risk zones.

ALARP is a principle used in risk management to define the zone when a risk level is neither too low to be acceptable nor too high to be unacceptable (Melchers, 2001). The ALARP principle is applied when the risk is located in this zone. Usually, matrix includes two dimensions, which are traditionally two main and equal risk contributing factors: severity and occurrence. This risk needs to be reduced if the costs bared during the risk mitigation process should not be significantly higher than possible gains from the prevented accident (Aven, 2011). As there are no commonly determining values on bared costs, obtained gain, and the institution's management usually predefines their relation, these limits of risk zones.

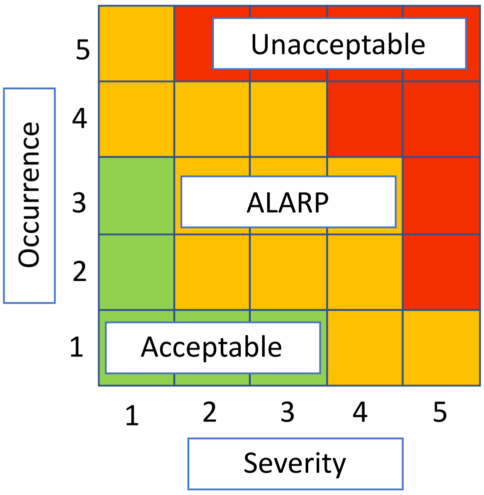


Figure 12. Risk matrix. ALARP

Depending on the risk aversion of organization (Committee of Sponsoring Organizations of the Treadway Commission, (COSO), 2017; International Organization for Standardization, 2018) which is meant to measure organization’s appetite or risk tolerance, coloring of the zones will be different. However, when we talk about risk appetite we mean the upside risk in contrary to tolerance. With a low risk tolerance, the red region of the matrix will be bigger and acceptable region can be smaller.

2.3.5 Risk Treatment

As a result of risk evaluation, existing risks are prioritized depending on their value. Afterward, the analyst identifies corrective measures (action) to address selected risks. Several options to address risk can be used: avoidance, retention, sharing, transferring, loss prevention, and reduction. All identified measures must be evaluated from different perspectives if the decision is made to treat the risk. The most critical one is their performance in the dimension of initial risk mitigation. Accident prevention is preferable to mitigation but not always possible. The STOP approach is one way to classify possible corrective measures (Reniers, Landucci and Khakzad, 2020). STOP stands for four types of corrective measures:

- Strategic measures. Modify the process by substitution, eliminating, etc., the hazard to reach a less threatening level of risk.
- Technical measures. These measures are used when strategic measures are not possible or not feasible. They can be applied to reduce the magnitude of possible consequences and lower the likelihood of an accident (failure) or hazard propagation. Technical installations achieve this positive effect.
- Organizational measures. This class of measures includes different organizational modifications that will affect the process. It can be training the employees, cleaning procedures, evacuation plans, response techniques, etc.
- Personal measures. This last category of the measures affects only the person directly involved in the process and working with hazard. Different types of PPE (personal protective equipment) are the most spread example of such measures.

Financial constraints are significant during risk mitigation (Aven, 2011). Risk reduction potential and feasibility of the measures can be necessary factors decision-making process (Cox, 2012). Different optimization algorithms can be used to assist with the decision-making process and to achieve optimal resource allocation (Reniers and Sörensen, 2013).

2.3.6 Risk Control

Control is essential to ensure that implemented corrective measures are still effective and efficient. Changes in the working environment, modifications, even minor processes, degradation of the measures, and change in the legal requirements can affect the level of the risk. Control includes an update of the information to identify whether the risk level is still within intended limits. Incident and accident information can serve as an indicator of the effectiveness of implemented corrective measures. The risk portfolio needs to be periodically analyzed and updated.

2.3.7 Risk Documentation

Documentation is an essential element in the risk management process. First, it creates a necessary formalization of the different roles and responsibilities of stakeholders involved in the process. This includes evaluation, action plan to implement corrective measures, and risk owner. Moreover, adequate documentation helps to create a ground basis for future analyses and training and helps establish a database on various aspects of risk management.

2.3.8 Risk Communication

Risk communication is essential for any efficient risk management approach. It helps analysts and decision-makers to evaluate previous decisions and improve future decision-making. It is also essential as it provides a realistic situation and gives a perspective of the risk "as it is" not "as expected". Communication is essential not only on the level of one institution but across different sectors, as it creates an opportunity for knowledge sharing and creation. Knowledge to influence the context of a risk management approach.

2.3.9 Continuous Improvement

Continuous improvement is necessary in the changing world. Not only do regulations change, but the circumstances. The Deming wheel is a widely applied principle of continuous improvement, see. It is also known as the PDCA cycle (Plan – Do – Check – Act). This tool is widely used in quality management (Dudin *et al.*, 2014). There are four steps in this process:

- Plan. Develop objectives and necessary actions to achieve these objectives.
- Do. Execute planned action. Collect data.
- Check. Monitor and evaluate the effectiveness of the actions.
- Act. Carry out improvements if the expected and actual results differ.

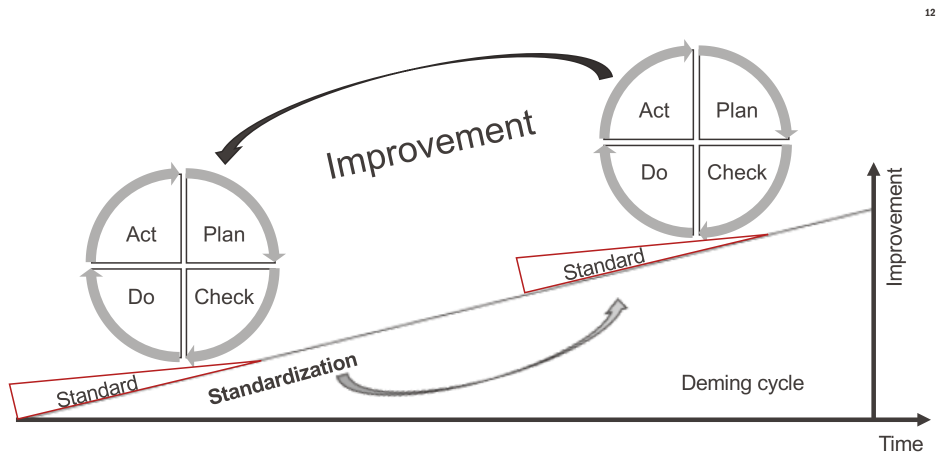


Figure 13. Deming cycle

The continuous improvement is conducted by iteration of the Deming cycle and consolidating the results using standardization.

2.4. Research design

Research design constitutes the final part of the methodological chapter, see Figure 14, and it describes the use of different research methods in this thesis.

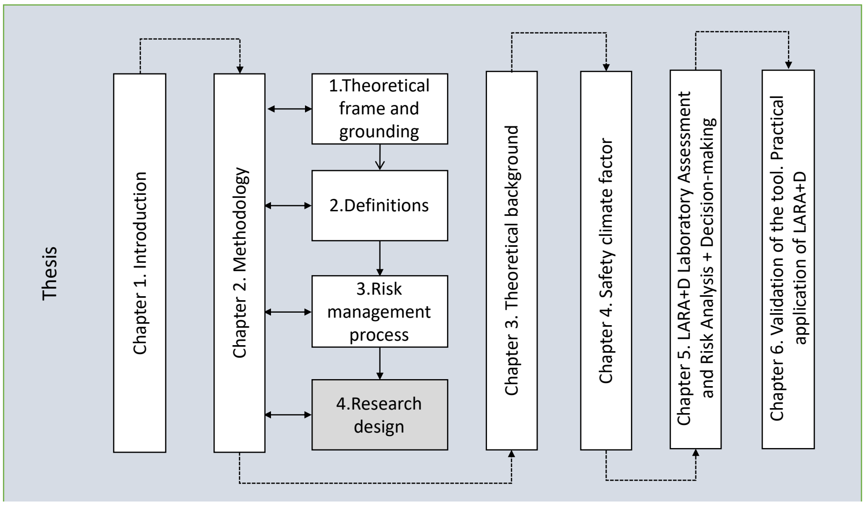


Figure 14. Structure of the thesis. Research design.

Research design is an essential element of each study; it serves as a guideline for research strategy and indicates necessary research steps. It helps a researcher address a problem coherently and logically, including a blueprint for the data collection, measurement, and analysis, see Figure 15.

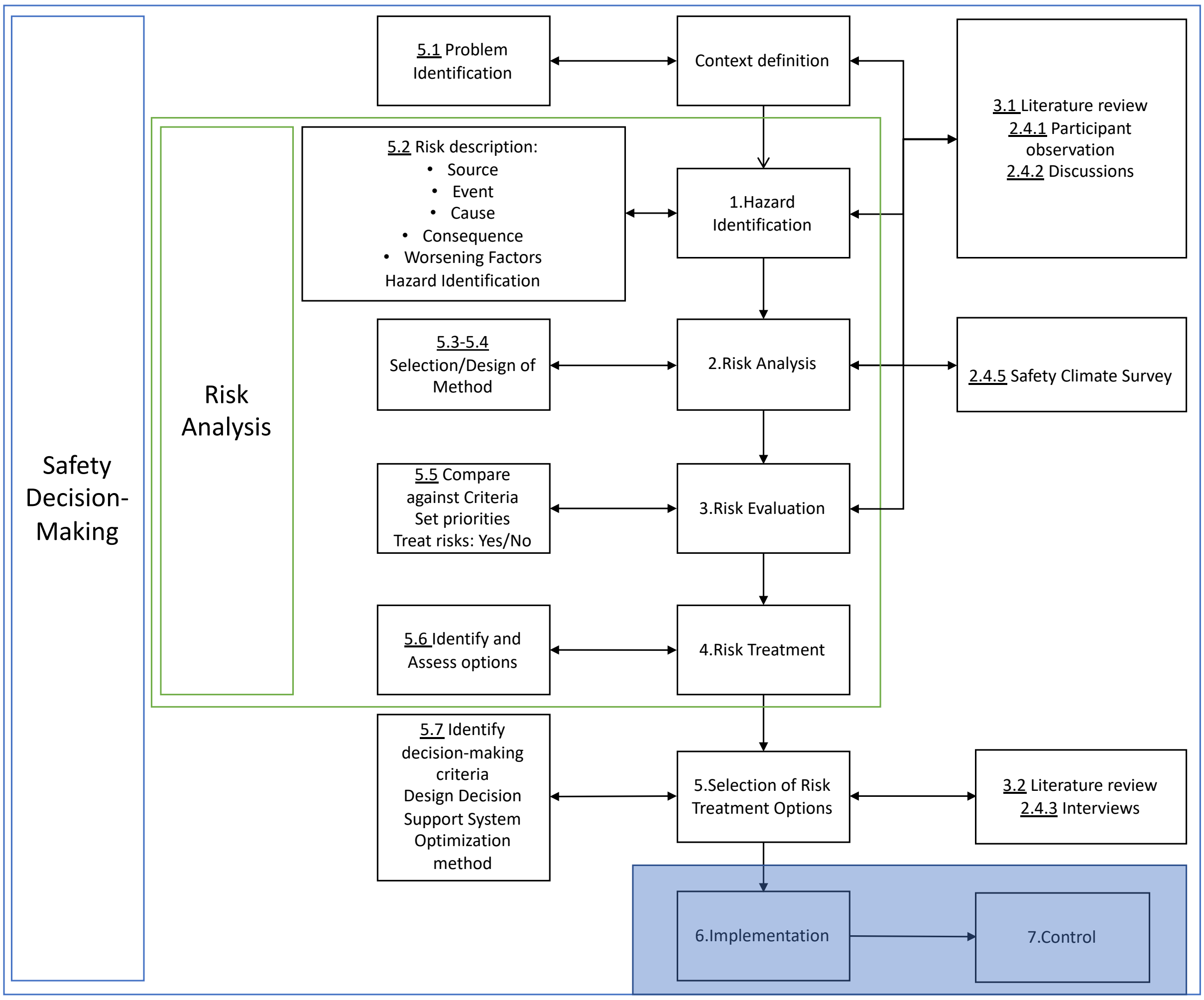


Figure 15. Flowchart of the safety decision-making process, underlined number references the number of the chapter in this thesis.

To understand and decompose the global decision-making problem, the research problem can be formulated using the terminology of ISO 31000: « Which uncertainties have to be managed in laboratory process risk assessment to promote "better" Safety decision making?». The optimal way to measure phenomena existing on different levels, and having different natures, is to use mixed methods (Feilzer, 2010). Combination of qualitative methods that are especially relevant when research understands the research problem and factors influencing decision-making (O'Hara *et al.*, 2014), with quantitative methods to evaluate their contribution and influence on the global factor. The most frequent challenge met by the researchers using mixed methods – is the absence of proper integration, meaning that phenomena are looked at separately from different perspectives rather than synthesis. Such research strategy has even more sense considering that research problems of decision-making are usually very complex and transdisciplinary, thus requiring a non-linear approach (Taylor, 2018).

2.4.1 Participant observation

DeMuck described participant observations as one of the primary methods for researchers doing fieldwork. Fieldwork is a complex approach, including several techniques such as informal interviewing, writing field notes, and observations (DeWalt and DeWalt, 2002). Participant observation is also defined as "learning through exposure to or involvement in the day-to-day activities" (Schensul, Schensul and LeCompte, 1999). Participant observations as regular observations can be used after interviews to fill the gaps and find inconsistencies or inaccuracies provided previously(Marshall and Rossman, 1989). According to DeWalt, this method helps a researcher to develop a "holistic understanding of the phenomena under study"(DeWalt and DeWalt, 2002). According to the authors, using this method, along with others, such as interviews, surveys, document analysis, etc., increases the validity of the research and is very useful during theory building. Participant observation can be used when:

- Researchers need to understand how everything is organized, communication among people, and priorities.
- To introduce the researcher to participants, thus facilitating interaction and further research.
- To provide the researcher with a source of questions that can be addressed on-site (Schensul, Schensul and LeCompte, 1999)
- To collect both quantitative and qualitative data(Bernard, 1994).

There are different degrees to which researchers can be involved in participation. According to Gold (Gold, 1958) four stances can be distinguished:

- Complete participant. A researcher is a member of the studied group and conceals his/her role from the group. In this stance, the researcher lacks objectivity, and group members can feel deceived after the role is relived.
- Participant as an observer. The researcher is a member of a studied group but is involved mainly in observation than active participation. The main disadvantage is the depth of confidential information that can be provided to the researcher.
- The observer as participant. The group is aware of the researcher's role, and he/she is actively participating in group activities.
- Complete observer. The researcher is hidden from the group and is unaware of being studied.

Ethics is extremely important during this type of qualitative study. Except on exceptional occasions, people with whom the researcher interacts need to be informed about his/her role and the purpose of the study. Another important aspect is preserving the anonymity of other participants in the report and field notes.

2.4.2 Informal interviews. Discussions

Some researchers consider informal interviews part participant observations(Bernard, 1994; Merriam, 1998; Kawulich, 2005). Different researchers widely use this method (Fisette, Jennifer, 2013; Simpson, Alexander; Slutskaya, Natasha; Hughes, Jason & Simpson, 2014). The term "informal interviews" has various synonyms and is sometimes referred to as "informal conversations", "unstructured interviews," or "ethnographic interviewing"(Bernard, 1994). This method is used in ethnology and as an additional data source in narrative methods, phenomenology, ethnomethodology, case studies, etc.

2.4.3 Semi-structured interviews

Semi-structured interviews are one of the most frequently used tools in qualitative research when deep and detailed information needs to be investigated (DiCicco-Bloom and Crabtree, 2006). The main advantage is its interactive and dynamic nature, allowing the researcher to adapt questions and improvise depending on participant responses(Rubin and Rubin, no date).

The purpose of conducting semi-structured interviews was a generation of strategic objectives for decision-making among selected decision-makers. Three groups of decision-makers were identified for the discussion. These groups were distinguished based on the financial sources they represent:

1) Safety Competence Center, which is responsible for the risk analysis and safety visits
2) DII, responsible for infrastructure
3) Laboratory management (P.I., head of the laboratory, etc.)

Different individuals will constitute the only third group of decision-makers. This group is also considered not expert and requires objective generation. This group is the only decision-maker for whom the safety of the process and, in general, any decision made concerning the risk assessment will not fall in the category of fundamental objectives but will play a role of means objectives (Bond, Carlson, and Keeney 2008). This group of potential decision-makers consisted of P.I.s, laboratory managers, and professors who, in the past, demonstrated their positive involvement in laboratory safety and good collaboration with the safety competence center.

It was considered that those participants who already showed sharing some of the safety objectives would be more eager to understand the problem and make their judgments connected with their experience. Undoubtedly, the involvement of individuals with opposite safety attitudes could contribute and might help overcome some difficulties experienced in safety management. However, at this step, it was more important first to collaborate and elicit opinions from those for whom safety is also partially a fundamental objective. We identified five individuals who will represent this group. To consider specific characteristics of basic science faculties, selected individuals represent different faculties (chemistry, physics, materials).

A process Boost. Even though the "master list" of objectives is a handy tool, in our case, it does not exist. We can consider one list of the objectives identified by one decision-maker, in which objective generation was unnecessary. This decision-maker is represented by a safety competence center, playing both an expert and a decision-maker. In both cases, even when such a list is available, potential decision-makers, to decrease bias, shall first deliberate their ideas.

STEP 1. A short presentation providing an overview of the risk assessment, its significant differences from audit, and included factors is shown to potential decision-makers to give a better introduction. The presentation consists of 8 slides, where two last drops have steps 2 and 4.

STEP 2. To facilitate the objective generation process, we used the approach proposed by Bond (Bond, Carlson, and Keeney 2010). Objectives were organized into three categories: safety, financial, and research, as depicted in Figure 16.

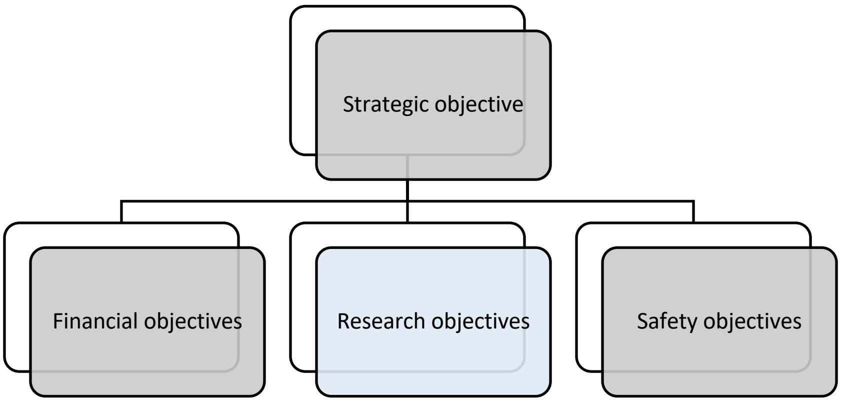


Figure 16 Categories of objectives

STEP 3. Afterwards, a short interview proposed by Keeney (Keeney 1996) was conducted. It includes ten types of questions, which were adapted to this specific case.

2.4.4 Survey

A survey can be quantitative and qualitative, depending on the questions and information collected. In the case of open questions, this tool is helpful for qualitative research to discover new information. According to Check & Schutt (Check and Schutt, 2012) survey is "the collection of information from a sample of individuals through their responses to questions". Three features can be identified to characterize this type of research:

- It gives a quantitative description of studied aspects of the population and studies the relationship among different variables.
- Data is subjective, as it is collected from different individuals
- Conclusions and results drawn up from the survey can be generalized (Glasow, 2005).

According to Pinsonneault & Kramer (Pinsonneault and Kraemer, 1993) survey is a "means for gathering information about the characteristics, actions, or opinions". A survey is one of the most valuable tools for collecting data from a large population (Neuman, 2003). Each respondent answers the same set of questions, which helps the researcher test the hypothesis. As with any tool, it has its limitations. The depth of answers details is limited to the question and understanding of the respondent (in open-type questions). According to Wilkinson (Wilkinson, 2000), information obtained from surveys is very static, as it represents a vision of the respondent at a particular time. Another problem is a low response rate (Heberlein and

Baumgartner, 1978), which means that it shall be distributed to a wide range of the population to obtain statistically significant results. This tool is also subject to Common Method Variance (CMV), as there is no visual observation of respondents and control over the research process(Podsakoff *et al.*, 2003; Yang and Mossholder, 2010).

Safety climate questionnaire. This questionnaire aimed to establish a relationship between different variables and their contribution to the model. Thus, it was constructed in a quantitative, mixed methods manner. Safety climate surveys, as well as focus groups and interviews with participant observations, are the most efficient way to measure and improve safety culture, moving it from level 4 to 6 Sigma (Hollnagel and Leonhardt, 2013). There have been dozens of various safety climate surveys conducted by and for different industries. Some of the main fields are:

- Public Occupational Health (Rantanen *et al.*, 2017; Alsalem, Bowie and Morrison, 2018)
- Industrial Engineering (Jaselskis and Suazo, 1994; Choudhry, Fang and Lingard, 2009; Ulubeyli, Kazaz and Er, 2014)
- Management (Glennon, 1982)
- Applied Psychology (Hall, Dollard and Coward, 2010)
- Operational Research and Management Science (Mohammadi and Tavakolan, 2020).

Due to the differences between the industrial and academic sectors, the results of those surveys are not entirely relevant to us (Wu, Liu and Lu, 2007). Several attempts have been made to conduct safety climate surveys (Wu, Liu and Lu, 2007; Stricker, Gerweck and Meyer, 2019) and construct a safety climate model in academia. One of the most extensive studies that have been conducted (van Noorden, 2013) had more than 50 questions and was conducted mainly in the U.K. and the USA.

Method. Some of the questions used in this survey were previously developed (*NPG. The topline edition of the 2012UC, BioRAFT and NPG Lab safetysurvey data*, 2014). The survey construct was developed based on a literature review. Initially, the survey was divided into five parts, one of which targeted hazard perception. The other four components were expected to contribute to the safety climate parameter, as depicted in Figure 17. Even though most of the questions were intercorrelated and could be classified into several categories simultaneously, only four main categories were distinguished. This model distinguishes observable and non-observable dimensions. A similar separation of the factors was proposed by Vierendeelsa et al. (Vierendeels *et al.*, 2018) with stage 3 of the TEAM model (The Egg Aggregated Model), which distinguishes two types of factors. The first group is observable dimensions: technology, training, procedures, behavior, and observable safety results, and the second group consists of non-observable factors, such as organizational and individual constructs. The theoretical model that we propose could be expressed by four components:

1. Awareness and behavior of lab members expressed as a level of hazard awareness, attitude to safety rules, perception of the safety requirements, and safety behavior.
2. Management and resources. These are combined into one group because the availability of resources and their quality will often depend on the lab manager's safety attitude. This latent factor, as well as the first one, can be observed through safety results.
3. Perceived safety in the laboratory is meant to measure the trust in the capacity of laboratory management to guarantee the necessary and desired level of safety.
4. The background of group members. As demonstrated by Becker (Becker, 1974) an individual construct can significantly contribute to the laboratory safety climate. While the health belief model's second dimension, which is psychological characteristics, would be challenging to measure, demographic variables were included in the safety climate model as described in Figure 17 (bigger version of the figure can be found in Attachment A2.).

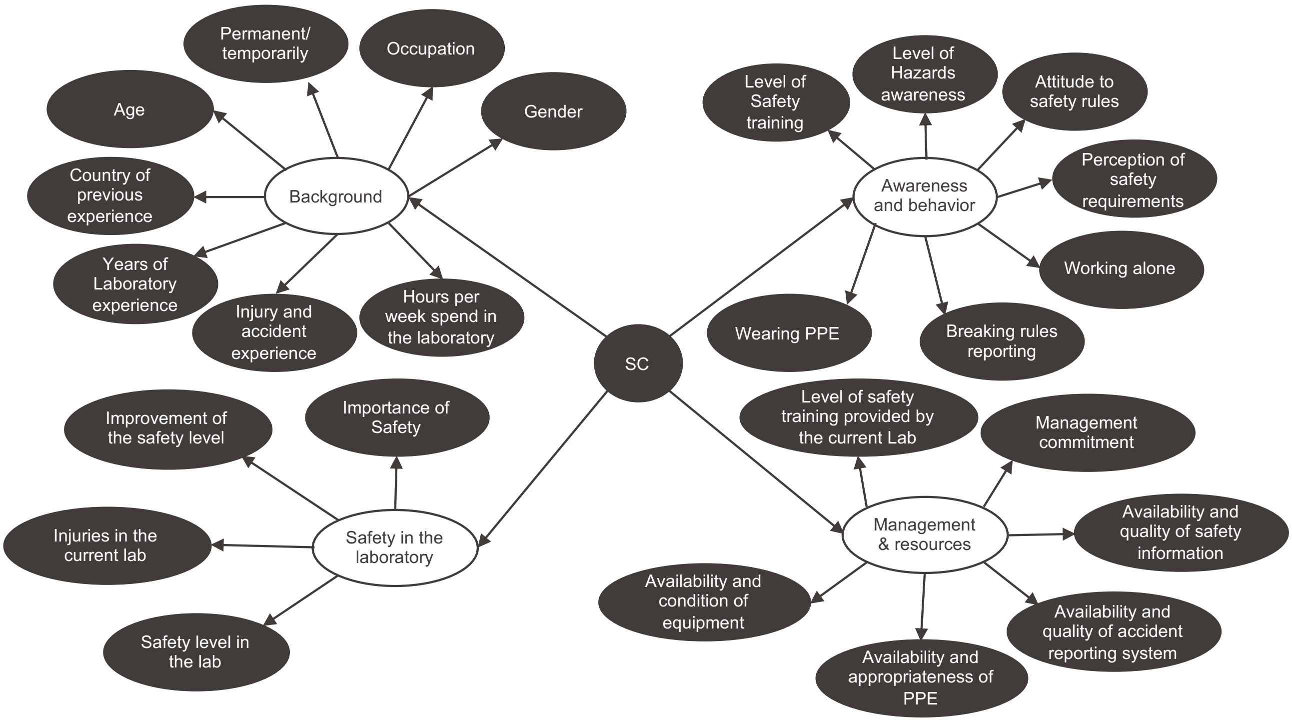


Figure 17. Conceptual model of safety climate for University laboratories.

The questionnaire was designed in English and was mainly distributed in English. French and Chinese versions were obtained through translation and validated by native speakers. All questions were validated and corrected by safety experts working in academia. Other validation steps included Exploratory and Confirmatory Factor Analysis (Aithal and Aithal, 2020).

Questionnaire administration. Even though there is a significant amount of literature on the advantages and disadvantages of internet-based research (Sax, Gilmartin and Bryant, no date; Solomon, 2001), no significant difference was found (Pealer *et al.*, 2001). Due to the participation of different universities located in different countries, the paper administration of the questionnaire was not feasible. The online version was created using the online platform "freeonlinesurvey" ('Freeonlinesurvey', no date), which design guaranteed compliance with the latest General Data Protection Regulation (Blackmer, 2018). Each participating university received a personalized link for the survey. The survey was distributed through newsletters lists or mailing lists. Participation was voluntary, and information about participants was reported to universities regardless of their names. Any information which could help to identify participants was kept confidential.

2.4.5 Uncertainty elicitation

There are different protocols for probability or uncertainty elicitation (Meyer and Booker, 1991; Meyer *et al.*, 2002). Interactive methods, such as focus groups, help the researcher obtain dynamic opinions and, as a result, consider different viewpoints of participants. On the other hand, some individuals in the group can be subject to the influence of others, biasing their opinion and the results (Meyer and Booker, 1991). Different methods can be used to overcome this limitation (Meyer and Booker, 1991; Meyer *et al.*, 2002; Cornelissen *et al.*, 2003; Krayer von Krauss, Casman and Small, 2004). The process was divided into two stages to elicit quantitative and qualitative information. The risk analysis template was given to selected experts during the first stage. Based on the provided information, selected safety experts were expected to evaluate risk factors, determine possible consequences, and propose safety solutions.

The list with definitions and examples of factors was given along with the assessment list. Experts were chosen based on their expertise in the field and were based at EPFL. All of them were familiar with the proposed risk analysis method. Information collected from the experts included fuzzy values for the risk subfactors and qualitative information on expected consequences and proposed safety solutions. The second stage included group discussion on the individual results of the assessment. The group discussion was necessary to clarify possible misunderstandings or misinterpretations during an individual assessment. Out of six experts, one changed the quantitative values he assigned when determining "Frequency/Duration of exposure to hazard", as the term was misunderstood. During the group discussion, experts were expected to assign their confidence value to the assessed factor. Quantitative information stated by the experts was the same; after the group discussion, experts agreed on the confidence interval for studied factors.

Case for uncertainty elicitation. A preliminary risk assessment using the proposed methodology was made for the chemical laboratory to replicate the process described by Lai (Lai *et al.*, 2015), see Figure 18. This process is used to prepare multi walled carbon nanotubes (MWNT) for further wet spinning. The figure below schematically describes preparation of PVA/MWNT spinning dope, the process of spinning by itself is not illustrated by this example.

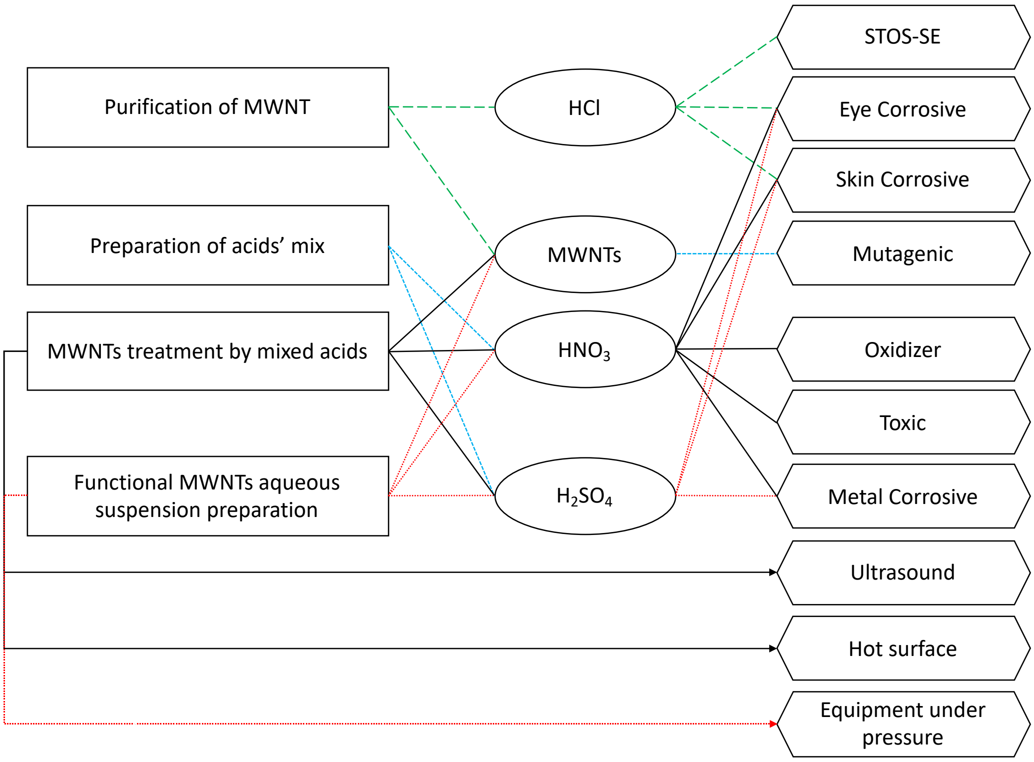


Figure 18. Hazard Identification for Preparation of water-soluble PVA/MWNT spinning dope.

Printed forms containing detailed information on the process were distributed to the experts.

Chapter 3. Theoretical background

Often, in the literature, risk management and decision-making are considered separately. However, they are strongly interconnected and can serve the ultimate goal – to identify and manage the risk only together. This chapter gives information on the tools used in both interrelated disciplines, which either used or served as a basis for the LARA+D safety risk management tool.

This chapter is divided into two parts. The first part of the chapter aims to present some of the risk assessment tools used in occupational and health safety. Even though there are more than a hundred commonly used methods (C. Ericson, 2005), not all apply to the university environment. The methodologies of the most widely used methods which potential application was considered to satisfy the needs of the projectare included in this chapter. Regarding the context and specificities of the research environment, human plays a significant role in risk management. The role of humans in risk management is addressed using different approaches. The first part of the chapter provides the reader with different methods of human error consideration in the risk assessment.

This chapter's second part focuses on the optimization approaches used in multicriteria decision-making. It provides information on the methods considered suitable for this project's purposes.

3.1. Risk assessment

All risk analysis steps are essential; however, risk assessment can be considered the most important. The success of the organization's capacity to manage existing risk will vastly depend on whether the method was correctly selected for the described context.

There are plenty of existing risk assessment methods that vary depending on their primary focus. Some methods are purely process-focused; others treat different system components or focus on deviations. Different risk analysis tools are. Often adapted for the needs of the industries and consider specific contexts. Using different approaches requires not only different inputs and data but results in different outputs, thus may influence the decision-making process in general. There are various classifications of the methods that can be distinguished:

- Nature. Deductive or Inductive. Deductive methods will be focused on determining influencing factors that lead to unwanted consequences. Inductive is focused on treating already the consequences.
- Type of data. Three types of assessment are available: qualitative, semi-qualitative, and quantitative. The complexity of the analysis and reliability of the results will often be directly correlated in these types of measures. However, applicability is always determined by the context and constraints.

This chapter presents the most widely used approaches, along with those suitable for the context of the research laboratory activities.

3.1.1 HAZOP

Hazard and Operability Analysis (HAZOP) was first introduced by the Imperial Chemical Industry (ICI) in the 60th to assess risk in chemical plants. The method became widely used after the Flixborough disaster of 1974 (Meyer and Reniers, 2013). Initially, process problems were supposed to occur when there were deviations from the normal state and were used for hazard analysis in complex systems (Lawley, 1974). It is widely used in different branches of the process industry (Robinson, 1995; C. A. Ericson, 2005) and even beyond: computers, transportation, and mechanical systems (Lee and Lee, 2018).

It aims to identify cause-consequences scenarios, considering system response when deviations occur (Rossing *et al.*, 2010). The IEC 61882 (International Electrotechnical Commission, 2016) provides application guidance on the method. As with any other method, it first requires defining the scope and describing the system. Afterward, the list, a combination of guidewords and parameters, is generated using a combination of guidewords. Parameters include elements, properties, and keywords, while guidewords are used to identify and state a deviation from expected. This combination of guidewords and parameters results in the list of applicable deviations. The example of the parameters is illustrated in Table 2.

Parameter	Meaningful Combination of Guidewords
Temperature	Higher, lower
Level	No, higher, lower, reverse
Reaction	No, higher, lower (rate of), reverse, as well as
Mixing	No, more, less

Table 2. Example of meaningful combinations of guidewords.

HAZOP analysis can be logically represented as a deviation – causes – effects – safety functions – action/measure (Kotek and Tabas, 2012). Even though the method is relatively simple in its use, it is usually performed by a team of several people as it is time-demanding and requires a certain level of expertise. The analysis aims to identify potential hazards and operability issues in the process and process corrective actions. HAZOP treats system deviations as sources of hazards. To address these deviations, the system is divided using different parameters: measurable physical quantities, operations, actions, and functions-situations (Meyer and Reniers, 2013).

Like all methods, it has its advantages and limitations. Initially, it was intended as a qualitative method, which evolved into a semi-qualitative that allows risk evaluation. The main characteristics of the method are illustrated in Table 3.

Advantages	Drawbacks
Easy to perform and master	Focused on a single event, no synergies are taken into account
Established structure helps to focus on system elements and hazards	Guidewords can cause an omission of hazards not related to these guidewords
Different viewpoints of the team can be encompassed	Training is essential
Available commercial software	Very time consuming

Table 3. Advantages and disadvantages of HAZOP method, adopted from (Meyer and Reniers, 2013)

The application of the HAZOP method can be very limited in a research environment. It is rarely feasible to allocate the required amount of time for the analysis. The concept of deviations is hardly applicable, as in novel processes sometimes challenging to estimate the normal performance function. The use of the keywords and lack of synergetic effect consideration is an additional drawback limiting this method's application. However, it can be efficiently used for the process and experiment design when more knowledge of the process's normal functioning is available.

3.1.2 FMECA

Failure Modes, Effects, and Criticality Analysis (FMECA) were first developed for the US Army and published as a Military procedure MIL-P-1629 (US Department of Defense, 1949). Later, this method was adapted by the National Aeronautics and Space Administration (NASA) and was used during the stage of rocket development (C. A. Ericson, 2005). Starting from the 70th method moved into the civil industry when Ford Motor Company started to apply it in its manufacturing. Depending on whether the concept of criticality is used, two similar methods can be distinguished: FMECA and FMEA. FMECA is often used in the early design stages when the reliability of the equipment is estimated. Three main types of FMECA can be distinguished:

- Design FMECA. It is carried out during equipment design and is used to assess all possible types of failures during the lifespan of this equipment.
- Process FMECA. It is applied at the next step when there is a need to assess which problems may arise from the manufacturing of equipment, its maintenance, and operation.
- System FMECA. It is the most global one focusing on broader problems arising in the production lines and possible bottlenecks.

FMECA is both a bottom-up and top-down approach. It can be used when a system concept has already been decided. It requires a detailed investigation of each component of the system. It is also called the hardware approach. The analysis can be considered complete when all components are assessed. The deductive approach, on the contrary, is used at the early stages of a design before the whole structure is decided. In this case, the analysis will focus on the system's functions – how they may fail. It can be used to focus on the most critical areas. There are several standards concerning FMECA application: SAE ARP 5580 (Society of Automotive Engineers (SAE), 2020), SAE J1739_202101 (Society of Automotive Engineers (SAE), 2021), AIAG FMEA (Automotive Industry Action Group, 2008).

This method became widely spread across different industries: food (Scipioni *et al.*, 2002) and nuclear (Guimarães and Lapa, 2007). Software for FMECA is available and supports different forms of the method. This method is relatively flexible and provides sufficient depth of analysis. The method requires particular expertise and training. However, its logical structure makes the application simple. As the semi-qualitative method, it does not require precise estimations.

Similar to HAZOP, the approach is quite time-consuming and thus expensive. It is not suitable for multiple failures ; see Table 4.

Advantages	Drawbacks
Easy to perform and master	Focused on a single event, no synergies are taken into account
A clear structure helps to focus on system elements and hazards	Not adapted to identify hazards related to failure modes
Provides a reliability prediction of the item being analyzed	Human error is not addressed sufficiently
Available commercial software	A limited examination of outside influences
	Requires in-depth knowledge and expertise over product/process under examination

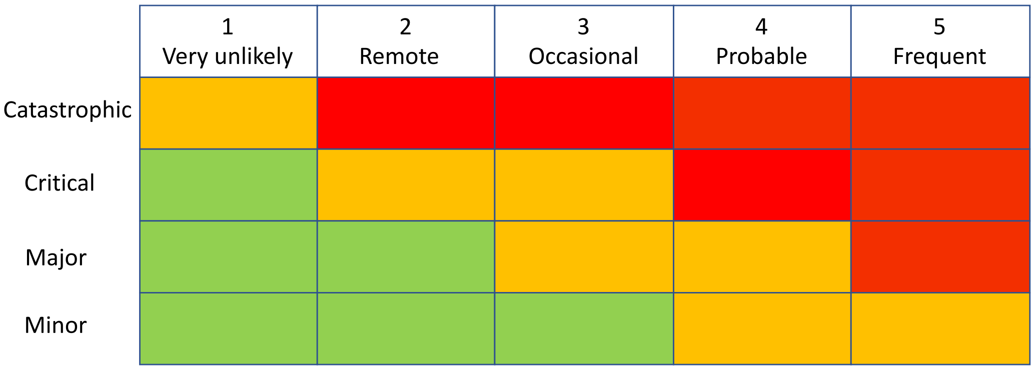
Table 4. Advantages and disadvantages of FMECA (Meyer and Reniers, 2013)

This method consists of 5 main steps. First, the system needs to be defined, set boundaries, and establish the context. It is also helpful to collect some historical information on similar designs. Secondly, the team initiates system structure analysis, during which the system is divided into measurable units and can be visualized using a functional block diagram (FBD). The system structure analysis is then carried on starting from higher hierarchical levels of the system to increase the time-efficiency of the analysis. During the third step, FMECA worksheets are prepared. Each system element shall include all the elements, functions, and operational modes and assess possible failures resulting in unacceptable system deviation. These worksheets include a semi-quantitative scale for assessing different components of the risk and the information on possible corrective actions, see Table 5.

Element	Function	Potential Failure mode	Failure cause	Effect	Risk matrix				Corrective action
					Fr	S	D	RPN	
Rotor	Energy conversion	Overheat	Inadequate ventilation Mechanical problems	Degraded performance	2	8	6	96	Monitoring Temp monitoring Insulation megger Dust cleaning
Stator	Energy conversion	Open/short circuit winding	Insulation breakdown Overcurrent Inadequate cooling system Voltage fluctuation	Shutdown	3	9	6	162	Monitoring Temp monitoring Insulation megger Dust cleaning

Table 5. Example of FMECA worksheet (Shanks, Hamad and Ameer, 2020).

The pre-last step consists of risk ranking and team review. The risk associated with failure modes can be presented using a risk matrix or (and) risk priority number (RPN), see Figure 19.



	1 Very unlikely	2 Remote	3 Occasional	4 Probable	5 Frequent
Catastrophic	🟨	🟥	🟥	🟧	🟧
Critical	🟩	🟨	🟨	🟥	🟧
Major	🟩	🟩	🟨	🟨	🟧
Minor	🟩	🟩	🟩	🟨	🟨

Figure 19. FMECA Risk matrix.

Like HAZOP, FMECA is suitable for the academic environment; however, its application in day-to-day operation could be limited due to the required relatively high time and expertise. Another drawback that cannot be omitted is the difficulty of identifying hazards with not defined failure modes, which can be difficult in an experimental setting, and the nature of some hazards. The lack of human error consideration essential for the research laboratories reduces the reliability of this method.

3.1.3 FTA

Bell Laboratories developed the Fault Tree Analysis on the Minuteman Guidance System (intercontinental ballistic system) (C. A. Ericson, 2005). The method was so successful that it spread from the military to a civilian branch of Boeing and across other industries (C. A. Ericson, 2005).

Contrary to the methods discussed above, this method is part of the family of quantitative methods and thus requires precise information. It is based on statistical, historical data and provides the user with exact calculation and estimation of the risk values. This method is used in the industries where reliability data is available, and there is a need for high-precision safety calculations, such as the nuclear power, aerospace, military, chemical, and oil & gas industries. The flexibility of the method is quite limited; however, some research has been done on its enhancement (Doytchev and Szwillus, 2009; Lavasani, Zendegani and Celik, 2015; Yan, Dunnett and Jackson, 2016). Some modifications of the method that made it applicable in an environment with limited data involved the introduction of Fuzzy logic (Markowski, Mannan and Bigoszewska, 2009) and a semi-quantitative approach (Hauptmanns, 2004).

FMECA is a detailed approach for analyzing complex systems or processes; FTA works well with simple systems. It becomes more difficult to apply within complex systems, see Table 6. Working well for a complete system, this method is less able to account for partial faults. For example, when an item of equipment in a complex system is at partial fault, FTA considers it a total fault. Such assumptions can lead to over-estimating the significance of actions, reducing the method's accuracy (Shanks, Hamad and Ameer, 2020).

Advantages	Drawbacks
Easy to perform and master	Very time consuming
A clear structure helps to focus on system elements and hazards.	Requires significant training and expertise in the method
Provides a reliability prediction of the item being analyzed	It can be challenging to apply to complex systems
Available commercial software	
Human error analysis is possible	
Visual representation of analysis	

Table 6. Advantages and disadvantages of FTA.

To start the analysis, the undesired top event is defined. FTA analysis is conducted using graphical representation and has a treelike structure. The basic symbols used in FTA are events, gates, and transfer symbols, see Table 7. Corresponding values of probabilities are usually depicted close to the events.

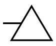
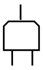
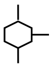
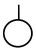
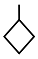
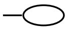
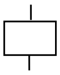
Symbols	Meaning
	Transfer-in
	Transfer-out
	AND gate
	OR gate
	Exclusive OR gate
	Priority AND gate
	Inhibit gate
	Basic event
	Incomplete event
	Conditional event
	Normal event
	Intermediate event

Table 7. FTA symbols (Waghmode, L. Y.; Patil, 2016).

Focus on events and the possibility of including different sources of errors makes this approach attractive for the research environment. Its clear and rigorous structure makes the assessment understandable for all the stakeholders and final users. However, the method is very resource and time-consuming, which is impossible for academia. Another significant drawback is the data requirement of the traditional method, which is not always possible. Casual event paths are not always apparent in the research environment, complicating tree generation.

3.1.4 ETA

Event tree analysis (ETA) can be traced to the nuclear power industry as a side product of FTA (C. A. Ericson, 2005). The purpose of this inductive method was to lower the complexity of failure tree analysis. ETA can be used to identify all potential accident scenarios and sequences in a complex system, see Table 8. EFA is often coupled with CFA, also called the bow-tie approach. Due to its quantitative nature, it is used in similar industries as CFA. The research proposed similar modifications to CFA to make this method more applicable in the environment with lower accessibility of data (Ferdous *et al.*, 2011; You and Tonon, 2012).

Advantages	Drawbacks
Easy to perform, master, and follow	It can be time consuming
Adequate performance on varying levels of design details	Requires significant training and practical experience
Models complex systems in a simple manner	
Available commercial software	Difficult to model timing and repair
Human error analysis is possible	Complicated to model multiple phases
Visual representation of analysis	

Table 8. Advantages and disadvantages of ETA.

ETA can be considered as the logical follow-up of CFA. It starts from the undesired event; the corresponding first sequence and following consequences are determined. Depending on the desired level of precision, several layers of pivotal events can be identified. These pivotal events are often associated with implemented safety barriers and describe associated functions. The corresponding probabilities are determined accordingly, see Figure 20. Based on the evaluations, additional improvements are suggested. Unanticipated events can be caused by: system or equipment failure, human error, or process upset.

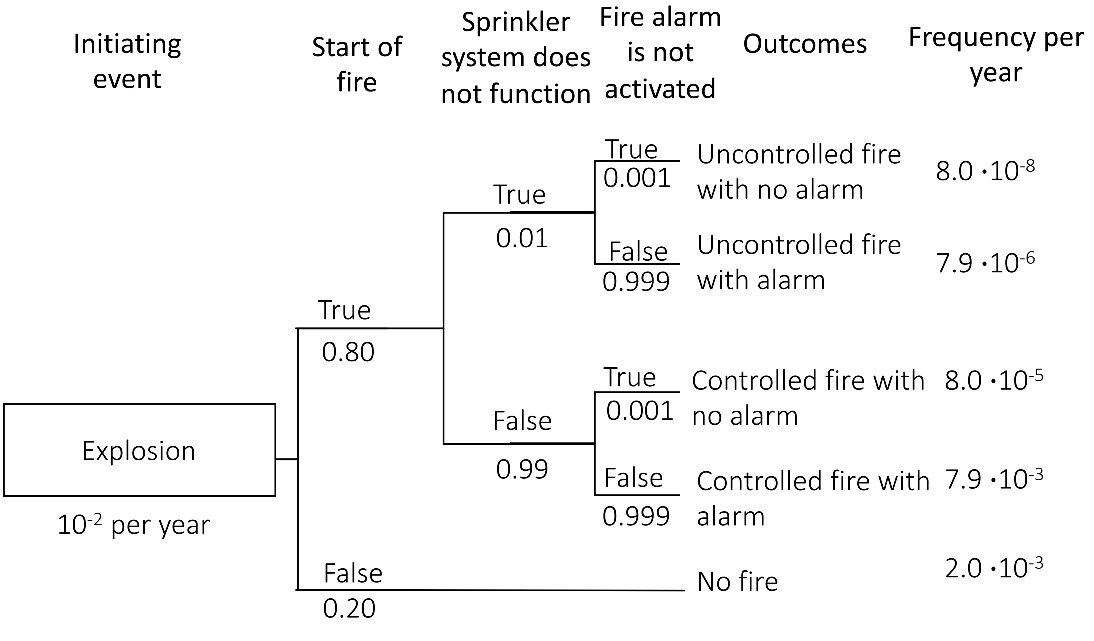


Figure 20. Example of ETA tree, taken from IEC 600300-3-9

Like FTA, Event Tree Analysis has some benefits for application in the research environment: good structure of the method makes it relatively easy to perform and learn; it allows to include human interactions in the analysis. Meanwhile, it is less complicated than FTA; the focus on consequences and safety measures is attractive in this result-oriented environment. However, some characteristics make the application of the method limited in academia: quantitative risk estimation and difficulty modeling dependent events.

3.1.5 Lab-HIRA

Lab-HIRA (Hazard Identification and Risk Analysis) was proposed by Leggett (Leggett, 2012a, 2012b) as the method specifically designed for chemical research laboratories. This method, for the moment, has a limited application; however, the software is available and can be acquired for implementation. This method includes the following steps: a preliminary hazard analysis called Chemical Hazard Review (CHR), an optional formal risk review based on the identified hazards, and the development and execution of risk mitigation measures.

The CHR is a characterization based on the properties of the chemicals and the corresponding synthesis. The physical properties of every chemical analyzed are determined at the beginning, such as boiling point, exposure limits, toxicology, autoignition temperature, etc. The second part focuses on the process's hazardous conditions: physical conditions, formation of hazardous functional groups, etc. Based on this information, hazardous elements are determined. This step constitutes a basic risk assessment. The second step of this method is optional. It is only recommended for hazardous elements from the previous step, which fall into a predefined risk category *as unacceptable*. Lab-HIRA suggests applying checklist-based methods or HAZOP for further in-depth analysis of risks. The third step is the development of corrective measures, which can be based either on step 1 or step 2.

This approach requires detailed information on the substances and can be complicated when the knowledge is still limited, which is often the case in a research environment. The requirements for the analyst are moderate, even though the expertise mainly focuses on system knowledge and expertise in the field of chemistry. It is focused solely on chemistry, which makes this method hardly applicable to other laboratories. On the other hand, preliminary hazard analysis draws attention to potentially more hazardous elements of the system and is helpful for the non-expert user.

3.1.6. Human errors

Accidents are a logical termination of a considerable number of incidents. Even though Heinrich's triangle has been widely criticized (Anderson & Denkl, 2010) (Johnson, 2001) due to its misinterpretation and abuse of the concept, partially in everyday routine, especially in research laboratories, this concept remains valid. Rasmussen (Rasmussen, 1982) developed a widely used skilled-rule-knowledge model of human factors, see Figure 21.

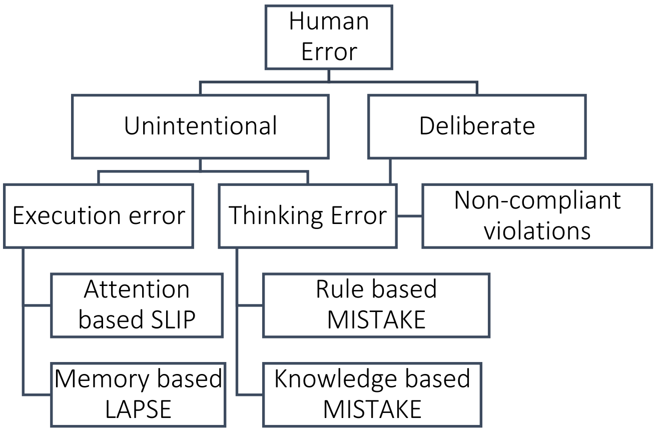


Figure 21. Types of human errors according to the Rasmussen model

Human Cognitive Reliability (HCR) decision tree (Hollnagel, 1998) connects some performance shaping factors, such as task characteristics and training, with possible error modes, see Figure 22. Downward branches of the tree correspond to a negative answer.

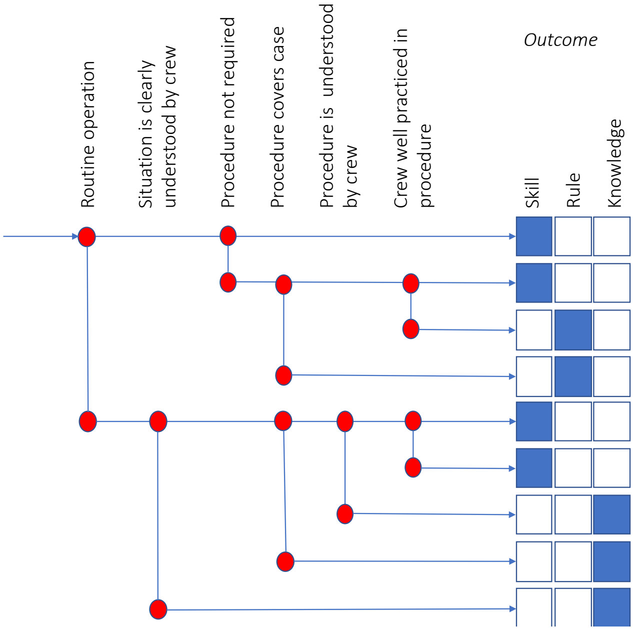


Figure 22. HCR decision tree connecting performance shaping factors and type of performance.

Cognitive stressors affect the human brain and lead to mistakes (Fischer, 2014). These mistakes usually result in near misses, which sometimes do and sometimes do not lead to incidents and further accidents, see Figure 23.

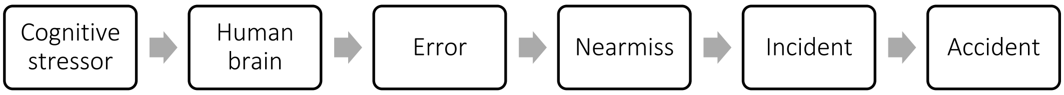


Figure 23. Effect of cognitive stressors on human cognition and evolution of accidents

Cognitive System Engineering (CSE) sees any human-machine interaction as a joint cognitive system (Hollnagel E. &., 1999). These systems are subject to environmental circumstances, resulting in a mismatch between cognition and working conditions (Massaiu, 2007). According to Hollnagel (Hollnagel E. , Human reliability analysis: context and control, 1993), human errors result from two influencing factors: human-machine mismatch and inherent human variability. Working environment conditions influence a person's cognitive state and affect attention, causing associative jumps and information forgetting.

According to Kirschner (Kirschner, 2002), three types of causal factors causing cognitive load can be identified. Paas & van Merriënboer (Paas, 1993) defined these factors as an operator's personal cognitive characteristics/abilities, properties of task, and surrounding environment. Thus, the factors assessed according to the proposed model are mental load, effort, and operator performance, plus three cognitive load factors (Figure 24).

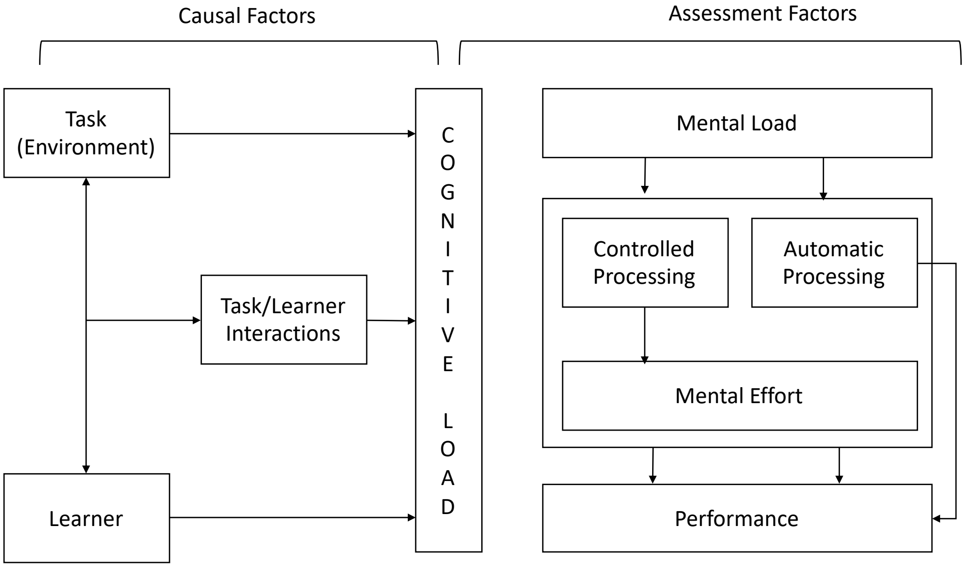


Figure 24. Factors determining the level of cognitive load (Kirschner, 2002).

The human brain has two types of memory: short-term or working memory (STM) and long-term memory (LTM) (Atkinson & Shiffrin, 1868). While the first one is a kind of "scratch-pad" used for temporary storing and processing information, LTM is responsible for learning and giving meaning to human actions. STM persists maximum of 30 seconds and can hold simultaneously only up to 7 items (Baddeley, 1994). Schema theory (Marshall, 1995) postulates that the brain stores knowledge in LTM schemata. Depending on the purpose and ways of use of such information, schemata categorize all new information differently (Chi, 1982). Information units can be integrated with schemata processing rules, thus leading to automation. Such automated information requires less time processing and cognitive control (Kirschner, 2002). Different types of tasks require a different amount of attention and focus. While performing actions requiring high skills or knowledge, we involve schemas with a complex hierarchy consisting of lower-level schemas. On the other hand, by performing simple repetitive actions, our brain atomically recalls familiar and more easily accessible schemata.

Cognitive load can be increased not only by a complication of the job and an increase in task number but by working conditions (Couffe C, 2017) (Jahncke H, 2011). Bad working cognitions affect physical ergonomics, which influence cognitive ergonomics and lead to mistakes caused by attention failures. However, lousy working conditions do not always result only in unintended mistakes and errors. Loud noise in the room, not comfortable working temperature, or poor lighting can bring high inconvenience to a person working in the laboratory. These will motivate him to leave the working space as quickly as possible, resulting in voluntary skipping check of equipment after work or leaving hazardous chemicals not in a proper place. Nevertheless, such situations are rare; a poor working environment substantially influences unintentional errors. Mearns and Flin (Mearns, 1995) proposed a socio-cognitive risk perception model, which connects hazard perception, personal behavior, and accidents, see Figure 25.

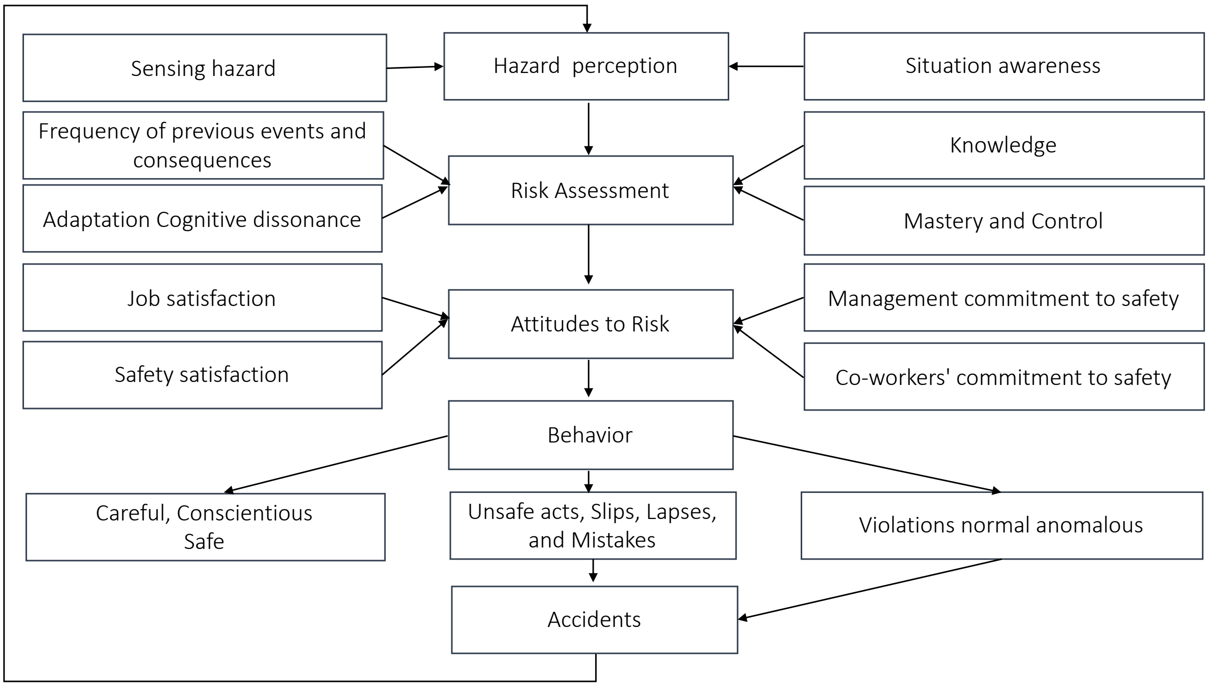


Figure 25. Mearns and Flin's (1995) socio-cognitive model of risk perception

Some factors mentioned in Mearns and Flin's risk perception model are incorporated into safety climate parameters. According to Dedobbeleer and Béland (Dedobbeleer, 1991) The following parameters constitute a safety climate:

- Management attitude towards safety practices
- Management attitude towards workers' safety
- Supervisors act to enforce safety
- Management safety activities – including safety instructions and availability of proper equipment

Causal Loop Diagram (CLD) proposed by Nardo (M. Di Nardo, 2015) connects organizational factors, physical environment, individual factors, and stress factors with human errors, see Figure 26.

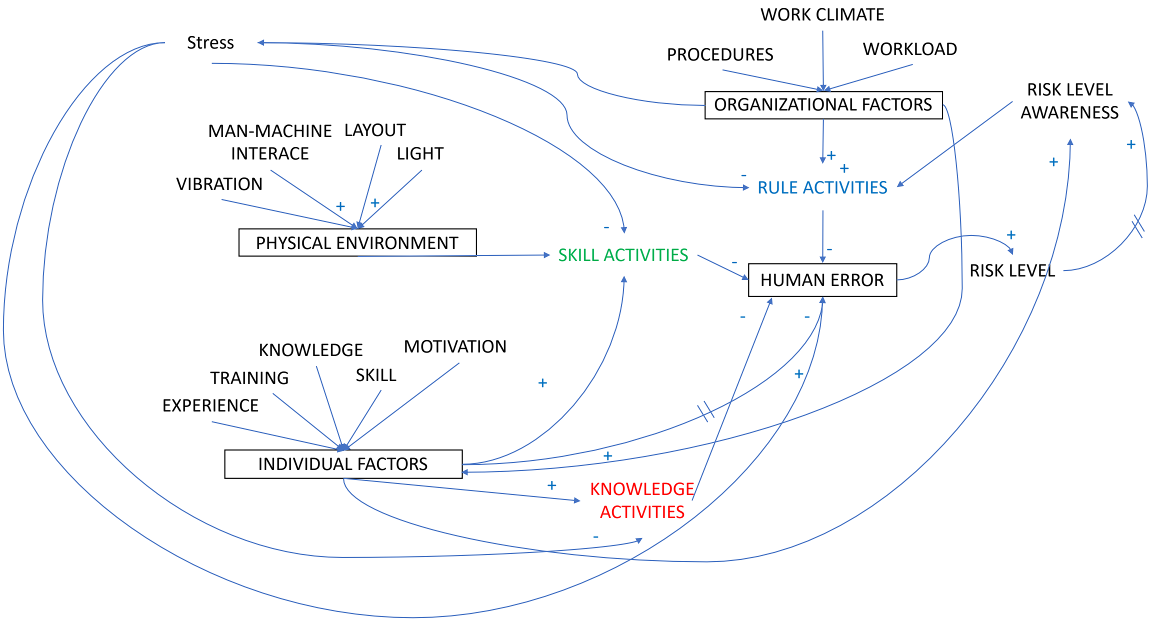


Figure 26. Causal effect diagram for human performance model

According to the authors, stress factors exist in the working environment and constitute psychological, physiological, and organizational events seen as stressful by an individual. Even though undoubtedly, all these factors play an essential role, it is almost impossible to estimate them considering the dynamic nature of activities and the individual's state. Depending on the type of activity, they can have different underlying reasons for human failures:

- Skilled-based Activity (SA) – Slip of Attention or Lack of Skills
- Knowledge-based Activity (KA) – Execution Mistake or Lack of Knowledge
- Rule-based Activity (RA) – Slip of Attention or Selection of Improper Rule

According to Brown (Brown, 1990). Attention Slip is the most spread type of mistake happening during SA. Long, multistep procedures are automated and lack cognitive control. They are easily influenced by external working conditions and the state of an individual. The most likely to make mistakes during RA, when too many overlapping or unclear rules are present. The last type of activity (KA) is vulnerable to an inaccurate and incomplete understanding of the process, personal overconfidence, mental fatigue, and wrong perception. According to the author, the probability of the error during different types of activities is following:

- SA – 67%
- RA – 27%
- KA – 11%

Memory performance is influenced by familiarity and supporting context (X. Ning, 2018). The performance model illustrates the connection of probability of an error in three types of activities, depending on attention and familiarity with the situation (Figure 27) (Swinton, 2018).

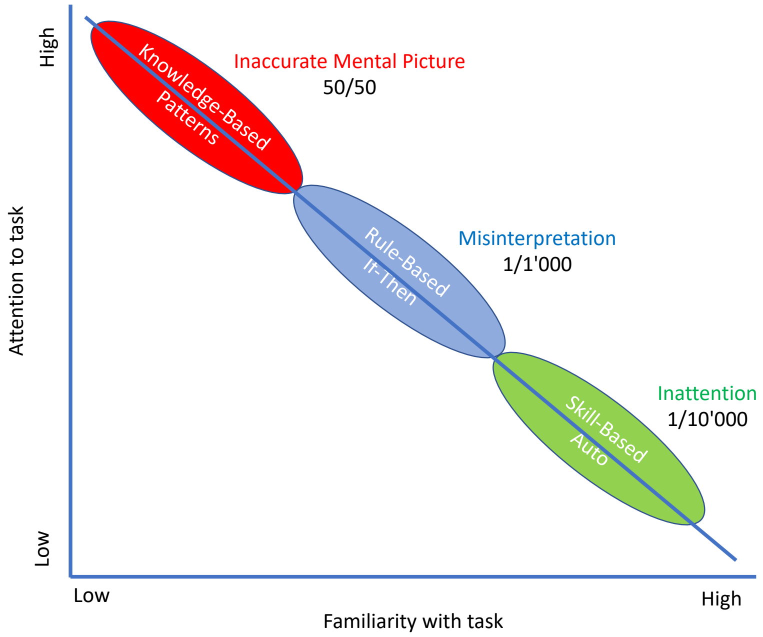


Figure 27.Performance Modes (Swinton, 2018).

The latest research on human error probability quantification (Sun Zhiqiang, 2009) demonstrated a relationship between behavior mode and interval of human error probability (HEP) Table 9.

Behavior Mode	Basic HEP interval	Basic HEP
SA	($5*10^{-5}$, $5*10^{-3}$)	$5*10^{-4}$
RA	($5*10^{-4}$, $5*10^{-2}$)	$5*10^{-3}$
KA	($5*10^{-3}$, 1)	$7*10^{-2}$

Table 9. Behavior modes and their probabilities (Sun Zhiqiang, 2009).

Combining the approach of three models, following the prediction model of failure shaping factors leading to accidents is proposed in Figure 28.

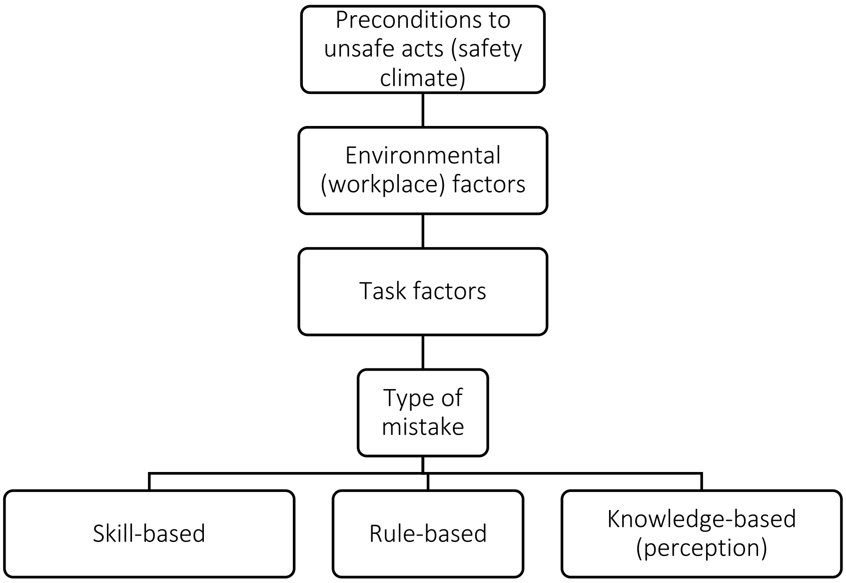


Figure 28.Failure shaping factors; general model.

Depending on the type of activity and human involvement, most failures can have either technical/equipment or human origin. Talking about human-related failures, we mainly focus on how to process characteristics that influence an individual's execution of the task. Some of these task factors are presented in Table 10. These factors have different probabilities depending on the type of possible human failure. The following table illustrates the type of failure contributing factor (FCF) and its corresponding value:

The human type of failures	FCF
Repetitiveness	$5*10^{-5}$
Complexity	$5*10^{-4}$
Physical complexity	$5*10^{-5}$
Specific knowledge is required	$5*10^{-3}$
Time-consuming process (mental fatigue)	$5*10^{-3}$
Time-consuming process (physical fatigue)	$5*10^{-5}$
Simultaneous procedures	$5*10^{-4}$
Procedures shall be performed fast	$5*10^{-5}$

Table 10. Task factors

Typically, when assessing the probability of failure (M. Havlikova, 2015) in human-machine (or equipment) systems, human and originating machine failures are considered, see Figure 29.

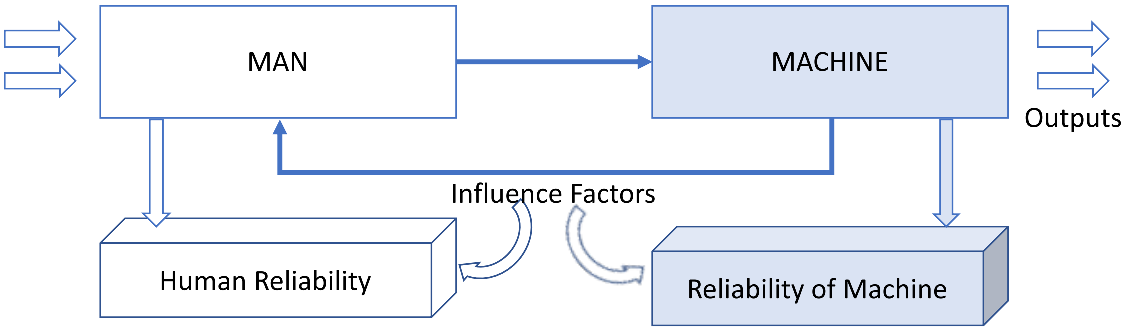


Figure 29. Human and technical reliability in MMS (M. Havlikova, 2015).

While, in most cases, even machine-related failures can have a hidden human reason (lack of maintenance, material fragility, etc.), the probability of such failures and human influence on the whole process is still lower. Some of the Machine/Equipment related factors influencing failure probability (Fred K. Geitner 2006):

- Inappropriate equipment/material 10^{-5}
- Complex design/construction 10^{-6}
- Sensitive design/construction 10^{-5}
- Fragile material 10^{-4}
- Requires constant maintenance 10^{-5}
- Requires constant control of the setup 10^{-5}
- In poor condition 10^{-4}
- Easily degrades 10^{-5}

Safety Climate also contributes to the failure. Having the role of precondition factor and shaping the perception and attitude of the team has a more substantial impact on the failure probability. Even when all other conditions are perfect, wrong perception and wrong attitude can lead to an accident. Power law can adequately connect some accidents (failures in our case) and workplace attitude (SC) (Mauro *et al.*, 2018). The formula proposed for the calculation of the failure probability (FP):

$$FP=HEP^{SC} \qquad \textit{Equation 1}$$

3.1.7. Safety Climate and Probability of an Accident

Safety Climate contribution is not only limited to the effect of efficiency but can contribute to the level of Risk. For example, laboratories with lower risk perception tend to more frequently violate safety rules and be less safe (Schroeder 2018). According to Zohar (Zohar, 2011), safety climate is both a leading and lagging indicator of incidents. The leading role is also supported by other research (Schneider and Reichers, 1983; Kuenzi and Schminke, 2009). Safety climate can be used to predict future incidents. Leading and lagging relationships are interdependent (Payne *et al.*, 2009). Safety climate and safety incidents are *dynamic.* They are each in constant, incremental adjustment relative to the other (Bergman *et al.*, 2014).

A straightforward inclusion of the Safety Climate parameter is rarely considered, as safety climate is usually treated separately; however, specific authors have proposed a model connecting safety climate and performance (E.A.Nadhim 2018, Curcuruto 2016). SC is also one of the main factors in human reliability analysis (S.C.Guedes 2010) and human error analysis (HSE (1999) Reducing error and influencing behavior, Hse.gov.uk. s.d.). Safety Climate also contributes to the failure. Having the role of precondition factor and shaping the perception and attitude of the team has a more substantial impact on the failure probability. Even when all other conditions are perfect, wrong perception and wrong attitude can lead to an accident. Power law can adequately connect a number of accidents (failures in our case) and workplace attitude (SC) (John C. Mauro, 2018):

$$N(x)=ax^{-k} \qquad \textit{Equation 2}$$

According to Seo (Seo, 2005), workers' perception of safety climate impacts safety behavior. Meanwhile, the safety index correlates linearly with worksite accidents and different safety climate dimensions (Laitinen, Marjamäki and Päivärinta, 1999). A direct correlation was found between HEP and employees' external and internal safety factors, which correlate with safety climate (Islam *et al.*, 2018). Some authors propose including work, social, task, and environmental factors using simple aggregation of weighted factors for Human Error Probability calculation (Samima and Sarma, 2021).

3.2 Multicriteria decision-making

We are making decisions every day and every moment of our life: deciding on daily activities, groceries, family and friend issues. Roy (1981) (Roy, 1981) identifies four types of decision problems daily that any person meets:

1. The problem of choice. It aims to identify the best option(s)from a given set.
2. The sorting problem. Options need to be categorized based on the same criteria.
3. The ranking problem. Available options must be ranked from best to worst (Ishizaka and Nemery, 2013).
4. The description problem. All options and their effects need to be described.

There are many different tools available in different industries. As was discussed in the introduction, safety decision-making is new to the academic sector. Thus, there is no literature available on this topic. Multicriteria decision-making (analysis) is one of the branches of operational research, focusing on resolving problems with several conflicting criteria impacting the evaluation of alternatives. It involves both quantitative and qualitative information. MCDM has been used in various fields, and occupational safety is one of the branches (Mardani *et al.*, 2015). The main issue of existing decision-making approaches and thus what differentiates them is the aggregation procedure for solving decision-making problems. Existing methods can be categorized using the following categories:

1. Full aggregation approaches (AHP, ANP, MAUT, MACBETH, etc.)
2. Outranking approaches (PROMETHEE, ELECTRE, etc.)
3. Goal, aspiration, or reference-level approach

Despite different approaches, any decision-making model's ultimate goal is to identify the most beneficial (optimal) for the organization/individual option from available. Existing methods can be classified into two main categories: discrete MCDM and continuous Multi-objective Decision-Making. In the first case, we are dealing with a limited number of alternatives, and the decision-aiding tool is required to help us to create a rating of the best alternatives. In the second case, a tool is required to help with design and planning to derive an optimal solution depending on the existing goals.

Three main patterns can be deemed as founding for any MCDM. Making a good decision means that there is no other which may be better in some aspects and not worse in every consideration. "Simple ordering" leads to Pareto Optimality and nondominated solutions (Wierzbicki, 2015). The second pillar is the human goal-seeking behavior, which results in the ultimate search for satisfying and compromising these goals and solutions. The last one is value maximization, which brings the need to study value function. Safety decision-making falls in the first category; in most cases, a number of possible safety alternatives will be limited, and the decision-maker needs to select among them. Ranking of individual alternatives or combined sets is meant to ease the selection procedure.

Most MCDM methods are based on what can be called intuitive, subjective ranking, which can be done using the experience of the decision-maker and his/her intuition. On the other hand, the "objective method" or, more correctly, the rational subjective method is based on the relevant decision case data and uses an approximation of personal preferences.

Decision-making is flown by various biases: conservatism, confirmation, recency, etc. Some decision-makers might be aware of them. Others will have blind-spot bias. Decision support systems are meant to reduce these biases. In reality, different optimization techniques help a decision-maker and are expected to provide a rational ranking of the alternatives, which is not impacted by personal preferences. A certain degree of objectivity is necessary as the decision will affect many people. Thus, their objectives need to be considered.

This chapter is aimed to provide information on some methods frequently used in the decision-making field to solve problems similar to the objective of this thesis. Similarly, to the 3.1 not all the methods discussed in this chapter were used to solve the research problem.

3.2.1 Fuzzy Analytical Hierarchy Process

Even if a person assessing something is considered an expert, some information cannot be assessed precisely, or results may vary depending on the context. An expert's opinion may vary depending on the context and individual perception. In a world where information is uncertain, deficient, incomplete, and sometimes contradictory fuzzy logic is used (Hamza, Yap and Choudhury, 2017) to make qualitative judgments about parameters having quantitative nature. Fuzzy logic is meant to handle different uncertainties (Zadeh, 1965); however, these uncertainties can differ. The first type can be internal uncertainties of the expert, who is probably not confident about the value he/she is assigning, thus a secureness level about his/her evaluation. Another type is external uncertainty which represents the lack of objective knowledge about a particular parameter or inconsistency due to external events (Volz, Schubotz and Von Cramon, 2004). Using the Fuzzy scale allows us to consider that most experts are biased in a certain way; however, it does not allow us to distinguish between the effect of these biases and the evaluation quality of different experts.

The analytical hierarchy process (AHP) was developed by Saaty (Saaty, 1977). This method has been widely used for decision-making applications in different fields (Vaidya and Kumar, 2006). This method has three main steps: constructing a pair-wise comparison matrix, synthesis of judgments, and test of consistency. Despite its wide application, the method has various drawbacks:

1. AHP relies on crisp judgments, which are not always realistic (Wang, Luo and Hua, 2008).
2. The actual mechanism of human decision-making can hardly be reflected due to the subjectivity of the choices (Abd, Abhary and Marian, 2017).
3. The method is unsuitable when information is uncertain and ambiguous (Shyjith, Ilangkumaran and Kumanan, 2008).

Combing AHP with Fuzzy set theory allows us to overcome some of these limitations (Özdağoğlu and Özdağoğlu, 2007). The fuzzy Analytical Hierarchy Process is widely used in Risk Management and Decision-Making (Peng *et al.*, 2021). FAHP, similar to AHP, includes three main steps: construction of a fuzzy comparison matrix, synthesis of judgments, and consistency test.

A. In the first step, a fuzzy matrix (A) is constructed from i'j, where i and j are the number of criteria (n). A=$\left[\tilde{a}_{ij}\right]_{n\times n}$is a preference matrix, such as $\tilde{a}_{ij}$=($\tilde{a}_{ij}^{l}$, $\tilde{a}_{ij}^{m}$, $\tilde{a}_{ij}^{n}$) is a triangular fuzzy number (TFN), a_{ij} represents the linguistic value of comparing criterion i to j:

$$A=\begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1j} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2j} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{a}_{i1} & \tilde{a}_{i2} & \cdots & \tilde{a}_{ij} \end{bmatrix} \quad \textit{Equation 3}$$

1) Using TFN, linguistic values are determined, denoted as (l,m,n), where l,m represent the smallest, most promising, and the largest value of comparing criterion i and j. Thus, $\tilde{a}_{ij} = \tilde{a}_{ij}^{-1} = (l_{ij},m_{ij},n_{ij})^{-1} = (\frac{1}{n_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}})$ and , $\tilde{a}_{ij} = (1,1,1)\ when\ i = j$:

$$A=\begin{bmatrix} (1,1,1) & (l_{12},m_{12},n_{12}) & \cdots & (l_{1j},m_{1j},n_{1j}) \\ (\frac{1}{n_{21}},\frac{1}{m_{21}},\frac{1}{l_{21}}) & (1,1,1) & \cdots & (l_{2j},m_{2j},n_{2j}) \\ \vdots & \vdots & \cdots & \vdots \\ (\frac{1}{n_{i1}},\frac{1}{m_{i1}},\frac{1}{l_{i1}}) & (\frac{1}{n_{i2}},\frac{1}{m_{i2}},\frac{1}{l_{i2}}) & \cdots & (1,1,1) \end{bmatrix} \quad \textit{Equation 4}$$

2) On the contrary, to AHP, instead of having one value for evaluating the criteria fuzzy triangle is used (Sharp and Hall, 2009) Figure 30.

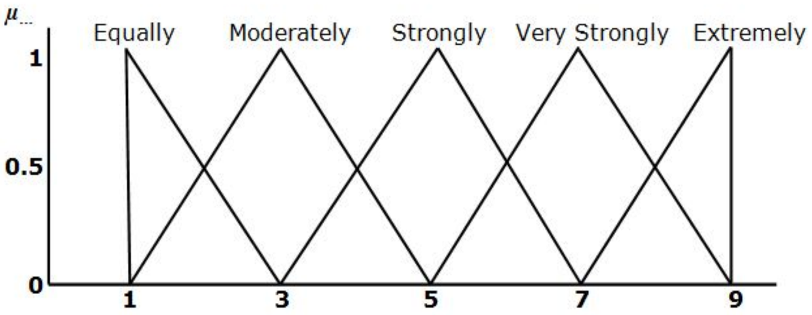


Figure 30. Linguistic variables for the importance of each criterion (Kabir, Golam, 2011).

Therefore, each value of a traditional AHP has a corresponding triangular fuzzy scale, see Table 11.

Linguistic scale for the importance	Fuzzy number	Triangular fuzzy scale(l,m,n)
Just equal	1	(1,1,1)
Weakly important	3	(1,5,7)
Essential	5	(3,5,7)
Very strongly important	7	(5,7,9)
Extremely preferred	9	(7,9,9)

Table 11. Linguistic variables describe the weights and values of ratings.

The example of comparison matrix for six criteria represented in table below.

CRI	C1	C2	C3	C4	C5	C6
C1	1.00 1.00 1.00	0.20 0.14 0.11	1.00 5.00 7.00	0.33 0.20 0.14	0.14 0.11 0.11	1.00 0.20 0.14
C2	5.00 7.00 9.00	1.00 1.00 1.00	5.00 7.00 9.00	0.20 0.14 0.11	0.33 0.20 0.14	1.00 0.20 0.14
C3	1.00 0.20 0.14	0.20 0.14 0.11	1.00 1.00 1.00	0.14 0.11 0.11	0.14 0.11 0.11	1.00 0.20 0.14
C4	3.00 5.00 7.00	5.00 7.00 9.00	7.00 9.00 9.00	1.00 1.00 1.00	0.33 0.20 0.14	0.33 0.20 0.14
C5	7.00 9.00 9.00	3.00 5.00 7.00	7.00 9.00 9.00	3.00 5.00 7.00	1.00 1.00 1.00	1.00 5.00 7.00
C6	1.00 5.00 7.00	1.00 5.00 7.00	1.00 5.00 7.00	3.00 5.00 7.00	1.00 0.20 0.14	1.00 1.00 1.00

Table 12. Comparison table for the FAHP for six criteria, collected from the safety expert.

B. In the second step, the fuzzy synthetic extent is calculated, where:

$$S_i=\sum_{ij}^{m} \tilde{a}_{ij} \times \left[\sum_{i=1}^{n}\sum_{j=1}^{m} \tilde{a}_{ij}\right]^{-1} \quad \textit{Equation 5}$$

And $\sum_{j=1}^{m} \tilde{a}_{ij}$ is obtained from fuzzy addition operation of m extent analysis value for a matrix such as:

$$\sum_{j=1}^{m} \tilde{a}_{ij} = \sum_{j=1}^{m} l_j , \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} n_j \quad \textit{Equation 6}$$

And $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} \tilde{a}_{ij}\right]^{-1}$ is obtained from the fuzzy operation of $\tilde{a}_{ij} = (j = 1,2,\dots,m)$ values that:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} \tilde{a}_{ij}=\left(\sum_{j=1}^{m} m_j, \sum_{j=1}^{m} n_j\right) \quad \textit{Equation 7}$$

1) The vector is computed:

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} \tilde{a}_{ij}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} n_{ij}}, \frac{1}{\sum_{i=1}^{n} m_{ij}}, \frac{1}{\sum_{i=1}^{n} l_{ij}}\right) \quad \textit{Equation 8}$$

2) Afterwards, fuzzy values are compared. Since $\tilde{a}_2$ and $\tilde{a}_1$ are two fuzzy triangular numbers, see Figure 30, the possibility that $\tilde{a}_2(l_2,m_2,n_2) \geq \tilde{a}_1(l_1,m_1,n_1)$ will be defined:

$$V(a_2 \geq a_1) = SUP_{X \geq Y}\left[\min\left(\mu_{a_1}(x), (\mu_{a_2}(y)\right)\right] = hgt\ (a_1 \cap a_2) = \mu_{a_2}(d) \quad \text{Equation 9}$$

Where d is the ordinate of the highest intersection point, see Figure 31 between μ_{a_1} and μ_{a_2}:

$$\mu_{a_2}(d) = \begin{cases} 1, m_2 \geq m_1 \\ 0, l_2 \geq l_1 \\ otherwise\ \frac{l_2 - n_2}{[(m_2 - n_2) - (m_1 - l_1)]} \end{cases} \quad \text{Equation 10}$$

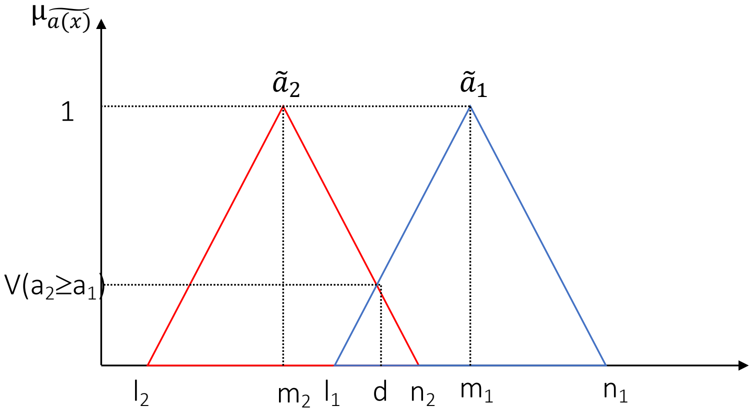


Figure 31. Interaction between points a_1 and a_2.

3) To calculate priority weights, we assume that degree of possibility for a convex fuzzy number to be greater than k convex fuzzy number a_i(i=1,2,…,k):

$$V(a \geq a_1, \ldots, a_k) = V\,[(a \geq a_1) \text{and} \ldots (a \geq a_k)] = \min V\,(a \geq a_i),\ i = 1,2,\ldots k. \quad \text{Equation 11}$$

4) Assuming that the weight vector is:

W'=$\{d'(C_1), d'(C_2), \ldots, d'(C_n),\}^T$, where C_1, C_2, …,C_n are n criteria.

In case of an example demonstrated in Table 12 the weight vectors will look as follows:

CRI	*Wi*		
C1	0.042	0.039	0.047
C2	0.099	0.083	0.102
C3	0.036	0.021	0.024
C4	0.137	0.156	0.203
C5	0.251	0.474	0.743
C6	0.109	0.228	0.357

Table 13. Weight vectors for six criteria. FAHP, example of calculation.

Then, the normalized weight vector is calculated, as in Table 14.

CRI	Averaged weight vector	Normalized weight vector	Rank
C1	0.043	0.041	5
C2	0.094	0.090	4
C3	0.027	0.026	6
C4	0.165	0.157	3
C5	0.489	0.466	1
C6	0.232	0.220	2

Table 14.Normalized weight vectors for six criteria. FAHP, an example of calculation.

C. The last step involves the consistency test, which involves consistency ratio (CR) calculation, which is done in three steps:

   1) Compute the maximum eigenvalue by calculating of consistency value of each row, which summation is divided by n.
   2) Calculation of consistency index (CI).
   3) The consistency ratio is calculated by dividing CI by the random index (RI)(Abd, Abhary and Marian, 2017).

To test applicability of the method as a part of a decision aiding block in LARA+D, it was used to estimate the weights of non-financial factors. In order to obtain weights, a pool of 10 experts working in the Safety Competence Center was identified. Questions, see Attachment A4 were distributed. Due to the different backgrounds and personal preferences judgments of the experts were different. However, eliminating some of the inconsistent results, which also varied from the average, more than 10% weights of each criterion were obtained. After evaluation of all expert's opinions following distribution of weights has been obtained:

Criteria:	Weight:
Simplicity	0.179
Acceptability	0.211
Compatibility with the surrounding environment	0.218
Compatibility with the process	0.392

Table 15. Relative weights for non-financial factors

3.2.2 Fuzzy TOPSIS

TOPSIS (Technique for Order of Preferences by Similarity to Ideal Solution) was initially developed by Hwang and Yoon (Hwang and Yoon, 1981). The method aims to select alternatives that are closest and farthest from ideal and worst points. It has similar limitations as AHP. Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (FTOPSIS) is often used in decision making as quick optimization of the results and their ranking representation based on the similarity of the alternative to the ideal solution. Instead of crisp numbers, similarly to FAHP, fuzzy values are used. The main steps of the FTOPSIS involve:

1) Establish a fuzzy decision matrix:

$$\tilde{D} = \begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{pmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{pmatrix} \end{array}$$ *Equation 12*

Where the elements $\bar{x}_{11}=(l\bar{x}_{11}, m\bar{x}_{11}, u\bar{x}_{11})$ are represented by linguistic variables, i corresponds to criterion index and j to alternative. $C_1,C_2,\ldots,C_n$ are criteria and $A_1,A_2,\ldots,A_m$ alternatives, see Table 16.

	C1			C2			C3			C4			C5			C6		
A1	3	5	7	7	9	9	7	9	9	7	9	9	7	9	9	1	3	5
A2	5	7	9	3	5	7	5	7	9	7	9	9	3	5	7	1	3	5
A3	3	5	7	7	9	9	3	5	7	7	9	9	7	9	9	3	5	7
A4	5	7	9	5	7	9	7	9	9	7	9	9	7	9	9	1	3	5
A5	7	9	9	3	5	7	3	5	7	3	5	7	3	5	7	1	3	5
A6	3	5	7	1	5	7	3	5	7	3	5	7	3	5	7	1	5	7
A7	3	5	7	3	5	7	7	9	9	5	7	9	5	7	9	1	5	7
A8	7	9	9	5	7	9	5	7	9	5	7	9	7	9	9	1	3	5
A*	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
A-	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 16. Decision matrix for 6 criteria (C) and 8 alternatives (A). An example, FTOPSIS.

2) Normalize the fuzzy decision matrix:

$$\tilde{R} = \left[r_{ij}\right]_{m\times n}$$ *Equation 13*

3) Compute the weighted decision matrix:

$$\tilde{v}_{ij}= \left[\tilde{v}_{ij}\right]_{m\times n} \tilde{r}_{ij} \otimes \tilde{w}_j=(l\tilde{r}_{ij}, m\tilde{r}_{ij}, n\tilde{r}_{ij}) \otimes (l\tilde{w}_j, m\tilde{w}_j, n\tilde{w}_j) \qquad \textit{Equation 14}$$

Where weights and corresponding fuzzy values are determined using TFN as in FAHP

4) Determine the positive- and negative-ideal solution and distance of each alternative using the closeness coefficient:

$$C_i= \frac{d_j^-}{d_j^+ + d_j^-} d_i^- / (d_i^- + d_i^+), \ i=1,2,\dots, m \qquad \textit{Equation 15}$$

Where $d_{ij}^+=\sum_{j=1}^{n} d\left(\tilde{v}_{ij} - \tilde{v}_j^+\right)$ with $\tilde{v}_{ij}^+=(9,9,9)$ and $\tilde{v}_{ij}^-(1,1,1)$ distances from the positive ideal solution $A^+=\left\{\tilde{v}_1^+, \tilde{v}_2^+, \dots, \tilde{v}_j^+\right\} = \left\{\left(max_i v_{ij} \middle| i = 1,2,\dots,m\right), j = 1,2,..n\right\}$ (Krohling and Pacheco, 2015). Distance from the negative solution A^- is calculated in the same way, see Table 17.

Di*	Di-	Cci	Rank	Alternative
0.0367	0.0753	0.6725	2	A1
0.0544	0.0480	0.4685	8	A2
0.0276	0.0774	0.7369	1	A3
0.0368	0.0751	0.6712	3	A4
0.0550	0.0467	0.4590	7	A5
0.0528	0.0491	0.4819	6	A6
0.0401	0.0658	0.6210	5	A7
0.0369	0.0748	0.6696	4	A8

Table 17. Closeness coefficient and ranking for 8 alternatives (A). An example FTOPSIS.

3.2.3 ELECTRE

Elimination and Choice Translating Reality or “ELimination Et Choix TRaduisant la REalité" (ELECTRE) is the method that was introduced by (Benayoun, Roy and Sussman, 1966). As mentioned above, this method belongs to the group of outranking methods and uses pair-wise comparison for alternatives separately under each criterion (Triantaphyllou, 2000). This method, like any other, has its benefits and drawbacks. First, it allows users to deal with qualitative information and use different scales simultaneously. Secondly, it considers the user's limited knowledge during the construction of criteria, which is achieved by discriminating thresholds (Figueira *et al.*, 2013). The method's main disadvantage is the instability of the results, which can result in rank reversal if the set evolves. Moreover, the use of ELECTRE methods can result in intransitivity. However, there is no "right" decision, and the purpose of the decision aiding tool is to help find one of the potentially best solutions.

This method includes seven main steps:

A. Normalize decision matrix:

$$X=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad \textit{Equation 16}$$

Where $x_{ij}=\frac{a_{ij}}{\sqrt{\sum_{k=1}^{m} a_{kj}^2}}$ is the normalized preference measure of the i-th alternative in terms of j-th criterion, m number of alternatives, and n number of criteria, see Table 18

	C1	C2	C3	C4
A1	0.130188911	0.21320072	0.413802944	0.10153462
A2	0.520755644	0.53300179	0.413802944	0.40613847
A3	0.390566733	0.42640143	0.413802944	0.10153462
A4	0.260377822	0.31980107	0.413802944	0.50767308
A5	0.260377822	0.21320072	0.165521178	0.20306923
A6	0	0.21320072	0.331042355	0.50767308
A7	0	0.10660036	0.082760589	0

Table 18. Normalized decision matrix for 7 alternatives (A) and 4 criteria (C), with the initial scale 1-5. An example, ELECTRE.

B. Weighting the Normalized matrix:

$$Y=\begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix}=\begin{bmatrix} \omega_1 x_{11} & \omega_2 x_{12} & \cdots & \omega_n x_{1n} \\ \omega_1 x_{21} & \omega_2 x_{22} & \cdots & \omega_n x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \omega_1 x_{m1} & \omega_2 x_{m2} & \cdots & \omega_n x_{mn} \end{bmatrix} \quad \textit{Equation 17}$$

$$\text{Where } W=\begin{bmatrix} \omega_1 & 0 & \cdots & 0 \\ 0 & \omega_1 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & \omega_n \end{bmatrix} \text{ and } \sum_{i=1}^{n} \omega_i = 1. \quad \textit{Equation 18}$$

The corresponding weights $(\omega_1, \omega_2, \dots, \omega_n)$ are determined by the decision-maker (Table 19):

ω	0.43	0.3	0.1	0.17
	C1	C2	C3	C4
A1	0.05598123	0.06396021	0.04138029	0.01726088
A2	0.22392493	0.15990054	0.04138029	0.06904354
A3	0.1679437	0.12792043	0.04138029	0.01726088
A4	0.11196246	0.09594032	0.04138029	0.08630442
A5	0.11196246	0.06396021	0.01655212	0.03452177
A6	0	0.06396021	0.03310424	0.08630442
A7	0	0.03198011	0.00827606	0

Table 19. Weighted matrix for 7 alternatives (A) and 4 criteria (C), with the initial scale 1-5 and corresponding weights (ω). An example, ELECTRE.

C. Determine Concordance and Discordance Sets.

Concordance set C_{kl} of two alternatives A_k and A_l where $m \geq k$, $l \geq 1$ is defined as the set of all the criteria for which A_k is preferred to A_l, and the following shall be true:

$$C_{kl} = \{j, y_{kj} \geq y_{lj}\} \text{ for } j=1,2,3,\dots,n \quad \textit{Equation 19}$$

The discordance set is calculated in the opposite way:

$$D_{kl} = \{j, y_{kj} < y_{lj}\} \text{ for } j=1,2,3,\dots n. \quad \textit{Equation 20}$$

D. Construction of concordance and discordance matrices:

$$C=\begin{bmatrix} - & c_{12} & c_{13} & \cdots & c_{1m} \\ c_{21} & - & c_{23} & \cdots & c_{2m} \\ \vdots & c_{32} & - & \cdots & \vdots \\ c_{m1} & c_{m2} & c_{m3} & \cdots & - \end{bmatrix} \quad \textit{Equation 21}$$

Where $C_{kl}=\sum_{j \in C_{kl}} \omega_j$ is the concordance index for $j=1,2,3,\dots,n$ and $0 \leq c_{kl} \leq 1$. When $k=l$, the entries of matrix C are not defined, see Table 20.

	A1	A2	A3	A4	A5	A6	A7
A1	0	0.53	0.27	0.1	0.4	1	1
A2	1	0	1	0.83	1	1	1
A3	1	0.1	0	0.83	1	0.83	1
A4	1	0.27	0.27	0	1	1	1
A5	0.9	0	0.17	0.43	0	0.43	1
A6	0.47	0.17	0.17	0.17	0.57	0	1
A7	0	0	0	0	0	0	0

Table 20. Concordance matrix for 7 alternatives (A) and 4 criteria (C), with the initial scale 1-5. An example, ELECTRE.

Discordance matrix demonstrates that a certain alternative A_k is worse to a certain degree than A_l:

$$D=\begin{bmatrix} - & d_{12} & d_{13} & \cdots & d_{1m} \\ d_{21} & - & d_{23} & \cdots & d_{2m} \\ \vdots & d_{32} & - & \cdots & \vdots \\ d_{m1} & d_{m2} & d_{m3} & \cdots & - \end{bmatrix} \quad \textit{Equation 22}$$

$$\text{Where } d_{kl} = \frac{\max_{j\in D_{kl}} |y_{kj}-y_{lj}|}{\max_{j} |y_{kj}-y_{lj}|} \quad \textit{Equation 23}$$

Similar to the concordance matrix, the entries of D are not defined when k=l, see Table 21

	A1	A2	A3	A4	A5	A6	A7
A1	0.0000	1.0000	1.0000	1.0000	2.2547	1.0000	1.0000
A2	1.0000	0.0000	1.0000	0.1542	1.0000	0.0771	1.0000
A3	1.0000	1.0000	0.0000	1.0000	1.0000	0.4111	1.0000
A4	1.0000	1.0000	0.8108	0.0000	1.0000	1.0000	1.0000
A5	1.0000	1.0000	1.0000	1.0000	0.0000	0.4625	1.0000
A6	0.8108	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
A7	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000

Table 21. Discordance matrix for 7 alternatives (A) and 4 criteria (C), with the initial scale 1-5. An example, ELECTRE.

E. Determine the Concordance and Discordance Dominance Matrices:

The concordance dominance matrix uses a predefined threshold value. It means that A_k can dominate A_l if its concordance matrix $C_k \geq \underline{C}$. Where C is the average concordance index:

$$\underline{C}=\frac{1}{m(m-1)}\sum_{\substack{k=1\\ and k\neq 1}}^{m} \sum_{\substack{k=1\\ and\ l\neq k}}^{m} c_{kl} \quad \textit{Equation 24}$$

The elements of concordance dominance matrix F are determined:

$$f_{kl}=1, \text{ if } C_{kl}\geq \underline{C}$$

$$f_{kl}=0,\ if\ C_{kl}\leq \underline{C}$$

Discordance dominance matrix G is determined similarly:

$$\underline{d}=\frac{1}{m(m-1)}\sum_{\substack{k=1\\ and k\neq 1}}^{m}\ \sum_{\substack{k=1\\ and\ l\neq k}}^{m} d_{kl} \qquad \text{Equation 25}$$

$$g_{kl}=1,\ if\ d_{kl}\geq \underline{d}$$
$$g_{kl}=0,\ if\ d_{kl}\leq \underline{d}$$

F. Determine the Aggregated Dominance Matrix:

$$e_{kl}= f_{kl}\times g_{kl} \qquad \text{Equation 26}$$

	A1	A2	A3	A4	A5	A6	A7
A1	0	0	0	0	0	1	1
A2	1	0	1	0	1	0	1
A3	1	0	0	1	1	0	1
A4	1	0	0	0	1	1	1
A5	1	0	0	0	0	0	1
A6	0	0	0	0	0	0	1
A7	0	0	0	0	0	0	0

Table 22.Aggregated dominance matrix for 7 alternatives (A) and 4 criteria (C), with the initial scale 1-5. An example, ELECTRE

G. Eliminate the less favorable alternatives. Using aggregated dominance matrix, a partial preference ordering can be obtained. If e_{kl}=1 means that $A_k$is preferred over A_l using both concordance and discordance criteria. If any column of aggregated dominance matrix has at least one element equal, this column may be eliminated (Triantaphyllou, 2000). Thus, for an example illustrated in Table 18 - Table 22, the following preference will be valid: A2=A3=A4>A5=A1>A6>A7

3.2.4 Two-reference "objective method."

The majority of approaches in MCDM are based on what can be considered a "subjective" ranking. Personal experience, thinking paradigms, memory, etc. Contrary to social sciences, managerial disciplines perceive objectivity as something attainable, despite its constraints (Wierzbicki, 2015). It is considered the limitations of the measurements and approximation of the true state of nature that have been discussed since the works of Heisenberg (Heisenberg, 1927).

Several assumptions are made and need to be considered during the application of this method.

1. The reference point approach assumes that specifications of the decision-maker preferences should be as general as possible. More detailed specifications would violate the right of the decision-maker to change his/her mind.
2. The general specifications contain a selection of criteria or objectives, which is accompanied by defining a partial order in the space of criteria (maximization or minimization).
3. Reference points or desired levels of criteria might be double, interval-type. They include aspiration and reservation levels, thus desirable and undesirable points for criteria. These reference points serve as an alternative to trade-off or weighting coefficients used by other MCDM methods. Later use is undesirable due to the linear representation of preferences and unbalanced decisions (Nakayama, 1995; Ruiz, Luque and Cabello, 2009).
4. The reference level approach implies the possibility of learning for decision-maker, which is possible during interaction with a decision support system. The latter is possible as utility or value function identification is not required.
5. Instead of a nonlinear value function, the preferences are approximated using the achievement function, which can be interpreted as a measure of the decision maker's satisfaction with the value of i-th criteria (Ogryczak, 2006). Ad hoc is a nonlinear approximation of the value function, which contains information on the partial order of criteria and the position of reference points (Wierzbicki, 2015).
6. This form of nonlinear approximation of the value function is determined by max-min terms, favoring solutions with balanced deviations from reference points. These max-min terms are corrected using regularizing coefficients and result in nondomination (Pareto optimality) of alternatives with maximization of achievement functions. Thus, for all discrete problems decision maker can select any nondominated alternative if reference points are modified, leading to high flexibility (Wierzbicki, 2015).

Decision-making problem with *n* criteria, indexed by *i=1,2,..n* and *m* alternatives, indexed by *j=1,2,..m* can be represented as follows:

$$\max_{j \in J} q_{ij} = q_i^{up} \qquad \textit{Equation 27}$$

	C1	C2	C3	C4	C5	C6	C7
Initial	9	0	-	-	-	-	
A1	-7 ($q_{1,1}$)	2 ($q_{1,2}$)	54($q_{1,3}$)	100($q_{1,4}$)	0($q_{1,5}$)	-1’500($q_{1,6}$)	-1
A2	-6.5($q_{2,1}$)	2.5 ($q_{2,2}$)	80($q_{2,3}$)	100($q_{2,4}$)	-250($q_{2,5}$)	-2’000($q_{2,6}$)	-2
A3	-5.5($q_{3,1}$)	3.5 ($q_{3,2}$)	48($q_{3,3}$)	100($q_{3,4}$)	-6’500($q_{3,5}$)	-2’000($q_{3,6}$)	-1
A4	-5 ($q_{4,1}$)	4 ($q_{4,2}$)	66($q_{4,3}$)	100($q_{4,4}$)	-6’750($q_{4,5}$)	-2’500($q_{4,6}$)	-1
A5	-6.5($q_{5,1}$)	2.5($q_{5,2}$)	45($q_{5,3}$)	100($q_{5,4}$)	-4’000($q_{5,5}$)	-500($q_{5,6}$)	-3
A6	-4.5($q_{6,1}$)	4.5($q_{6,2}$)	49($q_{6,3}$)	70($q_{6,4}$)	-25’5000($q_{6,5}$)	-100($q_{6,6}$)	-2
A7	-7 ($q_{7,1}$)	2($q_{7,2}$)	42($q_{7,3}$)	100($q_{7,4}$)	-7’500($q_{7,5}$)	-350($q_{7,6}$)	-2
A8	-6.5($q_{8,1}$)	2.5($q_{8,2}$)	62($q_{8,3}$)	100($q_{8,4}$)	-3’000($q_{8,5}$)	-1000($q_{8,6}$)	-2
A9	-7($q_{9,1}$)	2($q_{9,2}$)	74($q_{9,3}$)	80($q_{9,4}$)	-1’500($q_{9,5}$)	-150($q_{9,6}$)	-2

Table 23. Decision matrix for 9 alternatives (A) and 7 criteria (C). An example, Two-reference method.

a) After the specifications of aspiration and reservation levels, a_j and $_{RJ}$ for each criterion, a nonlinear aggregation of criteria by an achievement function is performed. To calculate individual achievement functions, each criterion is transformed to take into account satisfaction with its values:

$$\sigma_i(q_i, a_i, r_i) = \begin{cases} \frac{\alpha\left(q_j - q_j^{l0}\right)}{r_i - q_i^{lo}}, if\ q_i^{lo} \leq q_i < r_i \\ \alpha + \frac{(\beta-\alpha)(q_i - r_i)}{a - r_i}, if\ r_i \leq q_i < a_i \\ \beta + \frac{(10-\beta)(q_i - a_i)}{q_i^{up} - a_i}, if\ a_i \leq q_i < q_i^{up} \end{cases} \qquad \textit{Equation 28}$$

Where α and β, 0< α< β<10 denote the values of partial achievement function for q_j=r_j and q_j=a_j correspondingly, and $\sigma_{kj} = \sigma_j\left(q_j, a_j, r_j\right)$for a given alternative k∈K signifies the satisfaction level with the criterion value of the alternative, see Table 24.

	σ_A	σ_B	σ_C	σ_D	σ_E	σ_F	σ_G	σ total
A1	2.37	0	1.02	5.52	3.00	1.04	1.06	0.89
A2	3.26	2.67	3.63	5.52	2.76	2.18	2.1	6.09
A3	5.04	5.87	2.28	5.52	2.92	2.18	2.15	9.33
A4	9.6	9.6	3.55	5.52	2.84	0	0	11.47
A5	3.26	2.67	1.14	5.52	3.70	0.67	0.6	4.33
A6	11.4	11.4	2.66	0	0	3.01	3.01	12.8
A7	2.37	0	0	5.52	2.61	1.55	1.55	0.79
A8	3.26	2.67	2.71	5.52	0.05	2.7	2.7	3.87
A9	2.37	0	2.01	2.45	1.53	2.72	2.72	0.68
Average	*-6.06*	*2.94*	*0.57*	*0.94*	*-125*	*-420*	*-1.8*	
Aspiration	*-5.28*	*2.25*	*0.68*	*0.97*	*-62.5*	*-260*	*-1.4*	
Reservation	*-6.53*	*1.9*	*0.499*	*0.82*	*-12812.5*	*-1460*	*2.4*	
q_j^{lo}	-9	*2*	0.42	*0.7*	*-25500*	*-2500*	*-3*	
q_j^{up}	-4.5	4.5	0.8	1	*0*	-100	*-1*	

Table 24.Partial achievement functions for 9 alternatives (A) and 7 criteria (C). An example, Two-reference method.

b) After the overall achievement function for all the criteria is calculated:

$$\sigma(q,a,r) = \min_{i\epsilon I} \sigma_j(q_i,a_i,r_i) + \varepsilon/n \sum\nolimits_{i\epsilon I} \sigma_i(q_i,a_i,r_i) \quad \textit{Equation 29}$$

Where n – number of alternatives, $q=(q_1,q_2,..,q_n)$ vector of criteria values $a=(a_1,a_2,..,a_n)$ and $r=(r_1,r_2,..,r_n)$ vectors of aspiration and reservation levels.

c) Aspiration and reservation levels are calculated based on the available alternatives:

$$q_i^{av} = \sum\nolimits_{j\epsilon J} \frac{q_{ij}}{n}\ ;\ r_i = 0.5(q_i^{lo} + q_i^{av})\ ;\ a_i = 0.5(q_i^{up} + q_i^{av}) \quad \textit{Equation 30}$$

Most of the methods are based on simple weighted sum aggregation $\sigma_{jsum} = \sum_{i\epsilon I} \omega_i\, q_{ij}$, which has various limitations which are avoided in this method. However, it is vital to mention the limitations of those methods (such as AHP):

1. The weighted sum is based on an unstated assumption that an increase of another can compensate for a worsening value for one criterion.
2. Modifying weighting coefficients is often counterintuitive to changes in criteria values (Nakayama, 1995).

3. The linear aggregation of preferences in the weighted sum results in unbalanced decision-making; the Korhonen paradox is a typical example.
4. Only equal weighting allows an objective definition of the criteria (Wierzbicki, 2008).

Nonlinear approximation of decision-maker preferences allows for solving the abovementioned issues. Another benefit of this method is debiasing the decision-making process, proposing objective alternatives, thus protecting the output from the Decoy effect, wishful thinking, and framing (Felfernig, 2014). In case when the decision-maker has primarily available constraints, either reference levels can be modified or an intersubjective definition of essential factors for every criterion can be made (Wierzbicki A. P., 2007).

3.3 Concluding remarks

There are plenty of risk assessment methods, and we discussed the most spread ones in this chapter. Like any specifically designed tools, they all have certain applicational limitations and parts that can be adapted for academic usage. While the use of HAZOP is very disputable, FMECA attracts with the concept of risk index application and straightforward structure that can be easily adapted for some processes. On the other hand, it requires certain modifications to be less restrictive when failure modes are not that obvious. In academia, it is also necessary to enhance the method, including human factors. FTA is a more flexible method from the perspective of the failure source, which addresses the need for human factor consideration. However, the lack of statistical data doesn't allow the application of quantitative FTA in academia. The use of ETA is compromised for similar reasons. While Lab-HIRA was explicitly designed for academia, it satisfies the need for a risk assessment tool only for chemical laboratories. Moreover, it mainly allows preliminary risk analysis.

There is a need to integrate human factors assessment into the general framework of the risk assessment. There are plenty of approaches to consider. However, in one way or another, they are all based on the human capacity to make errors and surrounding factors that can either decrease or increase this capability. These factors can be related to the type of the task so that they can be classified as process-related to the human or outside environment. Some of these factors can be estimated and considered as they are more static, such as mood, bring a lot of variances, and can hardly be predicted. In the end, these factors can be classified as follows:

- We know and can influence (improve)
- We know and can take into account (but can’t improve)
- We know that can exist, but we can't either influence no take it into account.

Failure shaping factors allow us to consider the nature of the process and reduce the probability of an unwanted event. This group of factors is the easiest to consider, as they are almost not influenced by the outside environment. On the other hand, external factors, such as organization, ergonomics, individual, societal, etc., can affect the capability to make mistakes. This relationship is rather complex, and it is difficult to have an exhaustive chain of events leading to the failure. Nevertheless, considering key components allows us at least to grasp potential deviations, improving them before. Thus, enhancing the human error probability approach by integrating safety climate and ergonomic factors could predict the accident more reliably and realistic in the context of data absence.

The field of multi-criteria decision-making is broad that, during the years of its existence, developed various methods. The selection and application of these methods vastly depend on the ontological assumptions of the researcher. The use of the method and its limits also depend on the context of the problem (Guarini, Battisti and Chiovitti, 2018). There are much more methods than represented in this chapter. However, the goal of this thesis is not to review the MCDM approaches but rather to select the one that will satisfy the needs. Thus, applying one classical method (except reference-point) from each group of methods was demonstrated, see Table 25.

Method	Group	Advantages	Disadvantages
FAHP (AHP)	Full-aggregation	1)Decision-making problem represented hierarchal 2)Facilitates understanding of the problem 3)Computational method is straightforward	1)Restrained by the human capacity to compare alternatives 2)Pairwise comparison requires a lot of time 3) Adjustment of the list of alternatives will significantly impact the whole ranking 4) Preferences are not always clear 5) Interdependences between alternatives and objectives impact the final result 6) Strongly relies on decision-maker experience, thus imposing a bias 7) Complicated to apply when various decision-makers are involved 8) Use of weighted distance creates a risk of missing important Pareto points, as they might be contained in the interior and not on the boundary of the convex cover of the set. 9)Compensatory character of criteria is not always valid in interdisciplinary applications (Wierzbicki, 2010). 10) Linear aggregation promotes decisions with unbalanced criteria. 11) Difficult to achieve objectivity
ELECTRE	Outranking	1)Shows outranking relations 2)Based on threshold values 3) Commercially available software 4)Takes uncertainty and vagueness into account 5)Very poor performance of alternative on one criterion allows to eliminate it	1)Complex calculation 2)Incomplete ranking of alternatives 3)Possible incomparability among two alternatives
FTOPSIS (TOPSIS)	Reference	1)Does not require an extended pairwise comparison as AHP	1)No clear description of the weight elicitation procedure

		2)Efficient for the situation with many alternatives and attributes 3) Allows to include quantitative data 4)Based on the closeness to an ideal point	2)Does not consider the relative importance of distances 3) Requires DM preferences which are not always clear 4)Negative and positive values do not influence calculation, as it works on Euclidean distance 5)Deviation of one indicator influences results 6)Difficult to achieve objectivity
The two-reference method by Wierzbicki (Wierzbicki, 2010)	Reference	1) Specification of preferences is very general, which allows the decision-maker to change his preferences 2)Alternatives can be ranked 3)Ranking is "objective" as it is based only on available data 4)Possible to include criteria with both quantitative and semi-quantitative scales 5)Reference points are intuitive and based on data (Bandaru and Smedberg, 2019)	1)No commercially available software 2) Complicated computation 3) Modification of the criteria “neutrality” can impact the rank of alternative

Table 25. Comparison of MCDM.

Based on the comparison between different groups of methods, overall, reference-based approaches initially developed by Wierzbicki (Wierzbicki, 1980)fit better for the goals defined by this thesis. The presence of several decision-makers with conflicting preferences, the absence of clear preferences or their possible modifications during the assessment, the need to reduce biases during the decision-making process, and the predefined selection of the method. However, due to the problem of weights elicitations, integration of FTOPSIS was substituted by the two-reference point approach developed by Wierzbicki (Wierzbicki, 2015).

Chapter 4. Safety climate factor

Safety climate can serve as an indicator valuable during risk estimation. The role and effect of safety climate factor and human factors in general was discussed in chapters 3.1.6 and 3.1.7. The need to estimate effect of the human on the hazardous activity, thus a risk level is essential for academic setting. However, absence of data as well as non-standardized and diverse in their nature activities do not allow to use purely quantitative approach. Meanwhile, the need to take into account personality of the user, his/her safety perception lead us to the idea to integrate safety climate factor into the risk assessment method, as constituting risk index. To construct safety climate factor specifically designed for this purpose survey was used. This part of the project is discussed in the current chapter. The development of safety climate parameters is distinguished in a separate chapter from the development of the risk analysis method and decision-making toolbox. Nevertheless, it constitutes an essential part of the proposed methodology, as the developed factor is included in the probability of an accident calculation.

4.1. Participants and data pre-selection

The survey was distributed among 12 universities located mainly in Europe. We recruited different university actors for this study, including students of different levels, technicians, laboratory and university management, and technical and administrative staff (N=2'500), see Figure 32.

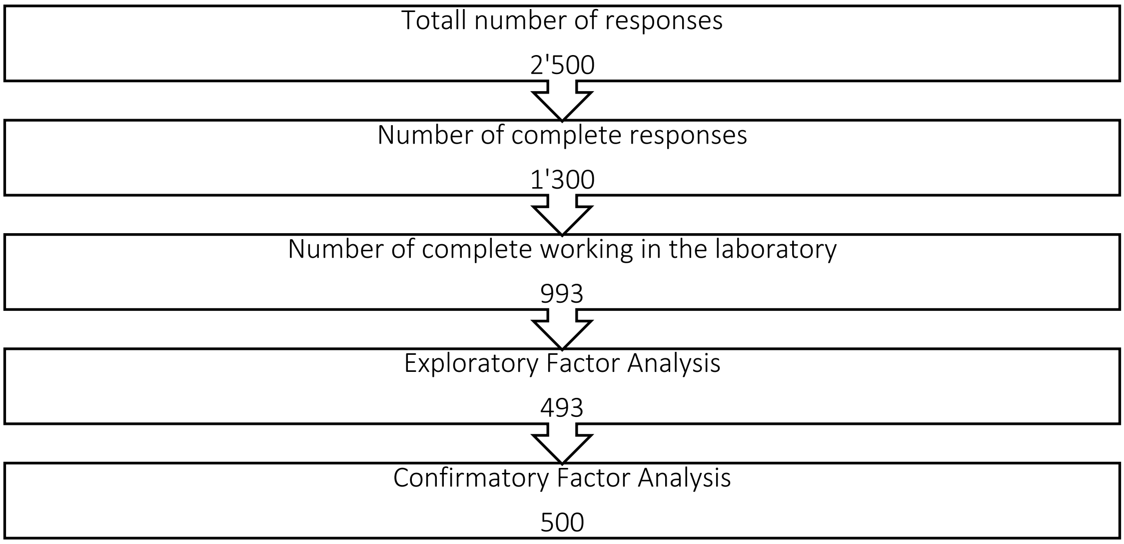


Figure 32 Data pre-selection

As the study's primary focus was on understanding and constructing the safety climate model, the number of participants was reduced based on two criteria (N=1'300). The first criteria for selecting the subpopulation was the completeness of the survey by the participant. In the second step, responses of people not working in the laboratory were filtered out. This filtering decreased the number of answers to a total of N=993.

4.2. Data analysis

Several statistical methods were used to specify the structure of the proposed theoretical model and correctly identify latent factors. All gathered data was first reduced to 993. Due to practical limitations of administering the survey to a broader range of universities, all data was randomly split into two samples (Mondo, Sechi and Cabras, 2021). Sample 1 contained 493 responses, while sample 2 had 500 responses.

Cross-validation is one of the methods commonly used to ensure the validity and reliability of the measurement (Thompson, 2013). The primary purpose is to test whether factor structure in the calibration (sample 1) will be replicated in other similar (validation) sample 2 (Byrne, 2013). The model's construct validity was tested using exploratory and confirmatory factor analysis. In the first step, Spearman’s rank correlation was set up, as it was used to verify the intensity of the correlations within and between sets of variables and to determine the type of rotation applicable for EFA. A random split of the initial sample is commonly used for cross-validation (Kyriazos, 2018; Ryan & Blascovich, 2015). Afterward, several iterations of EFA were conducted for Sample 1 to specify the proposed model. The modified model for safety climate was analyzed using CFA for Sample 2. Standardized estimates obtained from CFA were used to develop relative weights of factors, see Figure 33.

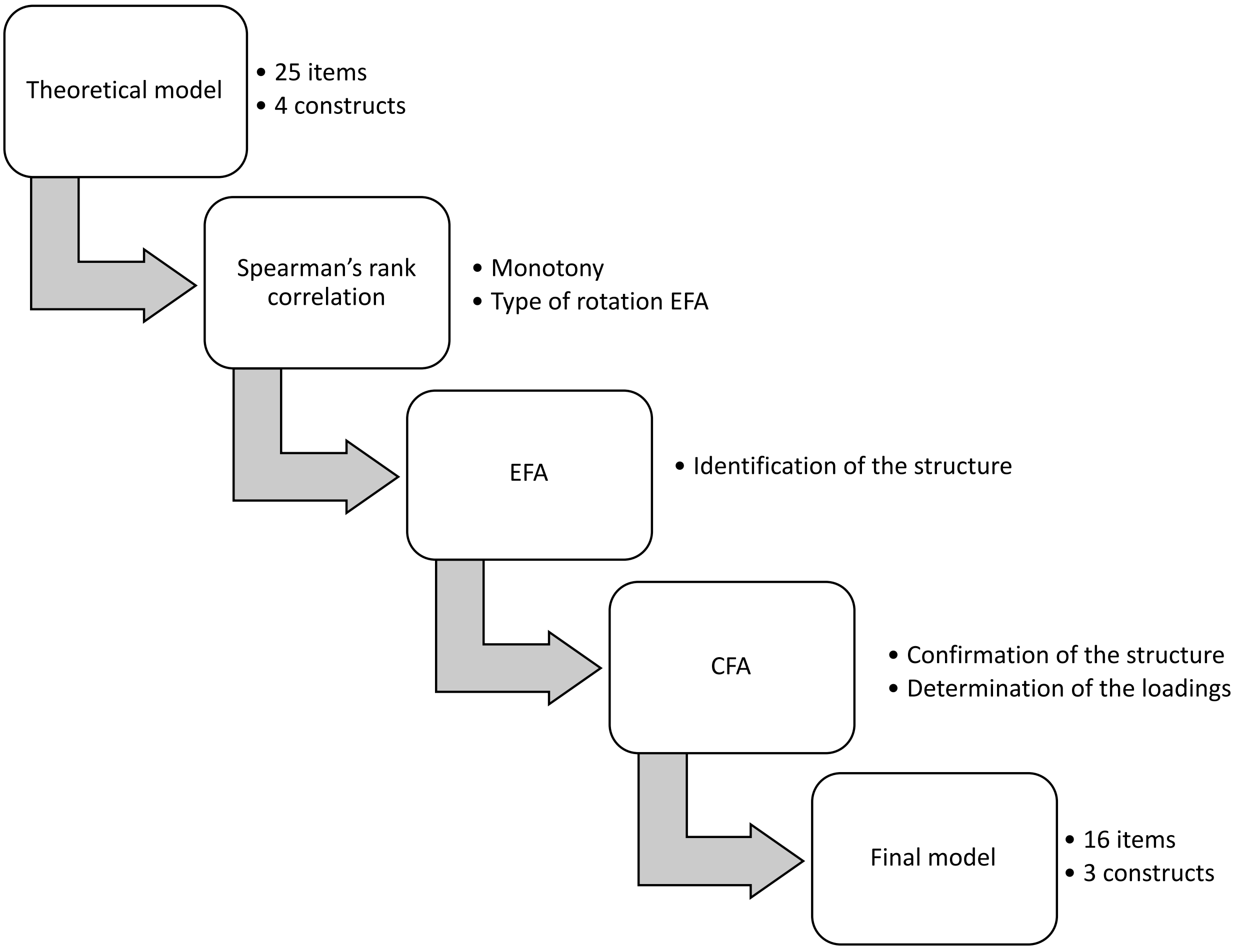


Figure 33. Data analysis and model development.

Spearman's rank correlation coefficient was used to evaluate relations among different variables (Sedgwick & George, 2016). Not all the variables demonstrated a strong correlation, which is why orthogonal rotation was selected for further Exploratory Factor Analysis (EFA) (Izquierdo et al., 2014). After reducing the number of variables and factors, a Confirmatory Factor Analysis was performed (Rossoni *et al.*, 2016) using SPSS Amos v23 software. χ^2 monitored the fitness of the proposed model, and the root mean squares estimated error (RSMEA)<0.08. RSMEA value between 0.05 and 0.08 indicates a good fit for the model (Cangur & Ercan, 2015). Other indexes such as the Normal fit index (NFI) and the goodness of fit (GFI) were used.

4.2.1 Spearman’s Correlation coefficient

Spearman’s rank correlation coefficient for variables is presented in Attachment B1. It was used to test a monotonic relationship between mentioned variables, the magnitude of the association, and its direction. No correlation above 0.8 was found (Gunzler et al., 2021). However, some variables were removed prior: gender, a field of work, and liability for an accident, as they were nominal. Moreover, the number of female and male participants was almost equal, despite the higher representation of male students and employees in the academic engineering sector (Faculty & Affairs, 2010).

4.2.2 Exploratory Factor Analysis

Although there was no issue with multicollinearity, some variables were excluded before conducting EFA; age and attitude to safety rules. The first factor was excluded because it provided similar information like years of working experience in the laboratory and occupation. Moreover, the analyzed dataset was a combination of responses from different universities. The age of respondents occupying the same position, thus having similar training and working experience, varied by 30% based on their country of initial education. Attitude to safety rules was excluded because it provided information similar to the perception of safety rules and was difficult to assess during the different interviews.

EFA aimed to determine a minimum number of factors sufficient to reproduce the item correlation matrix (Izquierdo et al., 2014). Kaiser-Varimax rotation has been chosen (Bruin, 2006) for principal component analysis as it is often considered one of the best and widely used orthogonal rotations (Fabrigar *et al.*, 1999). Orthogonal rotation minimizes the number of variables with high loadings on each factor and simplifies the interpretation of latent factors. After five iterations, three more items were removed: improvement of safety, type of accident experienced, and field of a participant, as they were cross-loading on multiple factors (Ngai et al., 2004). The remaining 21 variables were grouped into four factors. After extracting factors, reliability assessment by calculating Cronbach's α for the extracted variables, which measures reliability and consistency of the model, α =0.67, considered acceptable (Taber, 2018; van Griethuijsen et al., 2015). The final results of EFA are shown in Table 26. As the results of EFA were followed by CFA analysis, four extracted factors were not labeled at this stage. Simultaneous loadings into several factors were removed, and smaller values were removed, as the difference between loadings was higher than 0.2. This last round did not identify factors with loadings lower than 0.4 (Dahl et al., 2014); thus, no more factors required exclusion.

Variable	Factor 1	Factor 2	Factor 3	Factor 4
Occupation		0.768		
Permanent/Temporary position		0.436		
Previous experience		0.713		
Years of lab experience		0.736		
Safety training background		0.407		
Awareness		0.497		
Level of safety training			0.544	
Accident experience			0.618	
Hours per week in the lab			0.578	
Frequency of working alone			0.507	
Accident in the current lab	0.595			
Level of the lab safety	0.617			
Importance of safety	0.606			
Availability of safety information				0.731
Accident reporting system				0.642
Perception of safety requirements				0.579
Condition of equipment				0.540
Availability of PPE				0.643
Management commitment				0.589
Breaking rules reporting				0.867
The time when safety training was provided				0.453

Table 26 Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Rotation converged in 6 iterations.

4.2.3 Structural Equation modeling

While EFA is essential during the initial development of the model and helps a researcher identify latent factors in the model, CFA rather confirms the reliability of the proposed model (Worthington & Whittaker, 2006). According to some authors (Anderson & Gerbing, 1982; D. W. Gerbing & J. G. Hamilton, 1994), CFA is more appropriate for fine-tuning the model than its development. As it was expected for the proposed model to have two levels, CFA was used to specify and validate its structure. It is common to split data into several samples to validate a factor structure with another instrument (L. Milfont & Fischer, 2010).

The initial 4-factor model, constructed based on EFA analysis, was proved inadequate due to χ^2/pdf>5. The chi-square test is essential as it tests statistical significance but is also sensitive to sample size. Therefore, the proposed model was corrected. Implemented modifications included eliminating two factors: *when safety training was provided* and the *safety training background*. After the first step of modifications, a 4-factors model was generated; see Figure 34 (bigger version of the figure in Attachment B2).

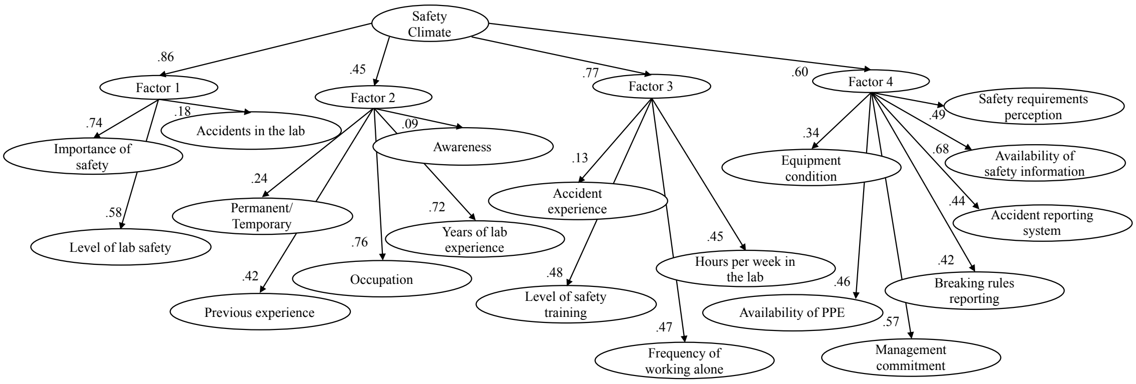


Figure 34. 4-factors model of safety climate for University laboratories. 19 items.

Several items were removed after consultation with safety experts, as it was considered complicated to obtain reliable results that would reflect actual reality, see Figure 35 (bigger version of the figure in Attachment B3). These items were: *accidents in the current laboratory*, *awareness,* and *accident experience*. The motivation to remove mentioned items is also supported by lower loading weights of these factors <0.20. However, the overall fitting of the model was still low. χ^2/df=3.97

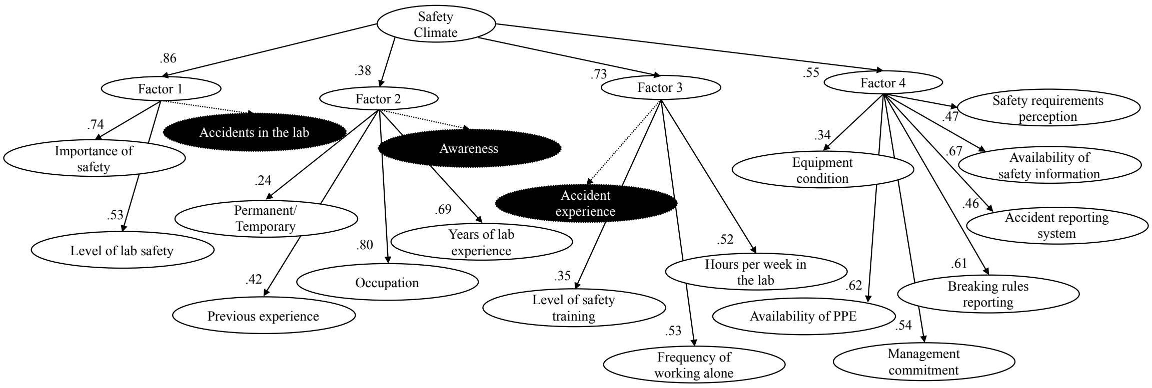


Figure 35. 4-factors model of safety climate for University laboratories. 16 items. Factors removed from the previous iteration are colored in black.

The number of factors was decreased to 3 to improve model fitting, see Figure 36 (bigger version of the figure in Attachment B4). Since factor 1 only had a two-item loading, factors 1 and 3 were merged into one. This allowed for improving the overall model fit.

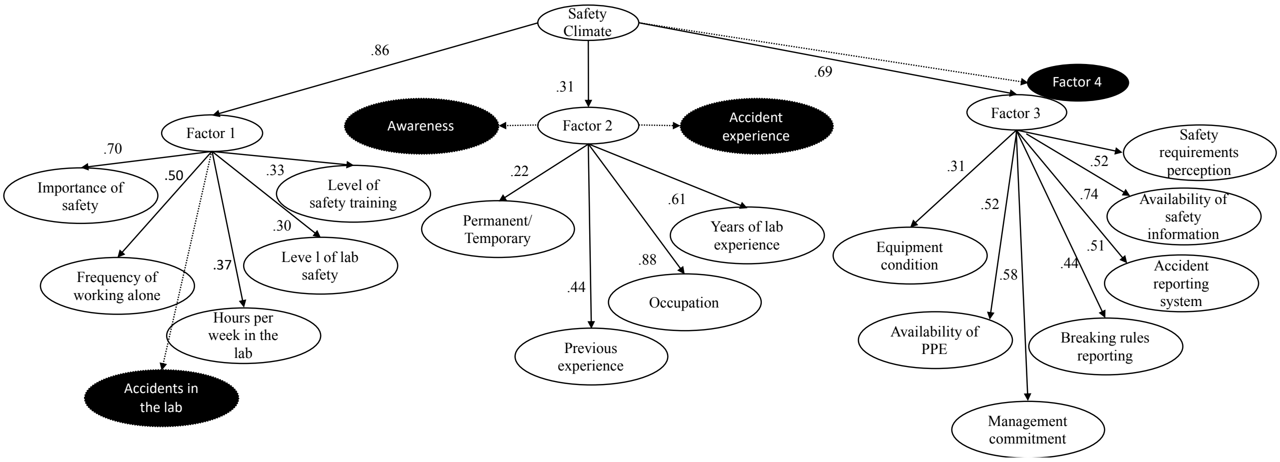


Figure 36. 3-factors model of safety climate for University laboratories. Factors removed from the previous iteration are colored in black.

Comparing 4 and 3-factors models, the 3-factors model demonstrates a better fit by all criteria, as seen in Table 27. For both models, all items had standardized regression weights ≥ 0.3.

Index	4-factor	3-factor
χ^2/df	3.95	3.77
χ^2	403	385
df	102	102
RSM	0.058	0.058
GFI	0.945	0.949
AGFA	0.925	0.928
CFI	0.88	0.91
NFI	0.87	0.92
TLI	0.86	0.90

Table 27. Comparison of fitness Indexes in a conceptual model.

The overall fitting of the 4-factors model was acceptable. However, due to the high sample size, some indexes showed lower goodness of fit CFI=0.88, NFI=0.87, and TLI=0.86 (Mogre & Amalba, 2021). The comparative fit index (CFI) examines discrepancies between actual data and the model. It can be potentially resolved by the item-parceling approach (Beauducel *et al.*, 2009), which was not applied due to the expected dimensionality of the model (Bandalos, 2002). Normed fit index (NFI) analysis discrepancies between null and hypothetical model chi-squares. It is frequently used as it is not sensitive to sample size. Tucker Lewis Index also compares hypothetical and null models; however, it is susceptible to sample size (Yadama &

Pandey, 1995). However, Fit indexes for the 3-factor model show better fit, like CFI, NFI, and TLI are above 0.90.

Regression analysis for 3 and 4-factors model demonstrated acceptable relationships: β_1=0.57, β_2=0.77, β_3=0.52, β_4=0.75, $p<0.001$ and β_1=0.86, β_2=0.31, β_3=0.69, $p<0.001$ respectively. In the final 3-factors model, all items had significant loadings, as seen in Table 28.

	Standardized Estimate	Non-standardized Estimate	The standard error (S.E)	Critical ratio (C.R)	P-value
F1→SC	0.859	0.71	0.179	3.96	***
F2→SC	0.309	0.80	0.105	7.62	***
F3→SC	0.693	1			***
Importance of safety→F1	0.702	1			***
Frequency of working alone →F1	0.498	0.527	0.051	10.33	***
Hours per week in the lab→F1	0.367	1.122	0.089	12.61	***
Level of lab safety→F1	0.298	1.461	0.065	22.48	***
Level of safety training→F1	0.329	1.354	0.086	15.74	***
Permanent/ Temporary→F2	0.218	0.061	0.009	6.78	0.06
Previous experience→F2	0.439	0.447	0.076	5.88	***
Occupation→F2	0.878	1			***
Years of lab experience→F2	0.608	1.513	0.181	8.36	***
Equipment condition→F3	0.307	1.451	0.068	21.33	***
Availability of PPE→F3	0.517	1.126	0.061	18.46	***
Management condition→F3	0.576	1.308	0.078	16.76	***
Breaking the rules reporting→F3	0.437	1.156	0.100	11.56	***
Accident reporting system→F3	0.506	1.075	0.055	19.54	***
Availability of safety information→F3	0.738	1			***
Safety requirements perception→F3	0.517	0.912	0.053	17.21	***

***, correlation is significant at the 0.001 level (2-tailed).

Table 28. Regression Weights in the Parameters of the Structural Equation Model in the final 3-factors model. Where SC – Safety Climate, F1-factor 1, F2-factor 2, F3-factor 3.

The final model's standardized and non-standardized coefficients and significance level between variables and factors are presented (Byrne, 2013). Both standard error (S.E.) and critical ratio (C.R.) demonstrate good fit, as C.R. is greater than 1.96 and S.E.is relatively small (Byrne, 2020). Thus, factor loadings can be used in the further construction of the model, and relative weights can be obtained using standardized loadings.

4.2.4 Final model

To find the weight of each index based on the initial survey results for the final model, we applied the method proposed by (Huang, 2014). The advantage of this method is that there is no need to use additional subjective methods, such as FAHP (Masmoudi & Dhiaf, 2018) and FTOPSIS (Krohling & Pacheco, 2015). Most of the goodness-of-fit indexes for the second-order 3-factors CFA model met reliability and validity requirements, as seen in Table 27. The final model of Safety Climate is gained by normalization of path coefficients of 3-factor second-order CFA, see Table 29.

Level-1 indicators (weights)	Level-2 indicators (weights)	
Factor 1 (F_1)	Importance of safety (P_1)	0.318
0.462	Frequency of working alone (P_2)	0.227
	Hours per week in the lab (P_3)	0.168
	Level of lab safety (P_4)	0.136
	Level of safety training (P_5)	0.15
Factor 2 (F_2)	Permanent/Temporary (P_6)	0.102
0.167	Previous experience (P_7)	0.205
	Occupation (P_8)	0.409
	Years of lab experience (P_9)	0.284
Factor 3 (F_3)	Equipment condition (P_{10})	0.086
0.371	Availability of PPE (P_{11})	0.144
	Management commitment (P_{12})	0.16
	Breaking rules reporting (P_{13})	0.122
	Accident reporting system (P_{14})	0.141
	Availability of safety information (P_{15})	0.204
	Safety requirements perception (P_{16})	0.144

Table 29. According to the final second level 3-factors CFA model, relative weights of indexes contribute to Safety Climate.

The first factor describes the *employee's perception of his current working situation and laboratory safety*. The second factor is *cumulative information about the employee's background*. The last factor is the *safety resources of the laboratory and management commitment*. Taking into account weights obtained from the second level 3-factor CFA model, Safety Climate Index can be calculated using the following formula:

$$SC=\sum_{i=1}^{3}\omega_{Fi} * V_{Fi}=0.462*V_{F1}+0.167*V_{F2}+0.371*V_{F3} \quad \textit{Equation 31}$$

$$V_{Fi} = \sum_{i=1}^{n}\omega_{Pi} * V_{Pi} \quad \textit{Equation 32.}$$

Where ω_{Fi}- relative weight of composing factors, V_{Fi}- value taken by this factor, ω_{Pi}- relative weight of first level parameters, V_{Pi}- value taken by this parameter from 1 to 3, based on initial questioner). The final model was derived from the initially proposed theoretical model with a clear separation of contributing personal and social components. In the final model, two of three factors can be associated with robust individual components: attitude, behaviour, and experiences. Some researchers argue that using such questionnaires as safety climate measurement tools only reflects organizational attitudes, neglecting individual values (Guldenmund, 2007). On the other hand, personal experience strongly affects attitude (Hughes & Ferrett, 2011), while there is a strong correlation between individual safety attitude and behavior (Li *et al.*, 2019).

As in the study conducted by (Yari *et al.*, 2019), we observed that variables associated with participant education, position, and previous background significantly impact safety climate. However, the results demonstrate that the contribution of the participant's individual experience is the lowest in safety climate. The third factor in the final model is responsible for the external manifestation of the safety climate in the laboratory and can be considered an organizational component. It can be expressed through management commitment, safety equipment maintenance, and communication (Jiang *et al.*, 2010). A comparison of the three factors' contributions to the safety climate illustrates the most substantial effect of the individual behavior. It is associated with its perception components, which proves the role of personal identity or personal safety culture in the overall safety culture of the group. Nevertheless, the effect of the organizational contributor is just slightly lower and proves the significant role of the organizational unit on safety climate. The primary purpose of safety climate factor is the application and integration as part of the risk assessment tool. This means that each process is assessed in connection with the "operator," focusing on its perception of the safety climate in the laboratory. However, to make an independent evaluation of the safety climate in the group, it is better to use several participants. Generated responses will also help identify the differences in perception and effect of an individual construct. Simultaneously conducting several assessments in the group will allow judging the role of group safety values and personal identity. Some of previous studies attempted to construct a unique safety climate factor based on safety climate surveys using subjective methods for further relative weighing of obtained criteria (Pungchompoo et al., 2014; Punniyamoorthy et al., 2011). The main reason why such an approach was avoided here is the individual bias of the experts and lack of agreement about the importance of the variables, which was determined among safety experts working in academia.

4.2.5 Practical application

Safety Climate assessment can be easily conducted as a part of the general risk assessment in the laboratory. To do so, the questionnaire as in Attachment B5 can be used. Such assessment was conducted using the questionnaire presented in Table 30. The table contains verbal responses selected by the employee and according to scores.

N^O	Question	Answer	Score
1	How important do you think safety is in your lab? (P_1)	Equally important to laboratory main activities	2
2	How often do you work alone? (P_2)	Almost every day	**1**
3	How much time per week do you spend working in the lab performing experiments? (P_3)	More than 40 hours per week	**1**
4	Your laboratory is a safe environment (P_4)	Neither agree nor disagree	2
5	What do you think about your level of safety training? (P_5)	I would like to have an additional training to better perform my work in the laboratory	2
6	What is your primary affiliation? For how long are you at this university? (P_6)	More than 1 year	3
7	How well does your previous experience help you to be integrated in your current lab? (P_7)	Really well	3
8	What is your current occupation? (P_8)	PhD student	2
9	What is your total lab working experience? (P_9)	More than 5 years	3
10	The research and safety equipment (fume hoods, biosafety cabinets, etc.) in your lab are safe and in good working order? (P_{10})	Neither agree nor disagree	2
11	In your lab, there is a sufficient supply of the appropriate PPE? (P_{11})	Agree	3
12	Does your supervisor encourage others to work safely, demonstrating with his/her own example? (P_{12})	He/she is always supportive and encourages safety initiative	3
13	Have you ever seen a colleague break a lab safety rule? (P_{13})	Yes, always corrected/commented	3
14	Are you aware about accident reporting system in your lab? (P_{14})	Yes, I know how to use it	3
15	What do you think about information about safety rules and procedures in your laboratory? (P_{15})	There is only general information available	2
16	What do you think about safety rules and regulations you need to follow? (P_{16})	It is important to follow safety rules and procedures	3

Table 30.Safety Climate assessment trial as a part of laboratory process risk assessment.

As the range of scores for **P_1**- **P_{16}** vary from 1 to 3, after normalization, first and second level factors of corresponding 2 level 3-factor CFA Safety climate model takes values represented inTable 31.

Factor	Normalized value
F_1	0.54
F_2	0.86
F_3	0.90
Safety Climate (SC)	0.74

Table 31. Normalized values for two levels of 3-factor CFA for the trial assessment from Table 28.

Thus, the SC value varies between 0.33 and 1. To use the safety climate model, the one or two employees involved in the analysed hazardous process can be surveyed with a questionnaire as Attachment B5. Scores corresponding to responses should be used only for calculation purposes and should not be visible to the interviewed person.

Each factor requires a set of acceptable limits similar to ALARA/ALARP for its qualitative application in safety management. We propose limits represented in Table 32.

Factor	Very low	Medium	Good
F1	<0.57	From 0.57 to 0.72	>0.72
F2	<0.63	From 0.63 to 0.73	>0.73
F3	<0.59	From 0.59 to 0.74	>0.74
SC	<0.57	From 0.57 to 0.73	>0.73

Table 32.Acceptability limits for Safety Climate and its subfactors.

In our case, limits were determined based on the importance of subfactors. For the lower limit, all subfactors took scores 2, except two subfactors with the lowest weight for F1 (*employee's perception of his current working situation and laboratory safety*) and F3 (*safety resources of the laboratory and management commitment)* and one subfactor for F2 (*cumulative information of the employee's background)*. For the upper limit, all subfactors were taking the value 2, except the subfactor with the third-lowest weight in the case of F1 and F3 and the second-lowest weight in the case of F2. These subfactors were scoring 3. However, all subfactors' acceptability limits can be modified, depending on the decision maker's preferences and the assessed environment's specifics. The difference between F2 and the other two factors can be noticed by comparing the subfactor with the lowest weight and the second smallest subfactor. In the case of F2 difference between these subfactors is 2-fold, while the same difference in cases F1 and F3 is smaller. F1 and F3, from one or another perspective, reflect a perception of the employee and contain a certain amount of subjectivity, thus closeness of the weights. F2 is almost an objective factor that describes facts.

In the example above, the overall safety climate can be considered good, suggesting that all measures can be advised: strategic, technical, organizational, and personal. Although it will be recommended to decrease the number of days when a person works alone and adjust the working schedule, selecting personal protective equipment from the range of measures will still be acceptable.

4.3. Concluding remarks

Safety culture is undoubtedly one of the most critical factors contributing to the safety of any organization. Its measurable aspect – safety climate is frequently used to evaluate the current safety in the organization. Safety culture is more static and complex factor that require very detailed study and preparation of necessary tools to be able to measure it. Until lately, no approaches were proposed to practically do so (van Nunen, Reniers and Ponnet, 2022). Academia, currently does not dispose resources and capacity to use this approach, thus the first step is measurement of perception dimension which is safety climate.

In most cases, understanding the safety climate remains qualitative and undoubtedly beneficial for any organization. However, in many cases, organizational risk management practices include quantitative or at least semi-quantitative risk assessment tools. Such quantification is essential as it allows better distinction and prioritization of existing risks. It also raises awareness and perception of the significance of safety incentives for all stakeholders. Integrating quantitative safety climate factors as one of the safety indicators in the risk management tools is a step forward in holistic risk management.

The quantitative model for the safety climate proposed in this chapter was elaborated specifically for the needs of university laboratories. The relative weighting of contributing variables was obtained based on the survey's statistical data. It can be applied as a separate safety indicator during an audit in the laboratory, based on answers of several respondents, or integrated as a contributing factor in the process risk assessment tool. In detail, the following chapters will illustrate how safety climate parameters can be integrated into the risk analysis model and which kind of practical actions can be taken based on such assessment.

Chapter 5. LARA+D Laboratory Assessment and Risk Analysis + Decision-making

In the first step, "due-diligence" of the existing risk analysis method was made. The existing method was developed in previous Ph.D. studies (Ouédraogo, 2011; Plüss, 2015). In order to understand existing problems, software usability issues were discussed with the current users (Safety Experts); see Figure 37. The list of issues was identified based on personal experience with the software and discussion with safety experts with different expertise. These issues were the main reasons why the software was not widely used. It is worth mentioning that list of issues identified by users with expertise in physics and chemistry was different and more extensive in the second case.

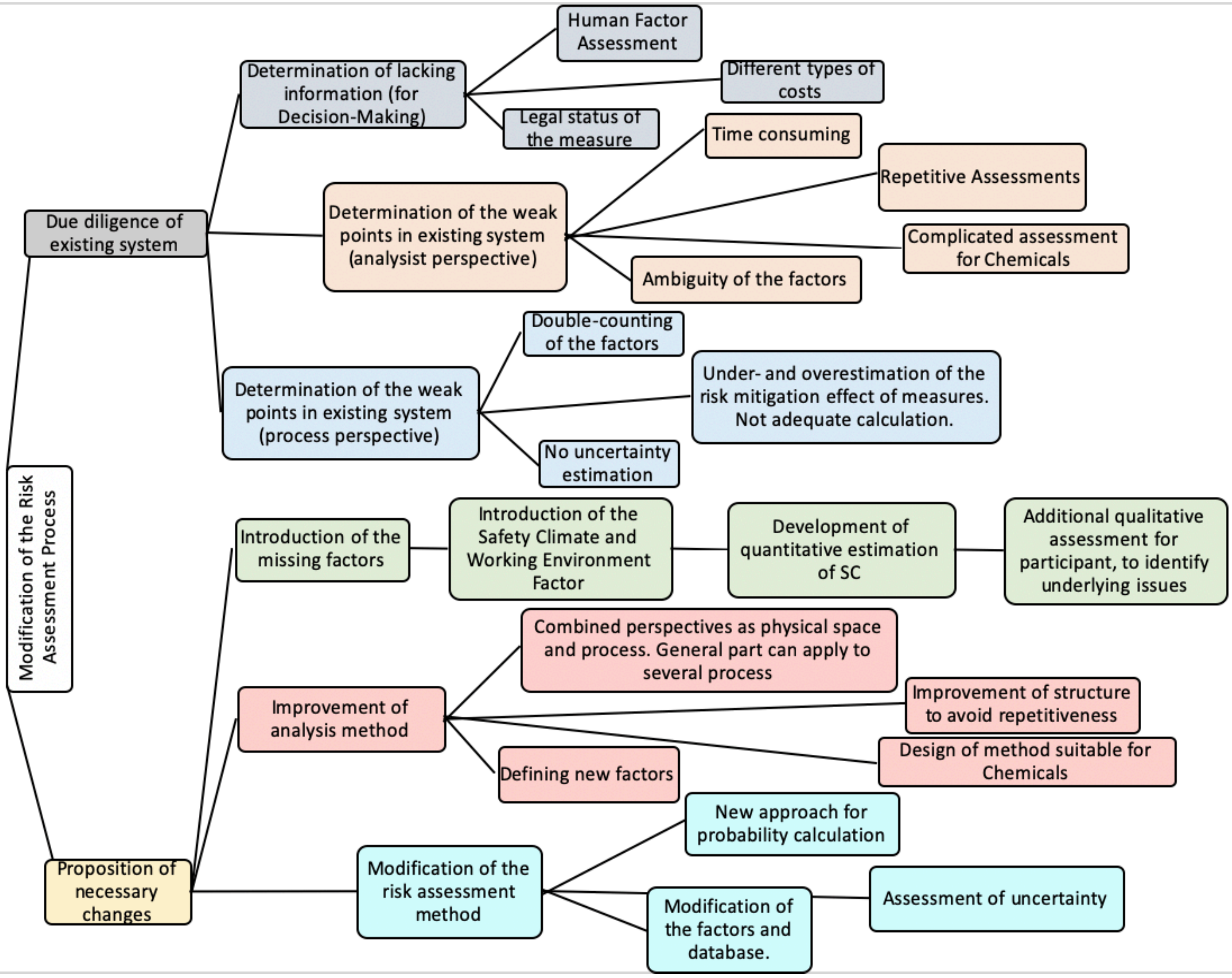


Figure 37. Risk Analyses modification.

Multiple simulations of the risk assessment illustrated not only problematic "ergonomics" of the method, such as time-consumption, intuitiveness of assessment, and repetitiveness. But also deeper, conceptual problems, such as unclear understanding of an accident in the tools. The last part of the software (risk treatment) demonstrated the inadequacy of scales, absence of correlation between a database of measures and factors used during risk assessment, and frequent overestimating.

Besides issues with the existing method, discussions with the users demonstrated their unwillingness to use the system in the existing state. Thus, apart from the objectives important for decision-maker, the newly proposed method is needed to satisfy the objectives of the users:

- Time-efficiency
- Connection of Hazards and chemicals
- Elimination of repetitiveness
- Automation and connection with database where possible

Main modifications introduced in the existing methodology included several aspects: introduction of missing factors, improvement of risk index calculation, modification of the assessment workflow, and classification of the hazards. Modifications concerning the risk index calculation included the introduction of the initially planned previous Ph.D. (Plüss, 2015) Bayesian calculation, which was modified accordingly with modification of the risk index structure. Initial uncertainties were estimated based on the expert's opinion elicitation. Additional block on decision-aiding was introduced to assist decision-makers with resource allocation problems.

The LARA+D orients on the general framework of the risk management approach mentioned in chapter 2.3. An overview of the workflow is presented in Figure 38. Each step will be explained in the following chapters. To illustrate the practical application of the method, a step-by-step demonstration of the case is given in the last chapter.

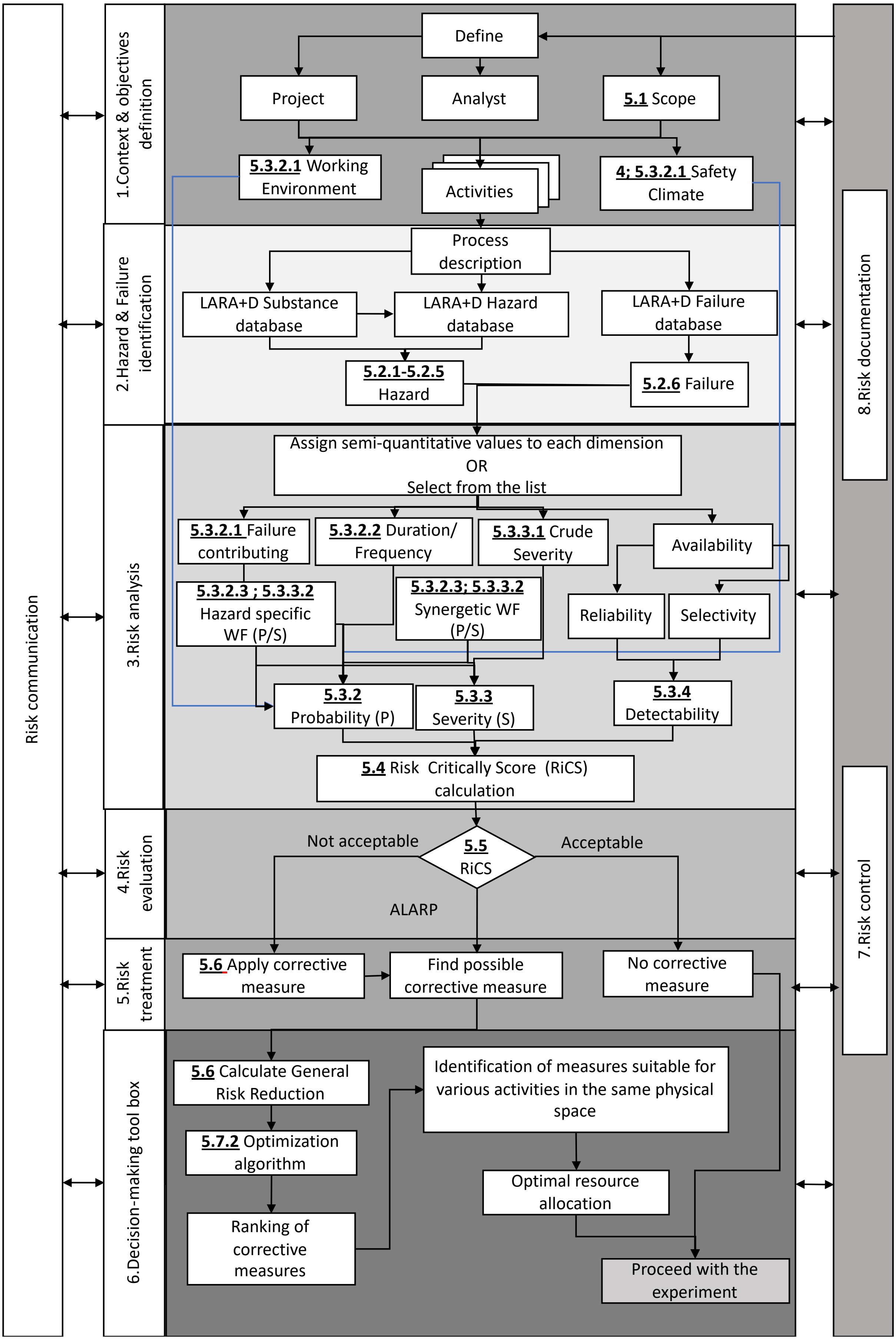


Figure 38 The detailed workflow of the LARA+D method.

5.1 Definition of the context

At this step, the context is defined on several levels. According to ISO 31000 (International Organization for Standardization, 2018), it is essential to establish external and internal factors, risk type, measurement plans, organizational details, and the process. On the macro-level, goals and critical points of the approach are defined. Micro-level includes technical specificities of the approach. Both levels are mutually dependent; thus, good risk management tool requires proper design of the whole workflow, taking into account these influences. This section is focused on disclosing the interconnection between different aspects of the context and their influence on LARA+D methodology.

Specific features of the academic environment define the macroscopic context of the LARA+D method. They define goals, expectations, requirements, and limitations. Based on this, different risk dimensions are established. Existing cultural and moral standards are framed by the basement's existing occupational health and safety regulations. The influence of different stakeholders' expectations and perceptions on the risk establishes risk acceptability thresholds. These limits are established not only for health-related matters but concern reputation, research, recruitment, funding, etc., as they can be at stake.

Contrary to a broader context, an organizational setting defines organizational details, roles, and responsibilities. LARA+D uses the existing safety framework at EPFL in its operation. At EPFL, as in all universities, occupational and health services establish safety rules and procedures based on international and national legislation and local safety directives. According to these rules and procedures, different departments provide technical support and safety training and organize and monitor daily safety-related operations of the laboratories. LARA+D is based on the existing organizational structure and integrated into the organizational safety framework of the University. For example, at the begging of any assessment, clear roles and responsibilities are defined based on the existing structure, see Figure 39.

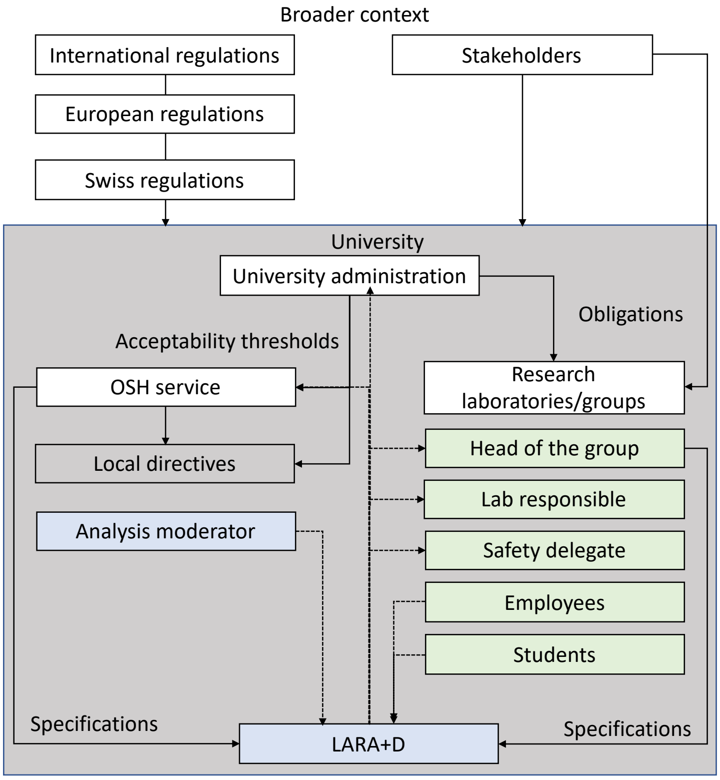


Figure 39.Overview of the roles and responsibilities in the LARA+D framework.

The university administration mainly defines an organizational framework. As in any other matter, management leadership in safety is essential to set a healthy functioning framework and implement a practical management approach. Not only does it set the obligations of different participants and establish internal rules and procedures, it also defines priorities and timeframes for different projects and establishes acceptability thresholds.

Occupational health and safety service are the only party that benefits from LARA+D (see Figure 39) and has a technical role in supporting and maintaining this tool. Updating databases, providing training to use LARA+D, and making modifications are critical activities necessary to maintain the high effectiveness of the tool. This service implements regulations, establishes necessary procedures, and assists technical and IT tools as a part of their duty. It schedules visits and audits and provides consultations to research groups, thus serving as an intermediate between university management and research laboratories. Keeping track of existing processes, controlling safety situations, and assessing the progress done in the safety field, OHS secures information flow between different participants in the system.

Research groups are composed of different types of people working and having temporary studying roles there. The Head of the group is at the top of the hierarchy and is subject to various types of pressure from stakeholders. The institution management establishes some obligations; others can arise from outside stakeholders (Jaeger & Thornton, 2006; Marmion et al., 2018). Their safety role includes the appointment of safety delegates and laboratory responsible, meeting existing regulations and directives, and operating within the acceptable limits of the risk. A safety delegate is an intermediate person between the group and OHS. It keeps track of existing and upcoming projects, schedules visits, and collaborates with OHS service to identify and eliminate safety irregularities or issues. The primary participant in hazardous activities is lab employees (scientists, postdocs, Ph.D. students, etc.) and master students having their projects in the labs. These participants can be considered principal risk owners from the sense of their direct involvement in the process. These are the stakeholders who will benefit the most from the use of the LARA+D methodology.

Different elements: materials, infrastructure, procedures, ergonomics, safety climate, etc., compose a technical context of LARA+D. Information covering these aspects is included in the LARA+D database and used during the assessment by the user. It is crucial to identify the analyzed object correctly during an assessment, see Figure 40. LARA+D methodology is designed in a way that different activities of the project are analyzed separately.

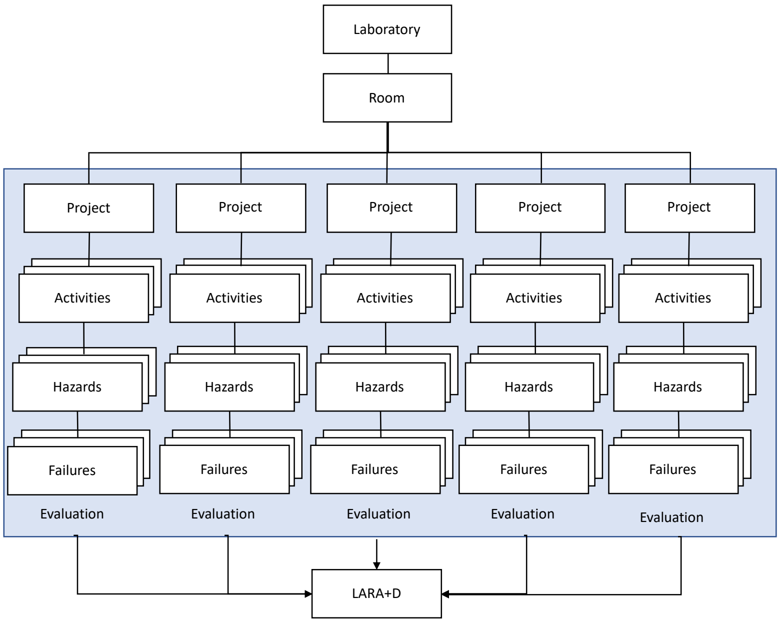


Figure 40.Relation between laboratory and LARA+D analysis

Example:

Exfoliation involves separation of platelets from one another. Liquid phase exfoliation is a method where a bulk material is dispersed in a solvent and then layers are broken apart. The layers are broken apart using ultrasonication where high frequency sound waves are transmitted through the solution, see Figure 41.

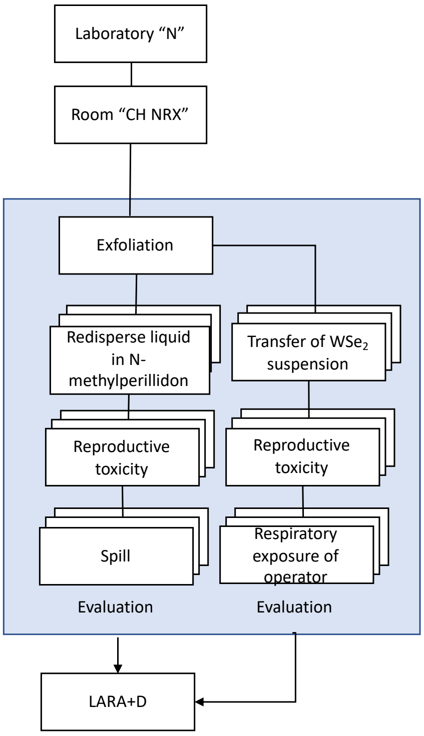


Figure 41. An example of the assessment workflow.

Before proceeding with the assessment, the user defines the context and describes the process. It is vital as some points will remain valid for several activities analyzed within the process, allowing one to focus on them once, see Figure 42.

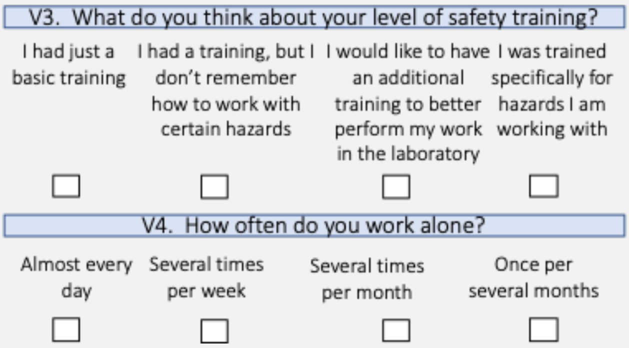
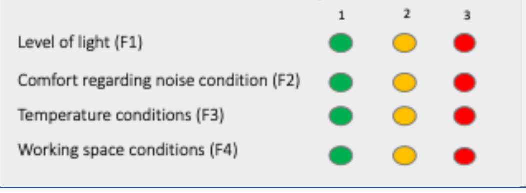
1. Definition of the context	
Intention	Example
- Identification of the process	- Exfoliation of D-material *Description.* Exfoliation involves separation of platelets from one another. Liquid phase exfoliation is a method where a bulk material is dispersed in a solvent and then layers are broken apart. The layers are broken apart using ultrasonication where high frequency sound waves are transmitted through the solution.
- Context description	- Analysis moderator: Anastasia Jung - Analysis team: Ms. NNN KKK - Lab responsible: Prof. NNN - Date:2020-09-20 - Room: CH HN NMN - Organizational Unit: EPFL SB NNN MMMM - Budget limit: 1’000 CHF - Deadline for the project : 3 months
- Assessment of Working Environment factors and Safety Climate assessment	Safety Climate is ***good*** (Extraction from the SC form)  V3. What do you think about your level of safety training? I had just a basic training ☐ I had a training, but I don’t remember how to work with certain hazards ☐ I would like to have an additional training to better perform my work in the laboratory ☐ I was trained specifically for hazards I am working with ☐ V4. How often do you work alone? Almost every day ☐ Several times per week ☐ Several times per month ☐ Once per several months ☐ Working Environment is ***Moderate*** (Extraction WE)  **Working environment** good 1 medium 2 poor 3 Level of light (F1) ● ● ● Comfort regarding noise condition (F2) ● ● ● Temperature conditions (F3) ● ● ● Working space conditions (F4) ● ● ●

Figure 42. Steps performed in LARA+D. Example.

5.2 Risk identification

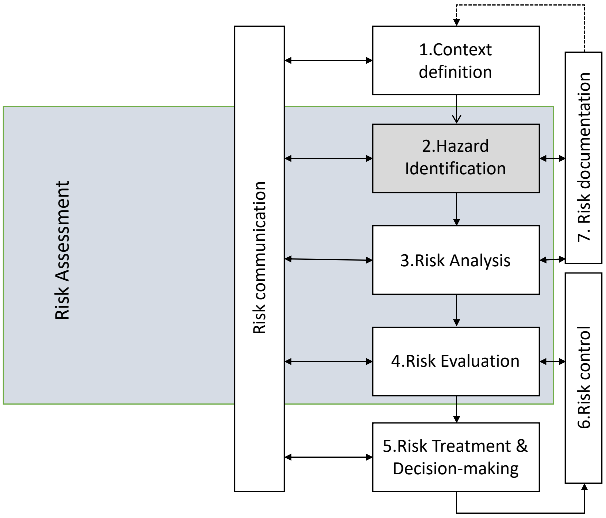


Figure 43. LARA+D workflow, risk identification step.

The second step of the LARA+D is aimed to identify existing hazards and associated failures. The focus of analysis is critical for hazard identification. In LARA+D, the main focus is the characteristic of the material, equipment, procedures, and activities. For example, the toxicity of the substance, laser, sharp edges, and repetitive movements. Hazard identification needs to be coordinated with failure identification. Available database both for hazards and failures eases this procedure for the non-expert. A database must be elaborated logically for the LARA+D method to work efficiently. The hazard identification system is based on the following classes of hazards: chemical hazards, physical hazards, mechanical hazards, biological hazards, and ergonomic. These categories are divided into different groups, where hazards are grouped based on their common effect or source. For example, corrosives to plastics, metals, glassware, paper-wood, skin, and eyes will be grouped in the category *corrosives*. Classification is done according to the considerations explained further.

5.2.1 Chemical Hazards

The primary approach to classifying chemicals was proposed by the Globally Harmonized System, Labeling and Packaging of Chemicals (GHS) (United Nations, 2007). It is implemented as the regulation for Classification, Labelling, and Packing (CLP), which is integrated into the level of the Europe Union. According to CLP, there are three main groups: physical, health, and environmental hazards. There are three ways to signal them by the system to identify them: pictograms, signal words, and hazard statements. Material Safety Datasheets (MSDS) provides detailed information about hazard, consequences, precautionary statements, and proposed safety measures. LARA+D is partially based on GHS principles. Not all chemicals are studied enough; thus, their potential effects are hypothetical. For example, the effect of nanoparticles is not always known; control banding is used to handle this kind of hazard (Groso *et al.*, 2010). In this case, a similar approach for applying corrective measures to address the hazard and mitigate the risk serves as the basis to group different sources as the group of hazards. Table 33 gives an overview of the chemical hazards classification.

Hazard Group	Hazard example
CMR/STOT	STOT SE
Flammables	Flammable gas
Acute toxics	Oral toxicity
Acute toxics	Respiratory toxicity
Hazardous to the environment	Hazardous to ozone
Corrosives	Corrosive to metal
Self-reactive and organic peroxide	Water-reactive

Table 33. Chemical hazards in LARA+D: hazard groups and examples of hazards.

Classification is made based on measures and corresponding exposure routes. The main question which needs to be asked is, "What and how does it affect?" Corresponding routes are essential for this classification. For example, the difference between respiratory and skin toxicity is the path of exposure. In the first case, intoxication happens due to inhaling a toxic substance; in the second, exposed skin is the reason. On the other hand, skin irritation and skin corrosion have the same type of exposure, similar consequences, and type of protection that will be used; thus, they can be considered as the same hazard having different severity of consequences.

5.2.2 Physical Hazards

While chemical hazards have a widely applied basis for classification, physical hazards do not have such. Different mechanism of transfer and the nature of the hazardous source serves as the basis for the LARA+D classification of physical hazards. Energy transfer from electric and thermic sources, mechanical waves such as noise, vibrations, etc., and pressure hazards (hypobaric and hyperbaric environment) are examples of physical hazards according to the

LARA+D database. While chemical hazards always originate from the properties and characteristics of the substance or material, a physical hazard is a phenomenon related to energy transfer and the circumstances of the environment. Contrary to chemical or biological hazards, they cannot always be seen or touched; thus, the target can be exposed without direct contact. Some examples of physical hazards are listed in Table 34.

Hazard Group	Hazard example
Sounds and vibrations	Ultrasound >20kHz
Electricity	Low voltage (AC 0-50V, DC 0-120V, I>2A)
Thermic Hazards	The work environment at T>33 C
Pressure Hazards	Compressed Gas (not toxic or flammable)
Laser	Laser class 3R visible beam
Electromagnetic fields	Static magnetic fields
UV / IR incoherent radiation	Incoherent UV
Ionizing Radiation	Open radioactive sources

Table 34. Physical hazards in LARA+D: hazard groups and examples of hazards.

5.2.3 Biological Hazards

Biological or organic substances which have the potential to cause harm to living organisms are considered biological hazards. There are various sources of biohazards: bacteria, viruses, parasites, or fungi. Even though the source might be different, classification of the hazards is made based on control banding, as the mechanism is not always known and complicated. Classification is made based on biosafety levels (BSL):

1) BSL1 is the lowest level; agents are well known and pose a minimal potential threat to adult humans and the environment. Laboratories are usually not isolated from the main building; standard microbiological practices are sufficient to maintain safe operation.
2) BSL2 includes work with well-characterized agents which pose moderate harm, i.e., HIV. This type of laboratory requires additional safety barriers, such as special safety equipment and buildings and additional training.
3) BSL3 is the highest, allowed at the EPFL level. Working with this agent requires special authorization and is strictly controlled at the state level. Exotic and indigenous agents pose a high threat and can lead to lethal consequences, i.e., yellow fever, West Nile virus, etc. Laboratories working with BSL3 must be separated from the main building and supplied with special PPE.

4) BSL4 facilities provide maximum protection and containment, as the agents are hazardous and pose a high risk. The main difference with BSL3 is the mitigation measures. In the case of exposure to biological agent group 4, no effective prophylaxis or treatment is available; thus, severity is higher. Examples of group 4 are Ebola and Lassa virus.

5.2.4 Mechanical Hazards

This source of an accident is one of the most spread in everyday life, outside workshops. Adverse effects of other types of hazards outside the laboratory are not always noticeable due to the low level of exposure, limits, or cumulative effect. This physical impact will almost always result in immediate and observable consequences. Mechanical hazards originate from the interaction of several objects, one of which is the human body. Classification can be made based on the cause of the movement. Several types can be distinguished: contact with not protected elements or machinery in the movement; contact with dangerous surfaces; not controlled contact with an element (i.e., ejecting of an object due to a malfunction of a machine) (SUVA, 2008). Some examples are listed in Table 35.

Hazard Group	Hazard example
Sharp objects	Needles
Moving Objects	Moving objects
Surfaces	Uneven surfaces
Work at height	Work at height

Table 35. Mechanical hazards in LARA+D: hazard groups and examples of hazards.

5.2.5 Ergonomic Hazards

Ergonomic hazards result from body positions undertaken due to the type of work done or specific conditions. Sometimes, not comfortable working positions can be considered just as worsening factors due to the limited time and minimal effect of such. However, in certain types of work, these hazards can become a reason for injury by themselves. Musculoskeletal injuries, on the contrary, happen not due to the outside hazard, as all above mentioned, but by wrong "operation" with the own body. Examples of ergonomic hazards are presented in Table 36. This type is typical for various types of workshops.

Hazard Group	Hazard example
Hazards to the musculoskeletal system	Imposed posture Lifting and handling heavyweight Repetitive movement

Table 36. Ergonomic hazards in LARA+D: hazard groups and examples of hazards.

5.2.6 Failures

LARA+D is scenario-oriented tool. In order to analyze the risk, it is essential to identify not only the sources of the harm but the way this harm can be made. It means that failures need to be identified in connection with hazards. To cover a wide range of scenarios, the list of failures is rather generic and allows flexibility for further assessment of magnitude. Example of the failures presented in the database:

1. Spill
2. Respiratory or Oral exposure
3. Dermal exposure
4. Splash (Cirafici *et al.*, 2020)
5. Contamination of the surface
6. Wrong concentration/amount
7. Wrong "setting" (e.g., frequency, power, intensity, etc.)
8. Leak
9. Rupture
10. Wear
11. Loss of function
12. Loss of pressure
13. Loss of integrity (American Bureau of Shipping, 2017)
14. Exposure to hazards to the environment
15. *Undesired* compound or material induced (Zúñiga *et al.*, 2020)
16. Loosening
17. Cracking
18. Fracturing
19. Oxidizing
20. Sticking
21. Short/Open circuited (Mode, 1994)
22. Deforming

For example, an analyst analyzes a substance that is identified as Toxic; the next step is identifying the scenario of the analysis. In the example below, the analyst selected two scenarios which will be analyzed separately.

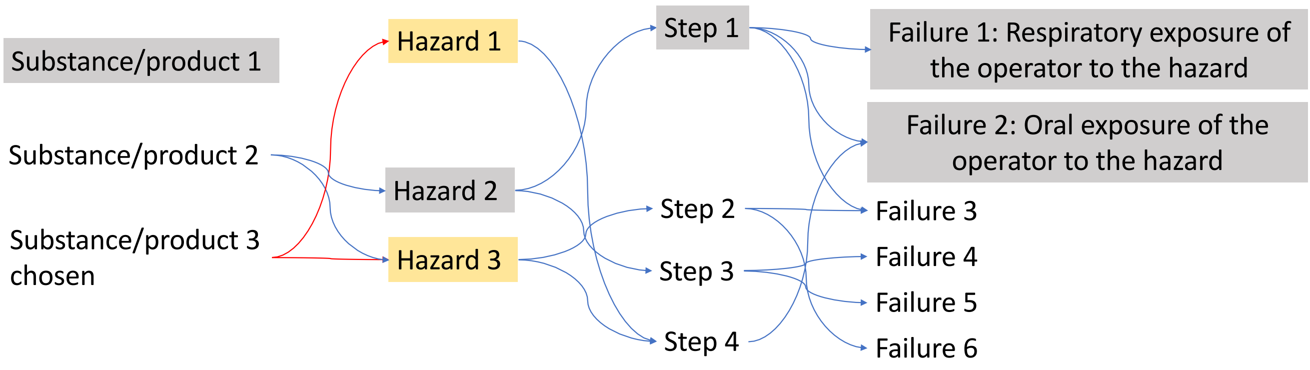


Figure 44. Failure identification.

5.3 Risk Analysis

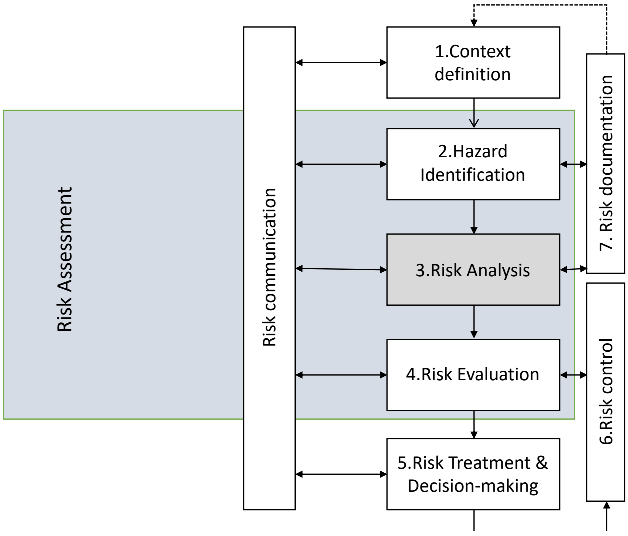


Figure 45. LARA+D workflow, risk analysis step.

Chapters 1 and 2 presented an overview of the requirements for the risk analysis method suitable for the research environment. Data is hardly available for this environment; thus, quantitative approaches are compromised. On the other hand, qualitative data are not detailed enough and can be the source of additional bias in the specified setting. For these reasons, LARA+D is designed as a semi-quantitative method. It uses qualitative scales and is associated with its quantitative values. It is valid for all dimensions. However, failure contributing factors are initially defined based on the available statistics on different types of failures to keep a minimal level of certainty. Failure probability is further rescaled after consideration of working environment factors and safety climate to a semi-quantitative scale. Values determined by the analyst are integer numbers. This section explains different risk dimensions and calculations used in the LARA+D method. This method is index-based, and the Risk Criticality Score (RiCS) is calculated at the end of each assessment.

5.3.1 Dimensions of risk estimation

Like FMEA or PFMEA, LARA+D operates in three dimensions: probability, severity, and detectability, see Figure 46. Similar to this method, a semi-quantitative approach is used to rank the severity of the consequences for the selected failure mode and probability to detect failure mode, effect, and cause.

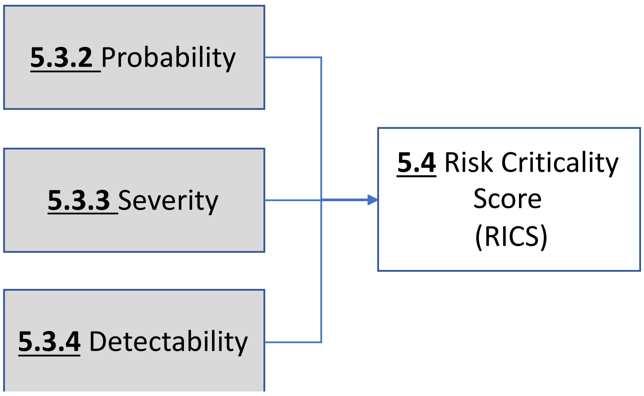


Figure 46. Dimensions of LARA+D.

5.3.2 Probability

The first dimension used for estimation is the probability of failure. This term is used instead of the probability of an accident not to confuse the analyst during the assessment and assess the probability of identified failure rather than the consequence. Previously, it was noticed that while applying the LARA method, experts sometimes evaluated the probability of selected consequences since severity assessment was a prior probability dimension. The only information available on the statistics of the accidents is associated with the injuries rather than the cause (Plüss, 2015). Thus, statistical approach was deemed as not suitable. Estimation of the probability is conducted indirectly and in several phases. The structure of the factor is presented in Figure 47.

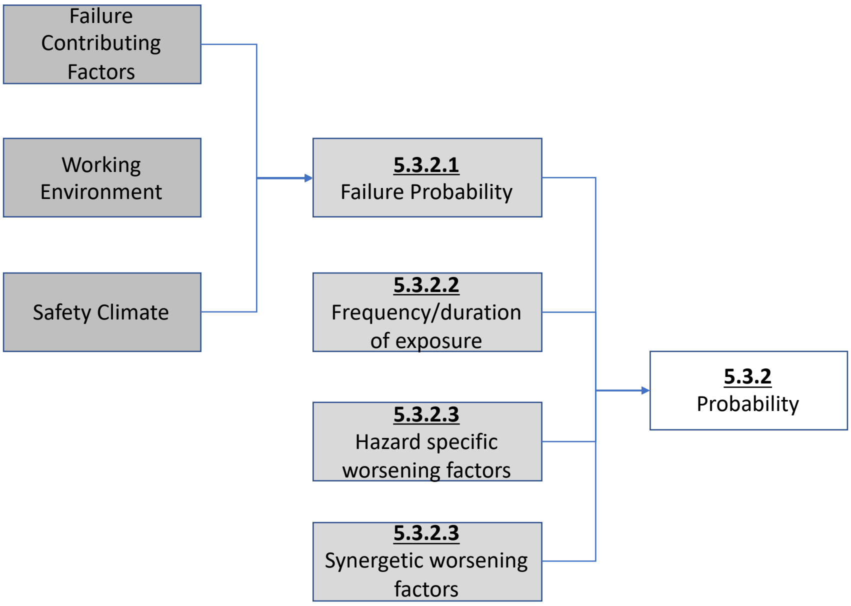


Figure 47. Factors used to estimate probability.

Probability can take values from 1 to 5 on the continuous scale, as the factor is obtained using calculation and values taken by its subfactors, see Table 37.

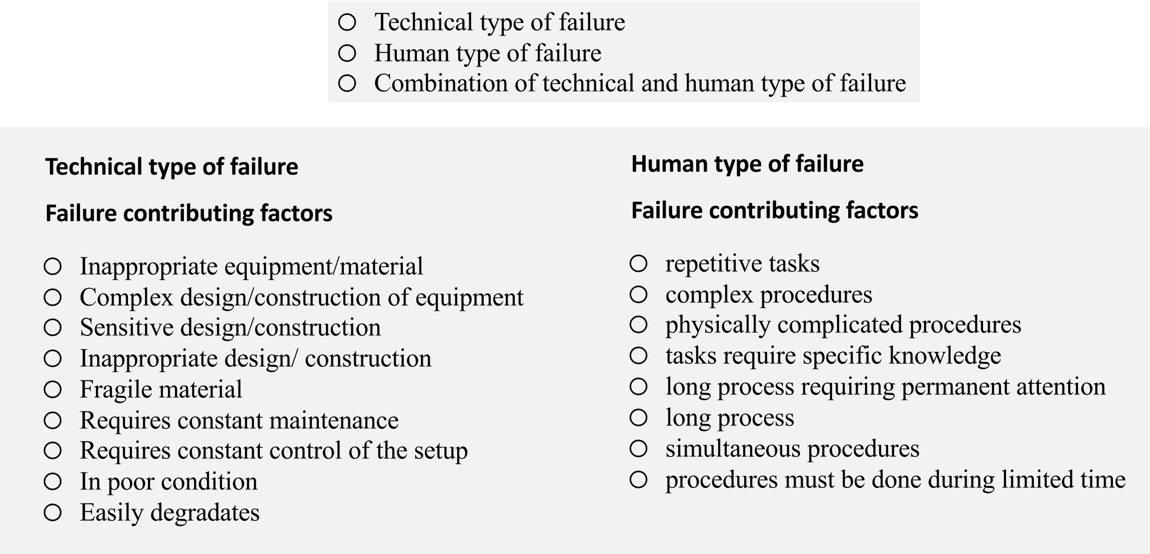
Qualitative description	Values
Very high	5
High	4
Moderate	3
Low	2
Very low	1

Table 37. Values and corresponding qualitative description for Probability.

5.3.2.1 Failure Probability

Failure probability is a complex semi-qualitative factor, composed of 3 subfactors. It was introduced instead of previously used accident probability (Plüss, 2015). Absence of historical data and a way to accurately assess this factor, resulted in biased and unreliable assessment which had a low consistency while performed by different experts. Thus, another approach was considered, it involved calculation of failure probability.

Failure contributing factors. After the generic selection of the failure, the analyst determines the failure contributing factors (FCF) that cause it. Two types of FCF can be distinguished: Technical and Human**.** Both types of failures can be selected simultaneously or individually. Failure contributing factors have an interaction between them to shape failure; thus, it is possible for failure to happen if only one contributing factor is a necessary condition (OR) or both are necessary to be present simultaneously (AND). An example of failure contributing factors is listed in Figure 48.



○ Technical type of failure
○ Human type of failure
○ Combination of technical and human type of failure

Technical type of failure

Failure contributing factors

○ Inappropriate equipment/material
○ Complex design/construction of equipment
○ Sensitive design/construction
○ Inappropriate design/ construction
○ Fragile material
○ Requires constant maintenance
○ Requires constant control of the setup
○ In poor condition
○ Easily degradates

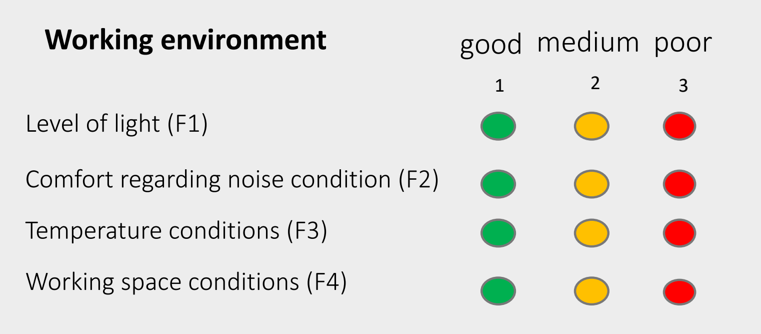
Human type of failure

Failure contributing factors

○ repetitive tasks
○ complex procedures
○ physically complicated procedures
○ tasks require specific knowledge
○ long process requiring permanent attention
○ long process
○ simultaneous procedures
○ procedures must be done during limited time

Figure 48. Failure contributing factors.

Safety climate factor, and working environment. Safety Climate (SC) and Working Environment (WE) factors are evaluated along with context description. The detailed calculation of SC is described in Chapter 4. The detailed description of the assessment qualitative form with corresponding quantitative values is presented in Attachment B5. Working Environment is assessed using a scale represented in Figure 49.



Working environment	good 1	medium 2	poor 3
Level of light (F1)	🟢	🟡	🔴
Comfort regarding noise condition (F2)	🟢	🟡	🔴
Temperature conditions (F3)	🟢	🟡	🔴
Working space conditions (F4)	🟢	🟡	🔴

Figure 49. Working Environment (WE) factors.

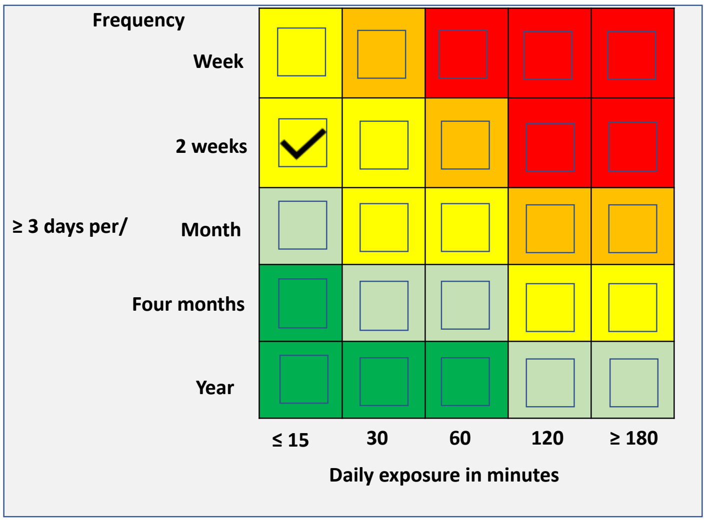
Three subfactors are combined in one formula to calculate Failure Probability: SC, WE, and FCF. Failure probability will be calculated using one of the formulas below similarly to FP=HEPSC Equation 1, depending on which relation is selected, "OR" or "AND":

$$FP=\left(\frac{\boldsymbol{WE}}{\boldsymbol{4}}\sum \boldsymbol{FCF}\right)^{SC} \qquad \text{Equation 33}$$

$$FP=\left(\frac{\boldsymbol{WE}}{\boldsymbol{4}}\prod \boldsymbol{FCF}\right)^{SC} \qquad \text{Equation 34}$$

5.3.2.2 Frequency. Duration of exposure

Not only will failure probability impact the probability of an accident, but the frequency of involvement in hazardous activity will also impact it. Assuming that an individual is rarely involved in the hazardous activity analyzed, the probability of an accident will be minimal compared to when such activity is performed daily. Activity is the object of analysis in LARA+D; thus, failures and accidents are estimated in this context. Although the duration of hazardous activity can be frequent, exposure to the source of danger can be limited. Here, by the duration of exposure, we mean working time or any other contact with a hazard during which the hazard target can be potentially harmed. During this time, the hazard is not insulated from the person or environment and involved in an activity. Different possible deviations (failure contributing factors) can go wrong and result in a near-accident. In order to estimate the overall time when a hazard has the potential to cause harm, the matrix represented in Figure 50 is used. For example, preparation of the setup by mixing different chemicals can be a frequently occurring step; however, maybe only 30% of the time, a person will be vulnerable to the corrosive.

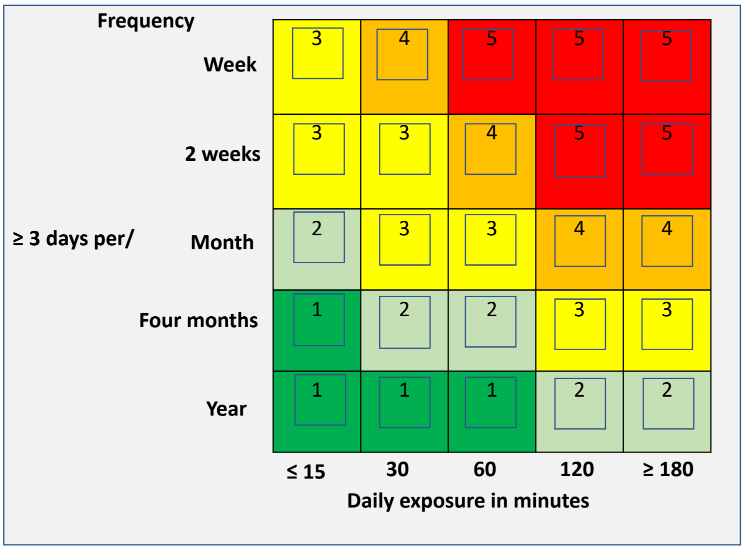


Frequency ≥ 3 days per/	≤ 15	30	60	120	≥ 180
Week					
2 weeks	✓				
Month					
Four months					
Year					

Daily exposure in minutes

Figure 50. Matrix for frequency/duration of exposure

The proposed matrix is developed based on the frequency/duration of activity proposed by Ouédraogo (Ouédraogo et al., 2011). These values are assigned for each analysis but differ for each hazard, as the exposure will vary. The matrix represented above corresponds to the values in Figure 51.



Frequency ≥ 3 days per/	≤ 15	30	60	120	≥ 180
Week	3	4	5	5	5
2 weeks	3	3	4	5	5
Month	2	3	3	4	4
Four months	1	2	2	3	3
Year	1	1	1	2	2

Daily exposure in minutes

Figure 51. Values for frequency/duration of exposure matrix.

Like all risk index subfactors, it is assessed on a scale from 1 to 5.

5.3.2.3 Hazard specific factors worsening probability & Synergetic factors worsening probability

Different outside influences can aggravate the risk, increasing either magnitude or probability. The concept of aggravating or worsening factors was initially introduced by Ouédraogo (Ouédraogo et al., 2011) as a separate, additional to other risk dimensions. Expansion of two main dimensions (probability and severity) with worsening factors will help to describe risks more accurately and take into account synergetic effects that are often present but not taken into account by other methods.

Hazard specific factors worsening probability are specific to a hazard and directly influence it. Often, safety guidelines contain information on what can worsen a risk or trigger an accident. Hazard Specific Factors worsening Probability can impact failure probability; for example, "Damaged packaging" will more likely cause a substance's leak. Another example can be an "exothermic reaction" conducted in a glass flask, and a case of improper equipment selection can result in the damage of glassware and personal injuries.

The list of the factors worsening probability shall be identified carefully per each type of failure and shall not be confused with the probability of consequences, which are associated with a hazard, see Table 38.

Hazard	Worsening factor	Effect
Flammable compressed gas	Odorless chemical	Fire or explosion
CMR or STOT RE	Insufficient ventilation	Intoxication
Corrosive to eye or skin/ Irritant	Damaged or wrong label (inadequate or missing information)	Skin or eye damage
Corrosive to metals	Use of metallic retention tray	A leak of a hazardous substance

Table 38. Hazard specific factors worsening probability.

Another kind of worsening factor affecting probability are a synergetic factor. Presents of this factor is meant to explain the synergetic effect of other hazards present in the activity. In certain situations, a risk or failure can be enabled. An example can be the presence of non-ionizing radiation, and flammable material can cause ignition. Different other combinations of hazards are possible to form similar situations, see Table 39

Hazard	Worsening factor	Effect
Blades	Holes	Piercing or cutting wound
Hot substance or surface	Flammable liquids	Fire
Lifting and handling heavyweight	Slippery surfaces	Body injury
Oxidizing liquid or solid	Flammable liquid or gas	Fire

Table 39. Synergetic factors worsening probability.

5.3.3 Severity

Severity is a combined factor composed of the severity of the consequences (crude) and possible factors which can worsen them, see Figure 52.

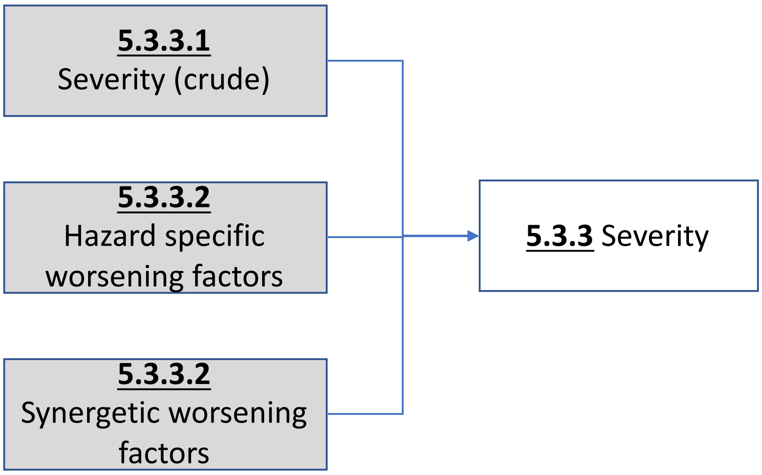


Figure 52. Factors used to estimate the severity

5.3.3.1 Severity (Crude)

The second dimension used in LARA+D for risk estimation is the severity of consequences. Quite often, the consequences are perceived subjectively. The financial evaluation of the losses is used as a general scale to palliate subjectivity. While, in the case of material damages, i.e., buildings and equipment, these values are easily determinable, it is different when human life is at stake.

Different insurance companies do the estimation of costs for humans, and it is a widely used practice. Various factors lay a basis for estimation: age (Thomas, 2018), education, health state, etc. However, there are different approaches for calculation, for example, the loss of manpower during sick leave or temporary absence. However, it is very complicated to determine even using these methods. In case of an accident, the loss of manpower should be calculated based on an hourly rate of a research scientist or a master's student who is not considered employed. This assessment is somewhat subjective; loss of health by an individual working on a scientifically promising experiment, who cannot continue his work anymore, will not be determined similarly by insurance companies, institutions, or even the scientific community, in order to avoid this kind of subjectivity and non-ethical estimation. LARA+D avoids financially based estimation of human life. LARA+D adapts the scale for human consequences estimation proposed by SUVA (SUVA, 2008), see Table 40

Not only humans and material equipment or infrastructure can be a target. The environment often suffers from the destructive effect of human activity. Environmental accidents are spread, especially during extensive and poorly controlled bio or chemical facilities activity. While industrial facilities are subject to strict monitoring and control from the authorities, academic research facilities are not that rigorous.

Reputational damages represent a separate dimension, as it is challenging to estimate the long-lasting effect and is not only limited to financial losses. They can exist independently or as the consequence of human, environmental or material losses.

Scales used for four dimensions of consequences are represented in Table 40. None of the scales can be considered of higher importance than another, as they affect different aspects. Scales are defined based on the ISO 14971 and NF EN 50126 terminology. LARA+D uses the most likely case scenario approach, meaning that type of consequences is determined based on their subjective probability. However, in some instances, the worst-case scenario approach can be applied. In case there is a lack of knowledge on hazardous potential (i.e., nanoparticles). Simultaneously, only one type of consequence can be selected, as the severity will be based on it. However, if the analyst prefers, he can duplicate assessments, selecting different scenarios of consequences.

	Qualitative description	Value	Specific qualitative description
Human	Very low	1	Wound without work interruption
	Low	2	Wound with work interruption
	Medium	3	Light handicap
	Serious	4	Serious handicap
	Very serious	5	Death
Environment	Very low	1	Negligible
	Low	2	Marginal
	Medium	3	Important
	Serious	4	Critical
	Very serious	5	Catastrophic
Direct cost	Very low	1	<1’000 CHF
	Low	2	1’000-5’000 CHF
	Medium	3	5’000-25’000 CHF
	Serious	4	25’000-125’000 CHF
	Very serious	5	>125’000 CHF
Reputational damage	Very low	1	Awareness in the laboratory
	Low	2	Awareness of the unit
	Medium	3	Awareness at institute
	Serious	4	Awareness outside the institute
	Very serious	5	Claims against the institute

Table 40. Impact rating scales are used in LARA+D for consequences.

5.3.3.2 Hazard specific factors worsening severity & Synergetic factors worsening severity

Similar to probability, various factors can aggravate severity. Hazard-specific factors worsening severity are specific to a hazard and directly influence it. Working alone with chemicals, such as corrosives, can sometimes lead to death in case of a spill or when working with mechanical hazards (van Noorden, 2011). Other examples can be working with substances causing reproductive toxicity for a pregnant woman or products that can cause asphyxiation for an asthmatic person, etc. see Table 41. All examples mentioned are not ordinally situations. Nevertheless, during risk evaluation, an expert makes an assessment based on the most spread or worst consequences, which are valid in most cases.

Hazard	Worsening factor	Effect
Flammable compressed gas	Significant quantities	Fire or explosion
CMR or STOT RE	Not diluted substance	Intoxication
Corrosive to eye or skin/ Irritant	Exposed skin	Skin or eye damage
Imposed posture	The user was subject to back surgery	Back injury

Table 41. Hazard specific factors worsening severity.

The main difference between synergetic factors affecting probability and severity is that in the case of severity presence of other hazards can move the type of consequences from one category into another. For example, when working with laser class 4, an individual with correct protection equipment poses a minimal threat; on the other hand, material damage can be made in case of misalignment. However, if toxic substances are in the zone of potential exposure, leak of such due to their exposure will result in severe health consequences. Some examples of synergetic worsening factors are listed in Table 42.

Hazard	Worsening factor	Effect
Skin toxicity	Use of needles/sharps	Intoxication
Hot substance or surface	The nearby presence of an incompatible substance	Exposure to hazardous substance
Vibrations are transmitted to all body	Lifting and handling heavyweight	Severe body injury
Imposed posture	Work environment at T<15 C	Body injury

Table 42. Synergetic factors worsening severity.

5.3.4 Detectability

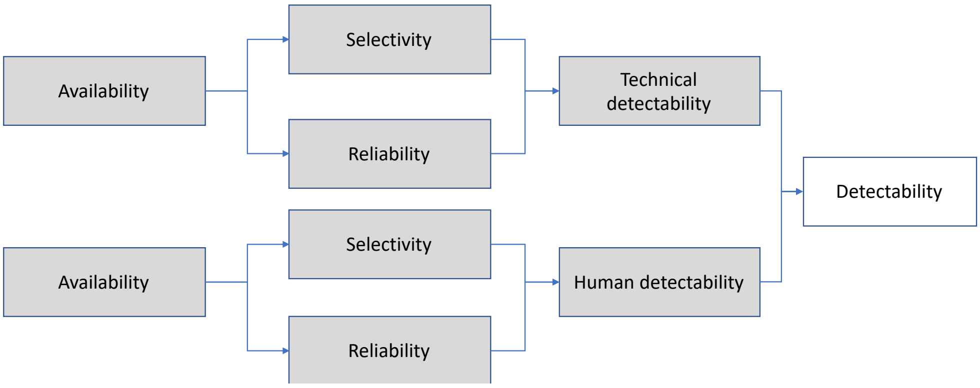


Figure 53. Factors used to estimate detectability.

The last dimension used in LARA+D is the detectability of an unwanted event. Whether the presence of a human or technical sensor can detect an upcoming unwanted event and stop at the stage of near-accident, it affects the magnitude of the risk significantly. Detection can lower impact and probability, depending on the definition of failure limits. There are two types of sensors: human and technical devices. Different types of gas-specific sensors are widely used in laboratories. Meanwhile, certain volatile chemicals, such as toluene, are easily detectable and recognizable by human sensors. However, different types of detectors will have different efficiency. LARA+D uses two factors to evaluate the efficiency of detection. Before determining such, it is essential to identify first if any detection is available, see Figure 53. The first factor used to evaluate efficiency is the detector's selectivity. It describes whether and how much the detector can distinguish between different hazards. The second factor is the reliability of a detector. This factor describes if the detector is reliable in its functionality. Human senses will often have high selectivity but low reliability, as they cannot always be trusted and cannot always determine threshold concentrations posing a threat. LARA+D is designed as a semi-quantitative method, and a quantitative scale with values ranging from one to five is used for all dimensions; however, the intervals are higher for the detectability: high(1), fair(3), and low(5). Higher fuzziness of the description requires lower points estimation. Contrary to other dimensions, Detectability represents a positive aspect decreasing magnitude or probability; thus, for consistency reasons, the scale is inverted, as depicted in Table 43.

Qualitative description	Selectivity	Reliability
Low	5	5
Moderate	3	3
High	1	1

Table 43. Rating of the detectability sub-factors.

While selectivity and reliability can be differently qualified, the availability of the detector is a binary factor. It is either present or not. If it is present, the remaining two factors need to be assessed; whereas it is absent, detectability will automatically have a maximum score of 5.

The presence of two types of detectors, undoubtfully, is more beneficial than one, as it serves as a fail-safe in case one type of detector fails. Nevertheless, in the case of both detectors, a human detector has lower importance than a technical one and should not substitute.

5.4 Risk estimation

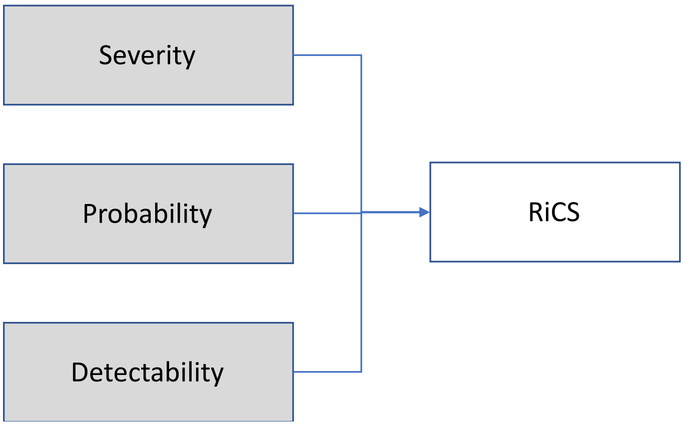


Figure 54. Combination of risk dimensions in RiCS.

Prioritization of the risks is essential in risk management, as it helps correctly allocate resources and rationalize efforts and time. Risk estimation is necessary for such prioritization and, in the academic environment, turns out to be a very challenging task. The use of quantitative methods assumes access to some statistical data, absence or lack of such will result in the absence of statistical stability (Yun et al., 2009). The research environment is considerably innovative; thus, information on the reliability of equipment or substances is rarely available. Using a semi-quantitative approach for risk estimation allows for overcoming the data absence problem. Semi-quantitative methods often rely on linguistic terms used by the experts during an assessment, as was represented above. However, such terminology can be a reason for additional ambiguity as it bears different types of uncertainties, see 2.2.1.

Very often, semi-quantitative analysis performed by different experts can result in different results, as the applied terminology allows a significant degree of judgment subjectivity, contrary to quantitative methods. To ensure high reliability and consistency of the method, it is necessary to palliate this individual effect. Fuzzy logic (Darbra & Casal, 2009) or Bayesian networks (Ren *et al.*, 2007) aim to address linguistic uncertainties. The use of Bayesian networks is helpful as it not only considers uncertainties (Ren *et al.*, 2007) but is relatively easy to use and it allows visualization (Z. Yang et al., 2008), see Figure 55.

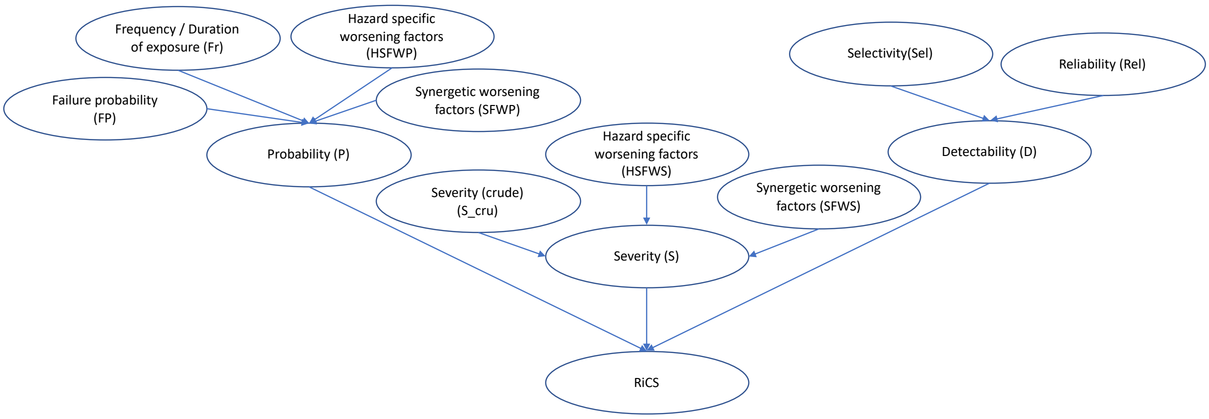


Figure 55. The Bayesian network is used for the calculation of RCS.

In semi-quantitative risk analysis techniques, different relations between qualitative statements and quantitative values are made. A scale of integer numbers between one and five is used for the sub-variables of severity (S) and probability (P). Detectability (D) is more challenging to determine; thus, a scale from one to three was used. FMECA is based on a multiplication formula to calculate Risk Index (RPN):

$$RPN=S\cdot P\cdot D \quad \textit{Equation 35}$$

This method has several drawbacks that were mentioned by Braband (Braband, 2004). The following flows are defined by (Bowles, 2003):

- Gaps in the ranges. The scale is not continuous; thus, only 120 out of 1000 numbers can be generated.
- Duplication of RPNs. Different combinations generate the same values of RPN.
- Sensitivity to slight changes. Disproportional changes in RPN delta, depending on initial values of subfactors.
- Misleading conclusions from RPN comparison. Compensatory effect of values modifications in subfactors. Thus, doubling detection (D), halving severity (S), and keeping occurrence constant will have zero effect on RPN. Therefore, wrong conclusions can be drawn from this calculation.

To overcome these drawbacks, an iRPN calculation was proposed (Braband, 2004). In the first version of LARA, a logarithm-based calculation of the risk index, similar to iRPN, was used (Ouédraogo et al., 2011a, 2011b). Weighting coefficients for the subfactors: a=1.66, b=5.78, c=6.06, and d=17.24 were obtained using Analytical Hierarchy Process (AHP):

$$LCI = RP(log_a(I_h) + log_b(RS) + log_c(HD) + log_d(POA))$$ *Equation 36.*

LCI denotes Laboratory Criticality Index, RP- risk perception, I_h- the impact of the hazard, which is a combination of Severity and worsening factors, RS – research specificities similar to safety climate, HD – hazard detectability, and POA – the probability of Occurrence of an accident.

The logarithm-based calculation solves the scale-related problems. Nevertheless, it remains susceptible to critical uncertainties. To overcome the problem, as mentioned earlier in the previous Ph.D. study, the implementation of Bayesian networks was proposed (Plüss, 2015). A similar approach was developed in work by (Z. Yang et al., 2008) and used Bayesian networks for Fuzzy rules modeling. To deal with imprecise qualitative input, fuzzy logic is often used in risk management. This method can be combined with the Bayesian network's approach to avoiding losing some information during the fuzzy Min-Max operation (Z. Yang et al., 2008). Thus, by combining qualitative information represented by predefined values with the rule basis, the output will be represented by the quantitative value. This method was proposed in the previous Ph.D. work (Plüss, 2015). The rule can be represented as follows:

Rule: IF

Low(2) (Severity)
AND Moderate (3) (Probability)
AND High (1) (Detectability)

Then

Low (2) (Risk Index)

One rule-base consists of one IF-Then rule, as represented in the example. For three factors with five statements each, the rule base will contain 125 rules, see Figure 56 This rule base is created with the help of experts based on their vision of interdependencies among different values.

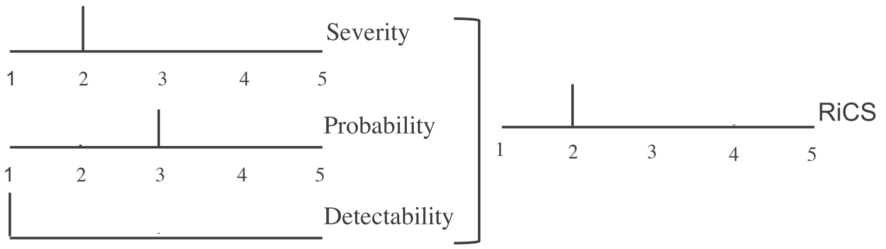


Figure 56. A schematic representation of a simple Fuzzy rule base.

However, it is still very subjective and poses only one degree of belief – interdependencies. In order to take into account subjective judgments of input values, this rule can be combined with belief degrees, see Figure 57.

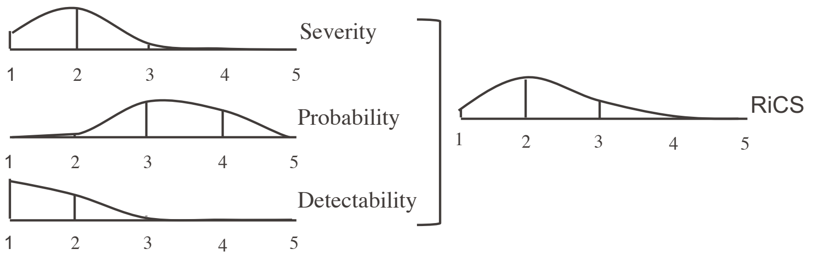


Figure 57. A schematic representation of a Fuzzy rule base with fuzzified inputs, used in LARA+D.

Thus, the rule becomes as follows:

Rule: IF

Low (2) (Severity)
AND Moderate (3) (Probability)
AND High (1) (Detectability)

Then

{(0.12*very low*),(0.58*low*),(0.29 *moderate*),(0.01*high*),(0.0*very high*)*Risk Index*}.

Translating this expression into conditional probabilities, the form will be as follows:

Given Severity (2), and Probability (3), and Detectability (1), the probability of Risk Index (h = 1, ..., 5) is (0.12, 0.58, 0.29, 0.01, 0.0)

or $p(RI_h|S(2),P(3),D(1))=(0.12,0.58,0.29,0.01,0.0)$

A more informative and realistic representation of an actual situation is possible by expressing output variables as a distribution instead of a single crisp value. A truncated normal distribution with a variance of 0.5 for calculating the Risk Index, see Figure 58. The average semi-quantitative input value of three risk dimensions is used. The weighting of input parameters can be determined based on the expert's evaluation and adjusted if necessary. This kind of distribution is used over normal distribution, as it has finite points. In the case of LARA+D, these points are 1 and 5. This allows the modeling of various forms, such as uniform distributions (Fenton et al., 2007). The experts determined the mean values using semi-quantitative scales presented in the previous chapter.

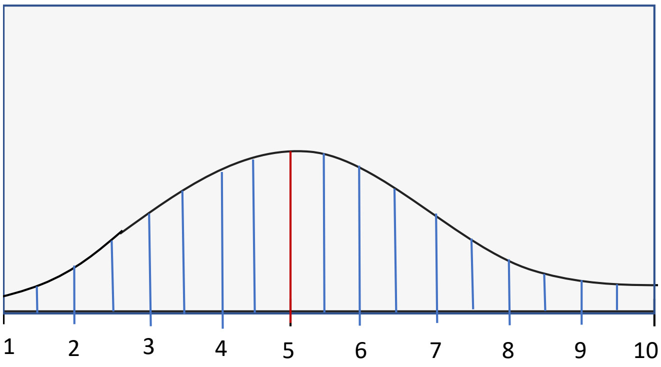


Figure 58. An example of a truncated distribution. Mean 5.0, variance 0.5, truncated between 1 and 10.

The use of Bayesian networks is widely spread in different branches of risk management (Marhavilas & Koulouriotis, 2008). Probability tables with different states for each network node are the basis of Bayesian networks (Fenton and Neil, 2013). In LARA+D, the input distribution gives the probability tables of each node, except FP. These tables were created using ranking nodes described by Fenton (Fenton, Neil and Caballero, 2007). The fuzzy rule is applied to create probability tables for the parent node. A schematic representation of the Bayesian network used for calculation is represented in Figure 55.

The states of the risk index (RiCS) node can be calculated using the following formula:

$$p(RiCS_h) = \sum_{i=1}^{5} \sum_{j=1}^{5} \sum_{k=1}^{5} p\left(RiCS_h \middle| S_i, P_j, D_k\right) \cdot p(S)_i \cdot p(P)_j \cdot p(D)_k \quad \text{Equation 37.}$$

The risk Index node is a probability distribution (Figure 57). To compare different risks, a single crisp number RCS is calculated with Equation 12. The adversity factor (A) for each state of the risk index node is used to have different weights for different states. It gives high flexibility in the calculation system.

$$RiCS = \sum_{h=1}^{5} p(RiCS_h) \cdot A_h \qquad \textit{Equation 38.}$$

It is essential to mention that the child nodes: severity, probability, and detectability, are not chosen directly by the analyst, but are combinations of their sub-factors, as was described previously. Thus, the values of these dimensions are calculated so that each dimension has its Fuzzy rule base.

After the Bayesian calculation was performed, the results are defuzzified in order to be able to compare different risks, see Figure 59.

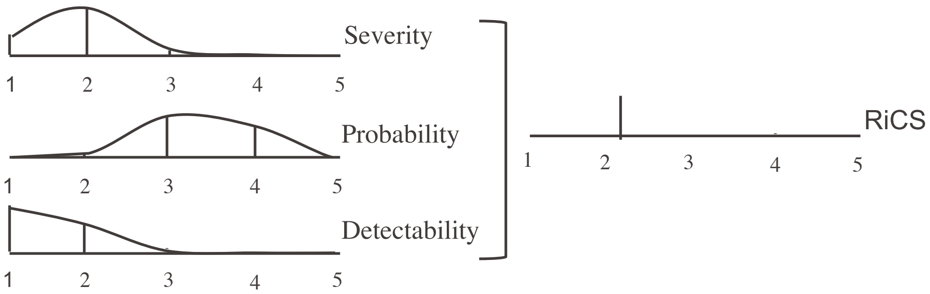


Figure 59. Defuzzified results of Bayesian calculation for RiCS, using Equation 14.

This calculation method was previously compared with RPN and iRPN calculations (Pluess, Groso and Meyer, 2013). Three risk indexes, LCI, RPN, and iRPN, composed of the same subfactors, were compared within the same risk assessment. The standard deviation of the selected method was lower than for RPN and iRPN. It is also proved that using the Fuzzy rule in combination with Bayesian networks allows more consistent risk estimation relative to other methods.

5.5 Risk Evaluation

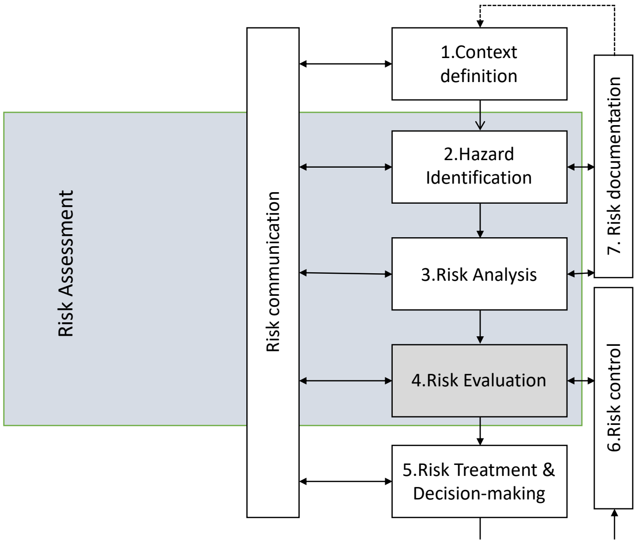


Figure 60. LARA+D workflow, risk evaluation step.

The next logical step after the magnitude of the risk is accessed is to decide whether it is necessary to treat the risk. To answer this question, first of all, it is essential to define what will be an acceptable risk and determine its limits. Many factors can influence acceptability limits, for example, regulations, existing knowledge, and risk perception in the society or individual risk perception if we are talking about personal risk management. In some legislation, this concept is defined on the level of legislation (UK, 1974). However, it requires a quantitative estimation of the risk. It allows not only to estimate the magnitude of the risk and compare different risks but to evaluate possible losses. Safety measures must be applied to reduce the risk when the risk is above the defined threshold. When the risk is below the threshold and considered unacceptable, it is not necessary shall be considered acceptable. The ALARP (As Low As Reasonably Practical) approach is often used to define this threshold. It shows an upper and lower risk limit, which either should not be tolerated or have no practical interest(Melchers, 2001). This concept works as a bridge between the technological and societal views of the risk.

The ALARP concept can be demonstrated in Figure 61. It can be either with the quantitative scale or other indicators to determine thresholds.

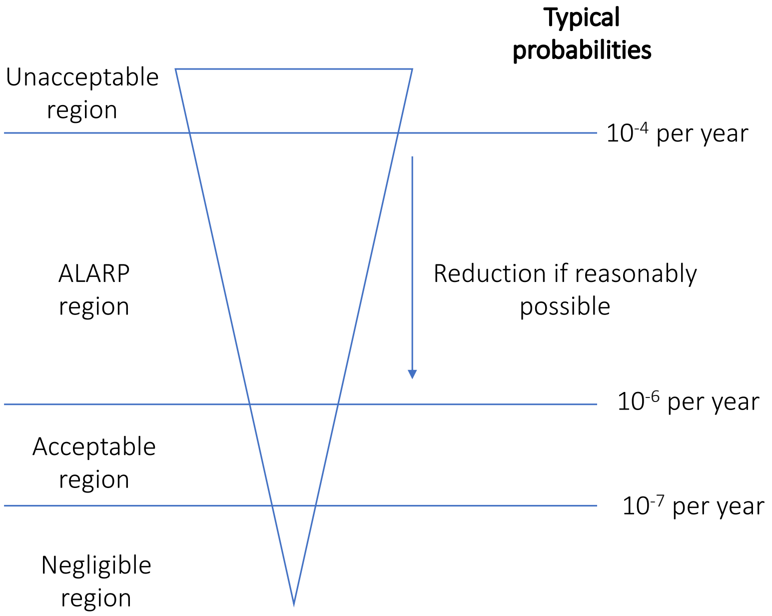


Figure 61. ALARP approach. Levels are determined by (HSE, 1992).

ALARP concept is based both on "reason" and "practicality". Thus, it combines subjective and objective views on the risk (Melchers, 2001). Similar uncertainties in the determination of ALARP region, as the expert judgments make this concept well integrated with the whole risk assessment framework. The concept depicted in Figure 61 is represented through one dimension – the probability of an event. However, it can be realized through a two-dimensional matrix, where the risk's magnitude is also considered. The risk matrix is a widely used representation of the ALARP concept, see Figure 62.

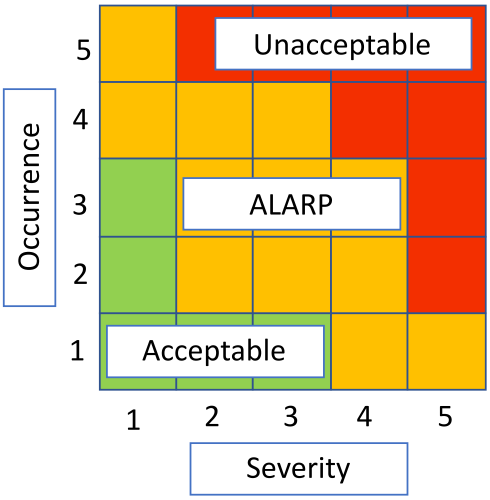


Figure 62. An example of a risk matrix illustrating the ALARP concept.

A similar approach can be used to define the ALARP concept for RiCS. However, in this case, instead of clearly defined dimensions, three combined values are integrated into one factor and used for ALARP.

(Teferra, 2017) an approach for three-dimensional determination of the ALARP region, including Probability, Severity, and detectability dimensions. In the first step, the scale is set for Probability and Severity factors; based on the location of the score; it is transferred into the matrix, including detectability see Figure 63. Detectability has a reversed qualitative scale.

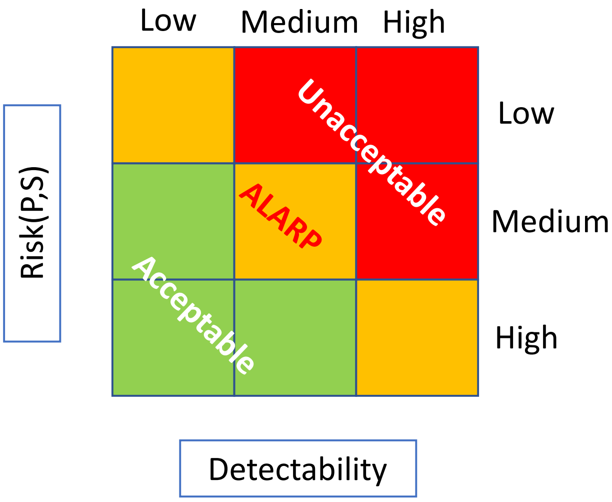
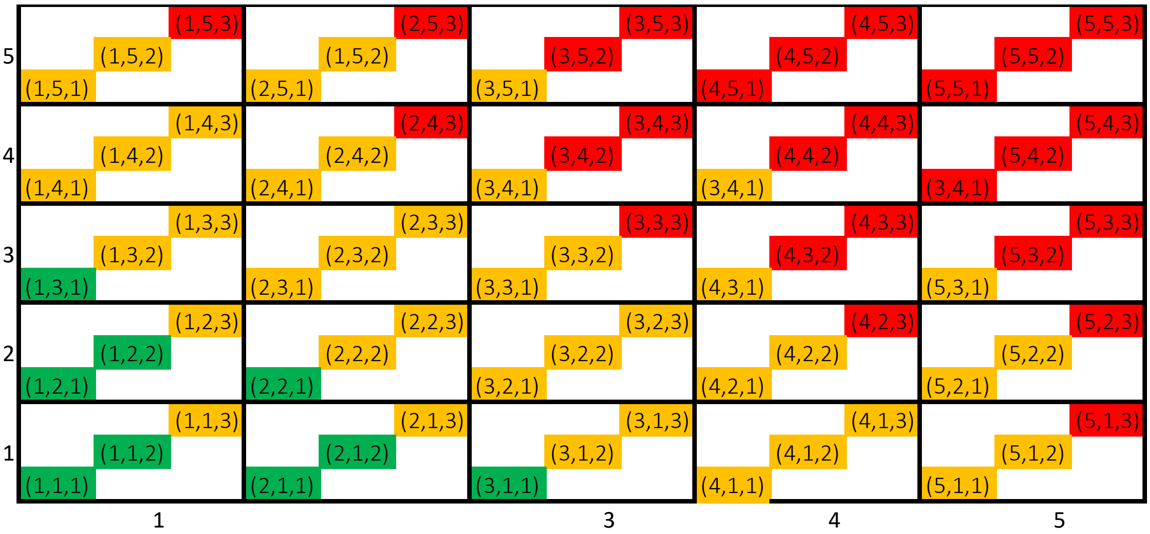


Figure 63. Schematic determination of ALARP using three dimensions.

To determine the location of the score, a two-dimensional matrix is used in Figure 62. Thus, the score can be located in one out of three zones. To determine acceptability limits, combinations are represented in Figure 64. The first number represents Occurrence (P), the second Severity (S), and the last detectability. For simplicity, detectability levels are represented by their actual number.



5	🟥 (1,5,3) 🟨 (1,5,2) 🟨 (1,5,1)	🟥 (2,5,3) 🟨 (1,5,2) 🟨 (2,5,1)	🟥 (3,5,3) 🟥 (3,5,2) 🟨 (3,5,1)	🟥 (4,5,3) 🟥 (4,5,2) 🟥 (4,5,1)	🟥 (5,5,3) 🟥 (5,5,2) 🟥 (5,5,1)
4	🟨 (1,4,3) 🟨 (1,4,2) 🟨 (1,4,1)	🟥 (2,4,3) 🟨 (2,4,2) 🟨 (2,4,1)	🟥 (3,4,3) 🟥 (3,4,2) 🟨 (3,4,1)	🟥 (4,4,3) 🟥 (4,4,2) 🟨 (3,4,1)	🟥 (5,4,3) 🟥 (5,4,2) 🟥 (3,4,1)
3	🟨 (1,3,3) 🟨 (1,3,2) 🟩 (1,3,1)	🟨 (2,3,3) 🟨 (2,3,2) 🟨 (2,3,1)	🟥 (3,3,3) 🟨 (3,3,2) 🟨 (3,3,1)	🟥 (4,3,3) 🟥 (4,3,2) 🟨 (4,3,1)	🟥 (5,3,3) 🟥 (5,3,2) 🟨 (5,3,1)
2	🟨 (1,2,3) 🟩 (1,2,2) 🟩 (1,2,1)	🟨 (2,2,3) 🟨 (2,2,2) 🟩 (2,2,1)	🟨 (3,2,3) 🟨 (3,2,2) 🟨 (3,2,1)	🟥 (4,2,3) 🟨 (4,2,2) 🟨 (4,2,1)	🟥 (5,2,3) 🟨 (5,2,2) 🟨 (5,2,1)
1	🟨 (1,1,3) 🟩 (1,1,2) 🟩 (1,1,1)	🟨 (2,1,3) 🟩 (2,1,2) 🟩 (2,1,1)	🟨 (3,1,3) 🟨 (3,1,2) 🟩 (3,1,1)	🟨 (4,1,3) 🟨 (4,1,2) 🟨 (4,1,1)	🟥 (5,1,3) 🟨 (5,1,2) 🟨 (5,1,1)
	1		3	4	5

Figure 64. Combinations of factors values used to determine the ALARP region

The following calculation of the ALARP region for RiCS is determined based on this matrix, contrary to previously adapted speculative scenario-based limits (Plüss, 2015). Based on the matrix mentioned above, the following thresholds of RiCS are defined, as depicted in Figure 65. The lower limit corresponds to 3.75, and the upper limit to 6.54.

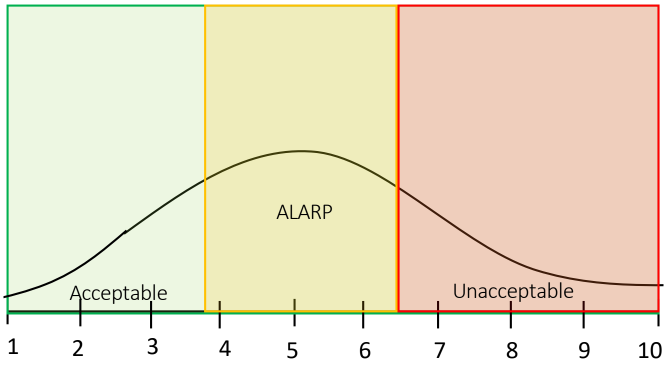


Figure 65. ALARP limits, lower 3.75 and upper 6.54.

Even though these limits are defined more objectively than previously (Plüss, 2015), the initial judgments on the ALARP region in the two-dimensional matrix remain relatively subjective, see Figure 62. These judgments are either done by the institution's board or can be based on the existing acceptability limits in compliance with existing regulations or safety practices. Limits can remain the same for all the hazards for comparability; however, in some instances, when risk perception of specific hazards is higher, they can be lowered.

5.6 Risk treatment

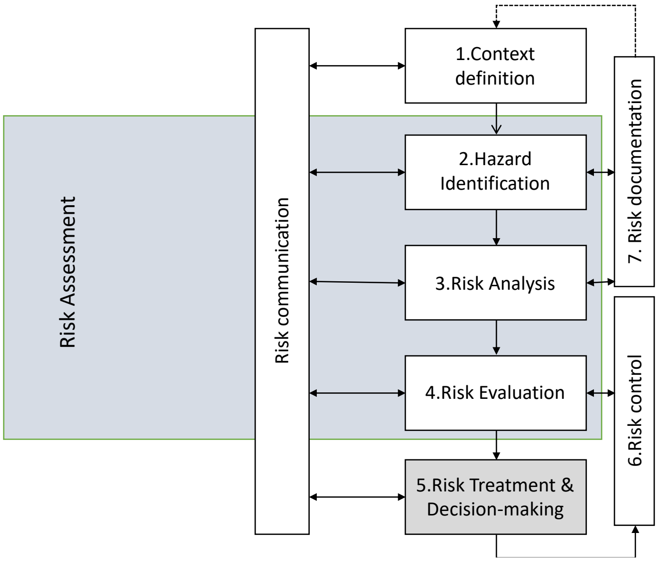


Figure 66. LARA+D workflow, risk treatment step.

Many publications in the field of risk management are devoted to different risk analysis techniques; however, the main objective of risk management is its treatment. Risk identification and quantification serve only as an intermediary step. Decisions on the risk treatment are not based solely on the level of the risk and their relative importance. Other factors can be crucial, especially when it concerns risk prioritization.

The amount of the resources used for risk treatment shall be proportioned with the magnitude or potential of the risk. Any decision-making problem exists only when there is an issue of choice. The choice is limited by different factors, which have not only financial nature. The same concerns risk treatment and selection of safety measures. If the risk treatment were only limited and based on the risk index, no decision problem would exist. However, the selection of safety measures is strongly connected to the financial aspect (Aven, 2011), the risk reduction potential of the measure (Cox, 2012), time, availability, etc. Especially in such a strongly influenced human behavior environment as academia, it is essential to consider other factors. In an environment where all the processes and work ergonomics are organized according to regulation, financial and technical specifications could be sufficient for decision-making. Due to its higher flexibility, Academia requires other factors integrated into the safety decision-making process to select efficient safety solutions.

In the previous chapter, RiCS values for all analyzed risks are calculated and evaluated against the established acceptability limits (ALARP), and the decisions on implementing safety measures are made. The regular work can be continued for the risks in the acceptable RiCS range (green on the matrix); no additional measures need to be implemented. The risks in the unacceptable range need to be treated until they either fall into the acceptability range or ALARP when a decision on their further treatment is made. In Academia, risk analysis is often conducted for designed and operating processes. It also limits the selection of possible safety solutions.

In LARA+D, several approaches were used to create a database of safety measures. STOP principle (see 2.3.5) is used to assist analysts when accessing the risk reduction potential of the measure. Secondly, all measures are classified based on their legal status: binding or recommendations. A limited number of binding measures must be integrated when working with one or another hazard, as there is a general requirement for protection. Moreover, depending on whether the application of the measure is based on the legislation or local ordinances, the legal status of the measure will vary. Each corrective measure suggests which risk dimension this measure affects to guide the analyst. The analyst decides the magnitude of this effect, as it will depend on the initial risk values. All the assessments are stored in the database and can be modified if necessary.

Often, several safety solutions can reduce risk to acceptable limits. However, their costs will be different. Two types of costs are considered for comparison and assessment purposes, see Figure 67. The first type is installation/purchase cost. For some measures, it will be a combination of two; for others, only one. For example, fumehood will have its purchase price, depending on the producer, technical specifications, etc., and will require installation. Installation cost will constitute manpower estimated on the hourly rate and infrastructural modifications required for the installation of such measure. Apart from this initial cost that is calculated and paid before the measure is installed, it will have some operational costs that will constitute maintenance and the cost of electricity. Thus, the costs are classified based on their longevity in time. One type of cost appears uniquely at one moment of the time– implementation of the measure; the second one accompanies the use of the measure and is continuous.

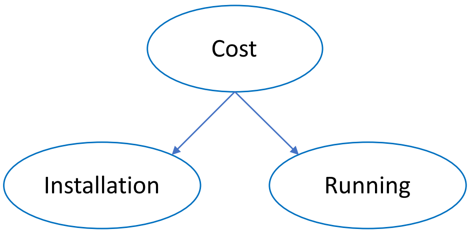


Figure 67. Types of the cost are used to estimate the safety measure's financial aspect.

Comparing different types of measures, using STOP classification, in the majority of the cases, the following will remain true:

- Strategic. Both types of costs can have a place, as the substitution of the Hazard can include modification of the equipment and difference in price for the substituted Hazard.
- Technical. Both types of costs exist. Technical safety measures will always have some running costs, which in some instances can be considered negligible.
- Organizational. Depending on the measure, both costs can have a place; however, as the organizational measures often have continuous use, running costs are high.
- Personal. The majority of cases will have mainly installation/purchase costs.

To be able to compare the costs of different measures, amortization over five years is used. This time frame is selected based on the assumption that most projects will run without significant modifications in five years. Previously, ten years amortization period was selected (Plüss, 2015), which was complicated for the analyst and user.

To select the preferable safety solutions, it is vital to consider their efficiency. The efficiency of the measures is not limited to their risk reduction potential but also must be evaluated in the context of the analyzed process, working environment, and people using these measures (Eggemeier, 1988). We suggest classifying the factors accessing efficiency of the measure based on technical and human reliability of the measures. The term reliability is used to describe the quality of the performance of the measure and its capacity to work as intended.

Human Reliability

Different safety measures will have a different degree to which their performance can be affected by the individual using them. It is way more complicated to bypass a technical measure than not to use PPE (personal protective equipment).

Sensitivity to human factors (SHF) is the extent to which the normal and intended performance of the measure can be affected by the human intervention directly affected by this measure. The reliability of measures with different sensitivity (SHF) in the same environment will be different, while the reliability measures of the same sensitivity will also vary in the different settings.

To access the SHF of different measures, we use the STOP classification. Similar to the hierarchy of control, where the measure's efficiency decreases moving from top to down, SHF is increasing, see Table 44.

Type of the measure	Value
S	1
T	0.9
O	0.8
P	0.7

Table 44. Sensitivity to human factors (SHF) according to to STOP classification.

In the case of strategic measures, a new assessment is required to estimate potential risk.

Acceptability

Acceptability (A) describes the extent to which the safety measure is accepted for usage by the individual directly affected and potentially using it. If the acceptability of the measure is low, a person(s) will always evade its usage. Thus, it will impact the overall effectiveness of the measure. There can be objective and subjective reasons for the low acceptability of the measure. Knowledge about such can improve the acceptability of the measure.

Example: Use of safety googles in the non-airconditioned area can have a low acceptance, as most safety googles accumulate fog within minutes of work and are thus rejected by employees.

Simplicity

Simplicity (S) describes the laboratory staff's ease of operation and use of the measure. If the safety measure is difficult to use, most likely, it will affect its acceptability. However, simplicity will depend on the activity, and generally, a well-accepted measure can be challenging to use in the analyzed process.

Example: Thermaprene gloves can be highly cumbersome, especially if they do not fit correctly and the activity requires various manipulations.

Safety Climate will impact perception and motivation to use the measure. It can play a positive role, stimulating to use of safety measures even if the user can bring a physical inconvenience; on the contrary, even highly acceptable measures will not be used if the working environment affects safety motivation (Kalugina and Meyer, 2021).

Thus, the human reliability of the measures can be calculated using the following formula:

$$\mathrm{HR}=\frac{(A+S)^{SHF}}{10} \qquad \textit{Equation 39}$$

Technical Reliability

Another group of factors is not connected to their use by the staff and is more technical. Technical reliability is meant to assess the measure's technical performance without considering human-measure interaction.

Compatibility with Process

Process Compatibility (CP) describes how well a particular measure is compatible with the process. It means that this measure needs to be compatible with the process and equipment used during it. Low process compatibility will significantly affect the effectiveness of the measure.

For example, "snorkel exhaust fume hood/elephant trunk" will have low compatibility when working with high amounts of highly volatile substances.

Compatibility with Environment

Compatibility with the environment (CE) defines the extent to which safety measure is compatible with the surrounding environment. Contrary to CP, the process is not relevant here, but the "ergonomics" or organization of the physical space of the room. For example, in a nosy environment a sound alarm will have very low compatibility.

To calculate technical reliability, the average from the process and environmental compatibility are taken; see equation 40.

$$TR = \frac{CP + CE}{10} \quad \textit{Equation 40}$$

To express non-financial factors with a single value, they are combined in a general reliability factor (GRF). It consists of human and technical reliability (HR and TR). This measure multiplied with risk reduction will give an analyst information on the actual risk reduction potential of the safety measure. This general risk reduction (GRR) is calculated using the following formula:

$$GRR = GRF * \Delta RiCS = (\omega_{HR} \cdot HR + \omega_{TR} \cdot TR) * \Delta RiCS = (0.8 \cdot HR + 0.2 \cdot TR) * \Delta RiCS$$

Equation 41

GRF can attain the maximum value of 100% or 1. The relative weights for HR and TR are determined based on the average contribution of a human error to the accident rate (Pasquale *et al.*, 2016).

5.7. Decision-Making

The main purpose of any risk assessment is the decision-making. It can be any decision: to take or not any actions, and if yes, we need to know which ones. Resource allocation problem arise as a shadow companion of decision-making. Decision aiding tools are meant to help us resolve this issues, ease selection of the most suitable alternatives, thus efficiently allocate available resources. In the context of this project, decision aiding tool is not only meant for this purpose, it also significantly impacted the structure of risk assessment method.

After the list of safety measures was identified, their efficiency, both from the risk reduction and non-financial perspective, was assessed, and required costs estimated; the next logical step is the selection of the most optimal solutions from this list. It can be done using different resource allocation matrixes (Plüss, 2015) or decision-making matrixes. In the second case, all decision-making factors are combined in one matrix, which shows their contribution, a total score of the alternative, and ranking.

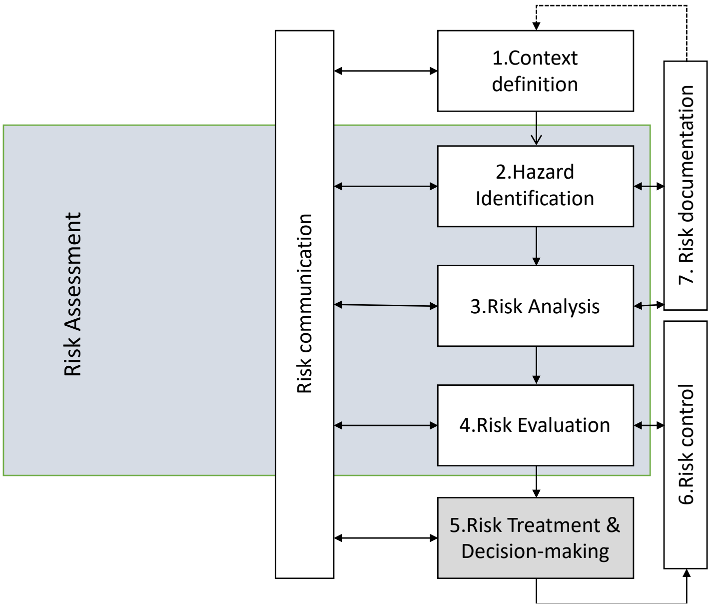


Figure 68. LARA+D workflow, decision-making step.

Decision-aiding can be very useful tool to facilitate decision-makers selection of the appropriate solutions. No decision-aiding tool is meant to substitute the real process of decision-making. However, the main reasons why such tools even exist are:

- Limited capacity of human brain to tackle a lot of information simultaneously
- The need to decrease biases of decision-maker
- The need of objectivity
- Absence of clear preferences
- Contradiction of goals among various stakeholders

Integration of decision-aiding tool as an essential part of any management system can help to resolve all above-mentioned issues and effectively reduce risks.

5.7.1 Identification of decision-making factors

Two types of decision-makers are present during the selection of safety measures: OHS services and Research Laboratory. One can be considered an expert; for this decision-maker, safety is the primary objective. While for the second one, it is an intermediate operational objective. Thus, there is less involvement and knowledge available.

Participant observations helped to identify challenges met by safety experts during safety visits, such as the unwillingness of some participants to modify their working habits or their colleagues, existing cultural differences of the participants that influence the quality and reliability of received information, strong dependence on the safety attitude and acceptability of proposed measures from the lab manager. Discussion with safety experts highlighted that preference among the measures would vastly depend on the knowledge about laboratory safety background, manager attitude, available finances, and safety level.

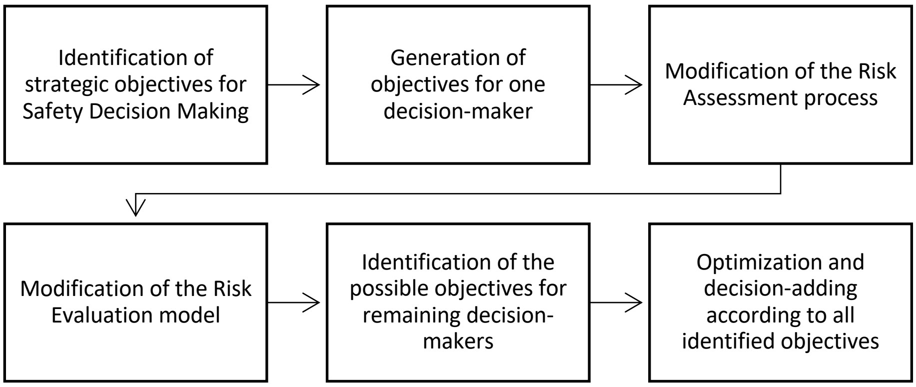


Figure 69. Flowchart of the research process.

Three strategic objectives determined further exploration of decision-making drivers. As one of the decision-makers is an expert in the field, based on the discussions with representatives and the case study, the list of the following objectives was identified, see Figure 70. These objectives correspond to three previously identified strategic objectives: research, safety, and finance.

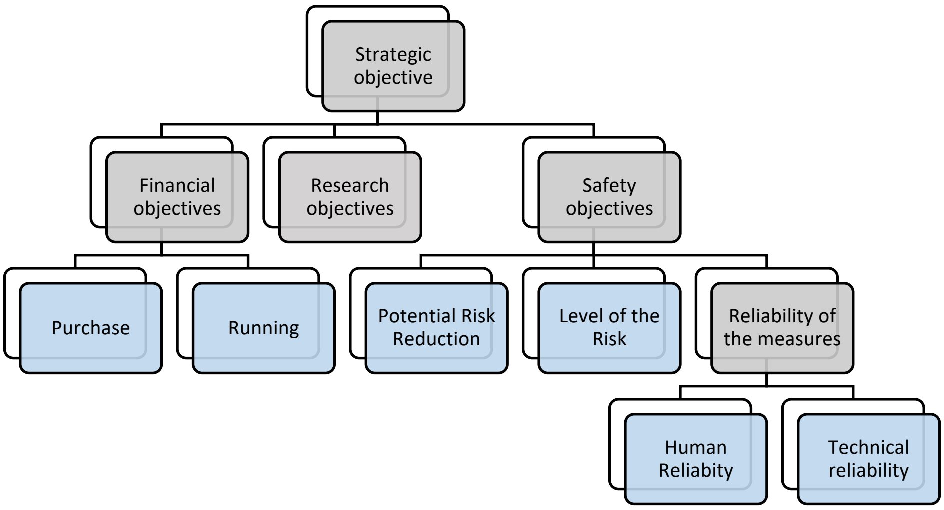


Figure 70. The first decision-maker identifies objectives in blue.

The objectives mentioned above were implicit. Objectives describing the reliability of the measures were the vaguest and were formalized as human and technical reliability, comparing literature review and safety experts' discussions. These primary objectives, see Figure 70 required modification of the risk assessment process.

To help the second decision-maker to identify decision-making objectives a short presentation introducing the context and scope of the interview was presented before interviewing. The presentation provided an overview of the risk assessment and its significant differences from audit and included factors shown to potential decision-makers to give a better introduction problem. The presentation consisted of 8 slides (10-12 minutes).

Initially, interviews were planned as structured using a modified question list proposed by Keeney (Keeney 1996). However, since the beginning of the first interview, it became clear that the unstructured form of the interview can bring more light to the vision of safety.

As the primary goal of the interview was to identify which information might be relevant for this group of the decision-makers, two topics were covered during the interviews:

1. Risk assessment. Specific features of the risk analysis tool which would benefit the laboratory.
2. Decision-making. Way of communication and information are considered significant during the selection process.

All the respondents were willing to discuss their vision of safety at EPFL, existing problems, and possible strategies to improve overall safety. Discussions can be classified into the following topics:

1. Educational objectives of PI's
2. Research objectives of the group
3. Social objectives of the group
4. Safety expectations from other safety management tools
5. Communication
6. Individual responsibility.

The detailed output of the discussion is included in Attachment C0.

5.7.2. Ranking of the alternatives

Multi-criteria optimization's goal is to find a solution to a decision problem by choosing the "best" among a set of alternatives. In order to do so, predetermined criteria are used to measure the "quality" of existing alternatives (Ehrgott, 2005).

Interviews with decision-makers clarified the structure of the decision-making matrix. Contrary to previous work (Plüss, 2015) , all non-financial factors were aggregated into one complex factor – Feasibility, Human and Technical Reliability- were kept as independent criteria for decision-making. Thus, aggregation using FAHP (see chapter 2.4.7) was not used in the final version of LARA+D. The use of other methods, such as FTOPSIS and ELECTRE, was also rejected for the reasons discussed in Chapter 3. The two-reference approach was selected as the basis for the decision-aiding block of LARA+D.

To proceed with the calculation, it is essential to prepare data. There are two types of factors; those with a "negative" value for decision-makers and those that can be considered "positive". Risk level and costs are "negative" factors, as the decision-maker would like to have them as low as possible. On the other hand, Technical and human reliability is "positive" and expected to be as high as possible. To treat data together, "negative" factors have to be reversed. Thus, the aspiration and reservation levels for these factors are opposite to "positive".

At the first step of the calculation, lower and upper points q_i^{l0} and q_i^{up}p are determined for all the factors, see Figure 71. Afterward, individual achievement functions are calculated, see chapter 3.2.4. The overall achievement function is used to rank alternatives.

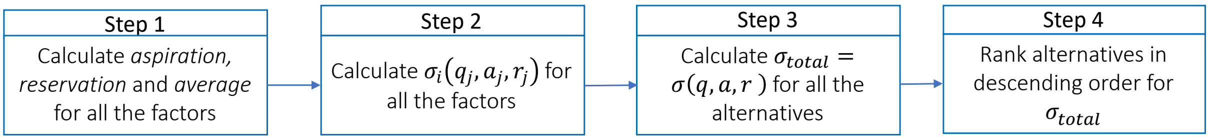


Figure 71. The workflow for the optimization algorithm.

Example. To demonstrate application of the optimization algorithm and further usage we use as an example decision-making matrix represented in Table 45.

Safety measure	RiCS (q_1)	ΔRiCS (q_2)	HR (q_3)	TR (q_4)	Implementation cost, CHF (q_5)	Running cost (q_6)
Use warning signs in gas storage areas	7.1	0.2	0.65	1	40	80
Eliminate all ignition sources	6.7	0.6	0.53	0.8	6900	200
Ensure gas equipment is in good operating order	7.1	0.2	0.42	1	0	1500
Equip the lab with gas-specific detectors	5.5	1.8	0.72	1	2500	500
Keep away from heat sources	6.5	0.8	0.53	0.8	4800	700
Store large gas cylinders in explosion-proof cupboards	6.3	1	0.42	0.6	8500	500
Use explosion-proof equipment	6.6	1.8	0.65	0.6	1600	150
Use flashback arrestors	5.5	1.8	0.65	0.9	350	1000

Table 45. Data for a risk analysis example. Input for optimization.

STEP 2 & 3. After, reservation, aspiration and averages were determined for all the factors artial and overall achievement functions are calculated for the further ranking, see Table 46. Formulas used for calculation are discussed in details in chapter 3.2.4. Two types of calculation were tested: with equal and hierarchal importance of criteria. The current version of LARA+D adapts approach of equal importance, however allows user to make modifications if necessary.

Safety measure	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6	σ_{total}	rank
Use warning signs in gas storage areas	**0.00**	**0.00**	**1.05**	**3.86**	**3.00**	**2.95**	**1.09**	**5**
	0.00	*0.00*	*0.87*	*3.86*	*3.86*	*3.00*	*0.99*	*5*
Eliminate all ignition sources	**0.31**	**4.03**	**1.06**	**1.78**	**1.79**	**2.81**	**1.49**	**4**
	0.21	*2.78*	*0.93*	*1.78*	*1.79*	*0.94*	*1.05*	*4*
Ensure gas equipment is in good operating order	**0.00**	**0.00**	**0.00**	**3.86**	**2.44**	**1.22**	**0.75**	**8**
	0.00	*0.00*	*0.00*	*3.86*	*2.44*	*0.41*	*0.67*	*7*
Equip the lab with gas-specific detectors	**1.23**	**18.34**	**3.92**	**3.86**	**4.00**	**2.44**	**4.61**	**1**
	0.82	*17.15*	*5.66*	*3.86*	*4.00*	*0.82*	*4.05*	*1*
Keep away from heat sources.	**0.46**	**5.03**	**1.06**	**1.78**	**2.84**	**2.20**	**1.80**	**3**
	0.31	*3.78*	*0.93*	*1.78*	*2.84*	*0.73*	*1.35*	*3*
Store large gas cylinders in explosion-proof cupboards	**0.62**	**6.03**	**0.00**	**0.00**	**0.99**	**2.44**	**1.01**	**6**
	0.41	*4.78*	*0.00*	*0.00*	*0.99*	*0.82*	*0.70*	*6*
Use explosion-proof equipment	**0.39**	**4.53**	**1.05**	**0.00**	**0.00**	**2.87**	**0.88**	**7**
	0.26	*3.28*	*0.87*	*0.00*	*0.00*	*0.96*	*0.54*	*8*
Use flashback arrestors	**1.23**	**18.34**	**1.05**	**3.78**	**2.62**	**1.83**	**3.93**	**2**
	0.82	*17.15*	*0.87*	*3.78*	*2.62*	*0.61*	*3.20*	*2*

Table 46. An example of objective ranking for the data from Table 21, with different coefficients.

For values in **bold**, we assumed that all factors have equal importance and achievement functions are neutral; thus, $\alpha = 3, \beta = 7$. Modifications of the importance q_1, q_2 – high; q_3- very high; q_4, q_5- neutral, and q_6 - very low change partial and overall achievement functions but do not impact the overall, except for measures 8 and 7, Table 46 (values in *italic*).In the second case, following coefficients were used: $\alpha = 3, \beta = 7 \text{ for}$ q_4 and q_5; $\alpha = 2, \beta = 6 \text{ for}$ q_1 and q_2; $\alpha = 1, \beta = 5$ for q_3 and $\alpha = 5, \beta = 9$ for q_6.

STEP 4. Based on Table 46 (neutral coefficients) following decision-making matrix is provided for the decision-maker. It includes information on the efficiency of the measures with the initial risk level and the ranking of these measures, see Table 47.

Safety measure	RiCS (q_1)	ΔRiCS (q_2)	HR (q_3)	TR (q_4)	Implementation cost (q_5)	Running cost (q_6)	Rank
No measures	7.6	-	-	-	-	-	
Use warning signs in gas storage areas.	7.1	0.5	0.65	1	40	80	5
Eliminate all ignition sources	6.7	0.9	0.53	0.8	6900	200	4
Ensure gas equipment is in good operating order	7.1	0.5	0.42	1	0	1500	8
Equip the lab with gas-specific detectors	5.5	2.1	0.72	1	2500	500	1
Keep away from heat sources	6.5	1.1	0.53	0.8	4800	700	3
Store large gas cylinders in explosion-proof cupboards	6.3	1.3	0.42	0.6	8500	500	6
Use explosion-proof equipment	6.6	1	0.65	0.6	1600	150	7
Use flashback arrestors	5.5	2.1	0.65	0.9	350	1000	2

Table 47. Decision-aiding matrix with the ranking of measures.

For the initial value of RiCS, ALARP thresholds are used, see Figure 65. The table below was used to determine different acceptability limits for the following factors.

	Low (Red)	Medium (Orange)	High (Green)
Delta RiCS	<10%	$10\% \leq value$	$20\% \leq value$
HR	<0.3	$0.3 \leq value$	$0.5 \leq value$
TR	<0.6	$0.6 \leq value$	$0.7 \leq value$
Cost	>2*installed budget	$\geq 1.5 * \text{installed budget}$	
RiCS	<6.54	$6.5 \leq value \leq 3.75$	$value > 3.75$
SC	<0.57	From $0.57 \leq value \leq 0.73$	$value > 0.73$
WE	<2.25	$2.25 \leq value$	$1.5 \leq value$

Table 48. Acceptability limits are used for the decision-making matrix.

In the example above, see Table 47, the corresponding expectations on the budget were not set; thus, no corresponding thresholds were determined.

Enhancement of LARA. The previous version of LARA was not limited only to risk analysis but provided decision-makers with several mechanisms for ranking, see Table 49. There was no optimal ranking mechanism, the analyst needed to select measures based either on: the priority of ΔRiCS/cost, ΔRiCS priority, or resource allocation matrix.

N°	Safety measure	$\Delta\mathrm{RiCS}$/cost 10^5	F	Priority $\Delta\mathrm{RiCS}$/cost	$\Delta\mathrm{RiCS}$ priority	**Objective ranking**
1	Use warning signs in gas storage areas	400	0.825	1	7-8	**5**
2	Eliminate all ignition sources	13	0.665	8	6	**4**
3	Ensure gas equipment is in good operating order	33	0.471	5	7-8	**8**
4	Equip the lab with gas-specific detectors	70	0.86	3	1-2	**1**
5	Keep away from heat sources	21	0.665	6	4	**3**
6	Store large gas cylinders in explosion-proof cupboards	15	0.51	7	3	**6**
7	Use explosion-proof equipment	57	0.625	4	5	**7**
8	Use flashback arrestors	156	0.775	2	1-2	**2**

Table 49. Comparison of ranking approaches proposed by this thesis and previously used in LARA. Where F – is Feasibility (Plüss, 2015)

As demonstrated in Table 49, the ranking of the measures is entirely different depending on the selected factors. Contrary to objective ranking, the other two prioritization approaches illustrated in the table above are limited to max two factors and do not consider others, which imposes biases. Ranking measures based only on the risk reduction priority will not help decision-makers to select among the measures with similar risk reduction potential. The only other method proposed by the previous work, including all the essential decision-making factors, is the resource allocation matrix, see Figure 72.

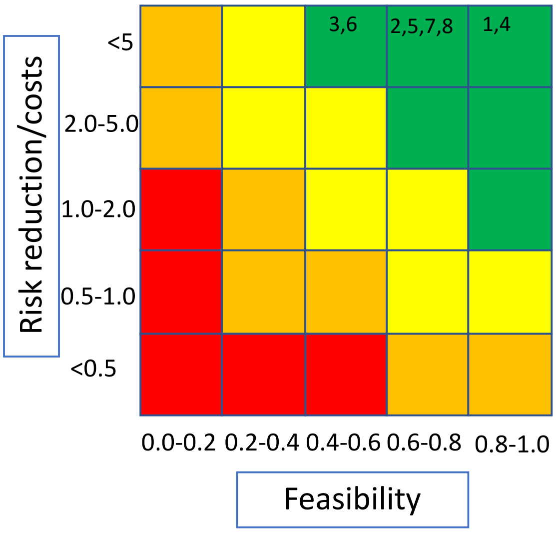


Figure 72. Resource allocation matrix proposed by Pluess (2015).

However, using the resource allocation matrix proposed earlier (Plüss, 2015) complicates the decision-making process, as the alternatives are concentrated in one part of the matrix. This problem was identified by various risk assessments conducted previously (Jung, 2018). Often, several measures were concentrated in the same cell of the resource allocation matrix, thus complicating the decision-making process.

Using information provided in Table 47 to select safety alternatives can significantly ease the decision-making process. Decision-making matrixes are widely spread for selecting alternatives when several factors need to be considered. It provides the decision-maker not only with the information on all the factors but suggests which alternative would be the most suitable for the case. For the laboratory, the financial aspect will be the least important if the source of the financing is not a laboratory. On the other hand, compatibility of measures with the working environment, their acceptability by the employees, and ease of use would be crucial when selecting between the measures. For other decision-makers, financial criteria can be more critical if there is a big difference in the cost of the measures and solid financial constraints with the budget. The optimization algorithm used to rank the measures acts as an interface between different groups of decision-makers and provides them options for further negotiations. Decision-making matrix provides user not only with the potentially most optimal solutions, but allows a flexibility between different preferential scenarios, thus adapting to each particular situation and circumstances.

Expanding decision-making to the whole process increases the number of hazards for evaluation but the difficulty of selection between alternatives and resource allocation. Accumulating all individual decision-making matrixes in one will give the decision-maker an overview of potential costs. It can help to select those measures that will efficiently reduce the risk of various hazards.

5.8 Risk control

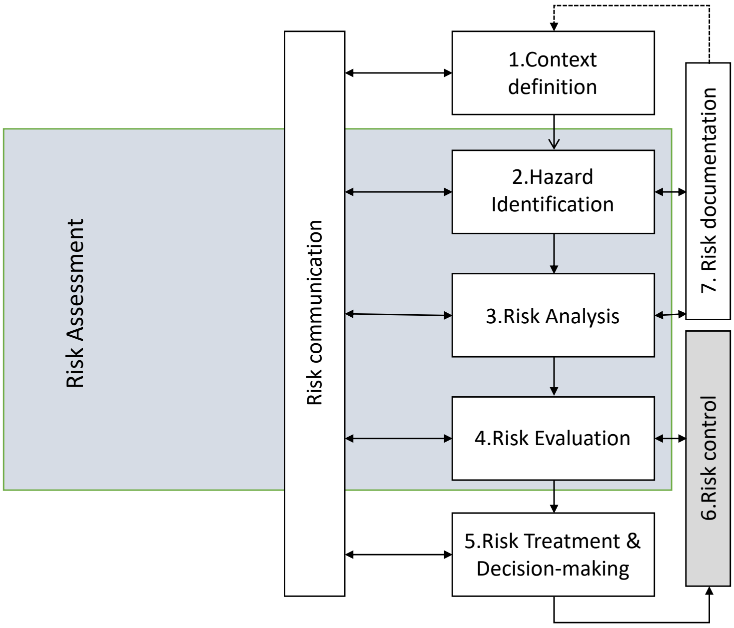


Figure 73. LARA+D workflow; Risk control.

Risk control is the next step in LARA+D. In general, the risk management process is continuous; it includes many iterations to control and improve existing situations. One of the responsibilities of OHS service is to ensure that decided measures are implemented and used as intended. Even though safety measures are meant to reduce risks, sometimes they modify the risk or become the source. To avoid potential risk transfer, implemented safety measures need to be periodically controlled. Structural reorganization changes the management objectives, operational goals, etc., which influences safety management. These context changes need to be addressed accordingly.

Definition of the context. Changes will differ depending on the context type: macroscopic, organizational, or technical. If the broader context is modified, changes most likely won't be rapid, but they will be significant and impact the whole system. In the case of organizational context, the system needs to be observed permanently, as the change in responsibilities and roles can affect the efficiency and performance of the system. The technical context will depend on the two levels mentioned above and the technical capacity.

Hazard Identification. The LARA+D database is a crucial element that allows its functioning and makes this tool suitable and efficient in the set environment. To reach this goal, the database shall be as extensive as possible. However, it is designed in a way that hazards can be entered or specified if some new knowledge becomes available. The system administrator, part of the OHS service, is responsible for such modifications.

Risk analysis. With the development of the database with new knowledge and applicational examples of the assessment, some modifications are possible. These modifications may include adjustments of the scales, weights, uncertainties, hazard associated worsening factors. These changes should be a subject of approval, as the user can impose a particular bias. The risk calculation represents the relationship between different dimensions and can be modified if the practice demonstrates that initially assumed relationships are not accurate enough.

Risk evaluation and treatment. Changes in the context will always impact how risks are evaluated and treated. It includes the factors needed for assessments, such as financial, reliability, risk related, etc., how they are assessed, and risk acceptability levels. If the calculation is modified, it influences the acceptability scale and requires appropriate modifications.

5.9 Risk documentation

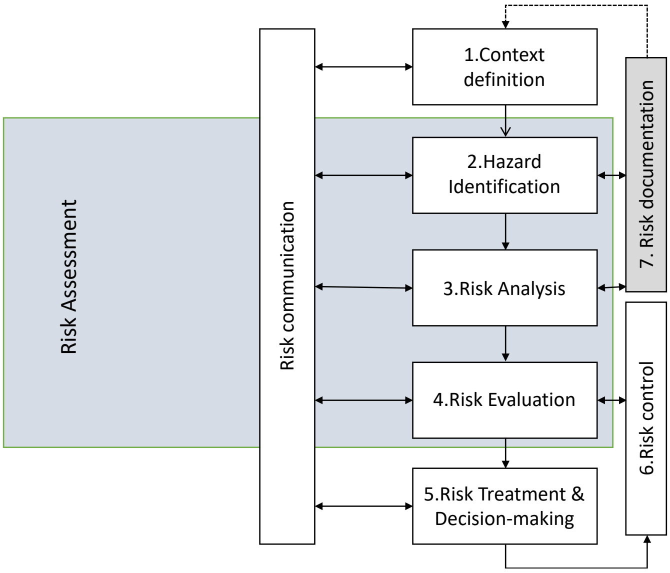


Figure 74.LARA+D workflow; Risk documentation.

Risk documentation is necessary for any risk management process and supports continuous learning and safety improvement. Depending on the macroscopic context, the requirements for the context and level of detail in the documentation/reporting might differ. It will also depend on the final user for whom this document is intended. In LARA+D detailed risk assessment report is generated. The form and content of the report were consulted with the decision-makers involved in the safety management process. Documentation in LARA+D contains the following information about each step of the process.

Definition of the context. In this part, the roles and responsibilities are stated. It also includes general information about the laboratory, room, safety climate, working environment assessment, and an available description of the process.

Hazard Identification. This step records all the hazards identified by the analyst, their presence in the steps, associated failures, and sources of risks. This kind of detailed documentation is also helpful for possible accidents investigation if they happen in a similar context, simulation of different scenarios, and improvement of the analysis approach.

Risk analysis. As the calculation method and underlying factors can be subject to modifications due to the context change, LARA+D keeps a detailed record of how particular assessment and calculation was made and the details of the calculation method. So that results and assessments can be reproduced or analyzed for further information.

Risk evaluation and treatment. LARA+D keeps track of the acceptability limits defined for different assessments. It allows constant modification and improvement of safety management in academia and holds the record of the existing risks.

To provide a user with a time-efficient tool, which is also helpful for a non-expert user, LARA+D keeps track of the different aspects of safety measures in its database. It includes costs, type of safety measures: mandatory or recommended, their classification, and corresponding efficiency according to STOP.

Risk control. LARA+D allows documentation of the follow-up of the risk treatment. It means that risks can be reassessed after specific safety improvements are made. The system will keep a record of these safety improvements.

5.10 Risk communication

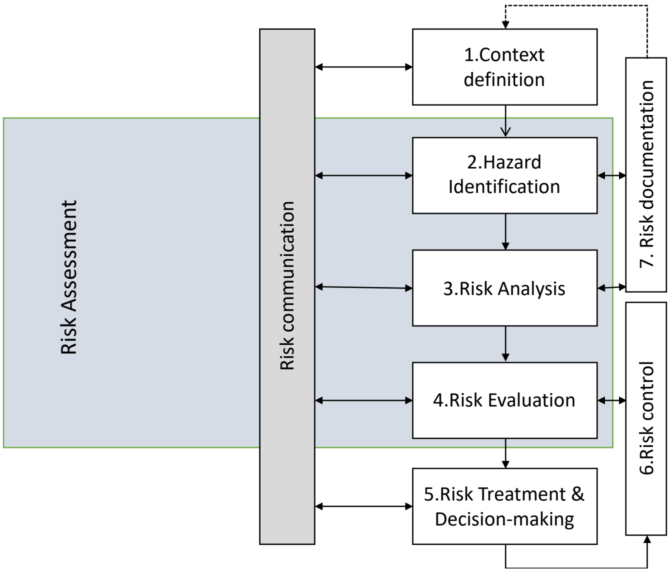


Figure 75.LARA+D workflow; Risk communication.

Risk communication is an iterative step in the LARA+D workflow. It affects all aspects, including the type and how to input information is collected, how it is evaluated, which outputs are generated, and how they can be presented. Risk communication is essential, as the decision-making and implementation depend on it.

Communication helps to transfer and improve existing knowledge, thus improving overall safety. However, disclosing information always bears certain risks. Making the results of assessments available and accessible can help to reduce accidents, as it will raise awareness; on the other hand, information on the novel processes that are still unpublished should remain confidential. The OHS service, along with the university board, is entitled to decide which part of information generated by LARA+D can be available for a broader audience and which shall be kept only for limited access.

Since LARA+D is designed for research labs in academia, one of the expectations is non-expert users in the laboratories can use that method. This tool can be used as a practical exercise for risk assessments. Thus, some of the simulated and experimental examples of these assessments should be available for educational purposes.

5.11 Concluding remarks

The goal of this project is not only to provide research laboratories in academia with an efficient process risk analysis method but to design a risk management tool that will cover all the stages of safety management, guiding users through the decision-making process as well. To successfully include LARA+D in the existing safety framework of EPFL, it was necessary to determine the general framework and context, its place, and applicational expectations. The developed tool was a continuous work on enhancing the process risk management technique, which started earlier.

All its specificities were considered and addressed to provide decision-makers with a holistic tool suitable for the academic environment. One of the main requirements of the tool was integration and consideration of the human influence aspect. It was done from two perspectives. First of all, LARA+D considers and includes in its risk analysis model different organizational, ergonomic, social, etc., factors present in the laboratory. These factors are used for the calculation of the risk index. The safety-II approach demonstrates that experts' expectations about how a particular function works are often different from reality. Unfortunately, implementation of the existing Safety-II techniques is not feasible in academia due to their high time and resource consumption. However, the intermediate strategy is selected to provide decision-makers with a better understanding of the actual situation and thus secure "better" decision-making. This strategy implies evaluating the efficiency of different safety solutions in terms of their use and performance by humans.

However, humans are not the only reason existing risk analysis techniques are not applicable in academia. New processes, not conventional equipment, require specific assessment and consideration. One of the ways to take this peculiarity into account is to evaluate the efficiency of the proposed safety solutions for the analyzed context. LARA+D provides users with detailed information on the risk reduction potential, both expected and actual, human and technical efficiency of the measures, and an overview of different types of costs. A report from different angles is meant to give decision-makers a complete picture of the situation and potential solutions. The ranking algorithm, which uses only available data without the preliminary requirement of the preferences, is meant to provide users with general guidance and recommendation.

The absence of historical data is another drawback in academia. It does not allow to implementation of quantitative methods or makes the use of such utterly useless due to their low reliability and precision. On the other hand, entirely qualitative approaches do not give sufficient information for decision-making and do not allow a good comparison of the risks. The semi-qualitative approach is meant to overcome or at least reduce this problem.

Even though it is expected that the use of a semi-quantitative approach bears some uncertainties in the evaluation, it is not always explicit. The use of Bayesian networks, which takes into account the uncertainty of the expert's evaluation, is meant to increase the reliability of the method and the usefulness of obtained results.

While there is guidance on how the severity of the accidents can be determined, it is difficult to do the same for the frequency/probability if there is no or limited knowledge available. It makes such judgment wholly intuitive and very biased. The absence of clearly established guidance on determining this aspect of the risk also results in the low reliability of any method. Introducing failure contributing, along with the influencing safety climate and working environment factors, is meant to solve this problem. Failure contributing factors, serve not only as guidance of probability of potential failure or incident in the analyzed process but are intended to reduce expert bias and make the assessment less intuitive by factual.

The diversity of laboratories and processes often makes hazard portfolios very complex. The hazard classification was based on two pillars to complete risk analysis more efficiently from the time perspective and avoid unnecessary repetition. The first factor considered was "what is the route of exposure?" or "how the harm can be made?". The second aspect was "how this harm can be prevented or mitigated?". To ensure that the hazard database is exhaustive and no hazards and associated risks are omitted, the safety experts approved the database at EPFL.

The result of the risk analysis is meant to be available and communicated to all stakeholders of the process. It implies the distribution of reports to the process user and decision-makers. For enhancement of safety knowledge and the existing database, all the assessments are stored in the Filemaker, allowing modifications and adjustments when such are necessary.

All these aspects of LARA+D make it suitable for integration into the safety framework of EPFL. However, as with any management tool, it can not be used exclusively and serves only intended goals. In the case of LARA+D, it includes selective process risk analysis, mainly for new or hazardous processes, or local analysis by the process users.

Chapter 6. Application examples of LARA+D

First chapters of this thesis demonstrated the need for a risk management technique which can help efficiently evaluate and reduce risks associated with occupational and health safety in research laboratories. Based on the conducted literature review and qualitative studies, the LARA+D methodology was proposed in the Chapter 5. In order to test applicability and feasibility of the method, LARA+D was tested in research environment using several examples. These examples are illustrated in this chapter. The main goal of these tests is to demonstrate that:

1. LARA+D provides a well suitable for the academic research environment risk assessment tool, considering its particularities
2. Traditionally demanding risk management techniques can be efficiently substituted by proposed method without compromising on quality and safety
3. User friendly software application supports proposed method, and allows not experienced users to conduct risk analysis with a different level of details
4. Decision-aiding block can assist both experienced and not experienced users, helping with the selection of the most suitable measures.

LARA+D as designed at EPFL, with the consideration of its structure, stakeholders involved in decision-making and existing relationship among them. The intend of this method is its wide applicability in other institutions as well. However, as the nature of relationship, key decision-makers and their roles may vary, the objectives of safety decision-making process might change.

This method is meant to be used for all the variety of labs existing in the university. However, applicational examples of LARA+D mainly cover chemistry and chemical engineering. This is caused by the fact, that previous experience of the author was in the chemistry, and the knowledge on the other topics is more limited.

This chapter is constructed as follows:

1. Detailed demonstration of the LARA+D method on a simple process, with a demonstration of capability of detailed failure focused analysis.
2. Less detailed demonstration of application at EPFL, in chemistry laboratories. Three examples are used for this purpose. The first example represents traditional type of organic synthesis with a medium duration. The second example is a short synthesis, which is closer to chemical engineering and involves usage of highly hazardous materials. The third example is long medium scale synthesis, where the risks level is high also due to the bigger volumes of highly hazardous substances.
3. Comparison with SUVA method.

Different steps of the workflow are tested:

1. **Definition of the context.** How well LARA+D can be applied in existing context? Is it possible to collect intended information? Which kind of conclusions and actions can be drown from it?
2. **Hazard identification.** Does LARA+D database and hazard classification allow to consider all existing hazards and consequently propose necessarily measures without omitting and compromising on safety aspects?
3. **Risk analysis.** Do the existing risk dimensions represent an appropriate picture of the real risk? All the necessary aspects are considered to effectively address risks? Do the RiCS values represent the actual risk levels?
4. **Risk treatment.** Does LARA+D suggest necessary measures to address different dimensions of risk? Are other aspects important for selection among the measures are considered?
5. **Decision-making.** Does ranking algorithm represents an optimal and relatively objective information on the recommended selection of the measures? Do other ways of information representation give decision-maker sufficient information on recommended course of action?
6. **Risk control, risk documentation and risk communication.** Does the report generated by LARA+D provides decision-maker and other stakeholders with all relevant information?

6.1. LARA+D procedure

A simple chemical procedure is used to demonstrate the LARA+D Procedure. A step-by-step application is discussed using this simple example to introduce the method. This process is conducted in the Laboratory for Molecular Engineering of Optoelectronic Nanomaterials, which belongs to the Institute of Chemical Engineering in the Faculty of Basic Sciences.

The objective of this evaluation is an exfoliation of D-material. This process is a routine for this lab, and can be considered as supportive to main activities. It was chosen to be evaluated in LARA+D as it is relatively simple and can serve as a good demonstration of step-by-step application of the method.

1. Process

Exfoliation of D-material is a standard procedure. It involves the separation of platelets from one another. Liquid phase exfoliation is a method where a bulk material is dispersed in a solvent, and then layers are broken apart. The layers are broken apart using ultrasonication, where high-frequency sound waves are transmitted through the solution. The process can be illustrated using Figure 76.

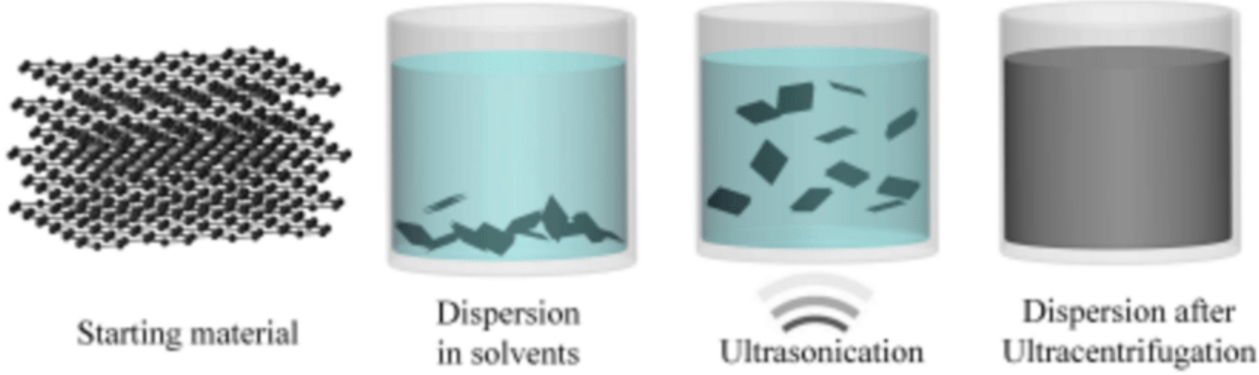


Figure 76. Exfoliation of D-material (Hogan et al., 2017).

D-material requires the separation of the layers using highly polar reagents.

2. Definition of the context

In the first step, we define the general information relevant to the activity. It includes an estimation of the psycho-social environment in the laboratory, perceived by the person involved in the hazardous activity analyzed in Table 50.

Question	Answer
Are there any hazardous materials/equipment in your laboratory which you don't feel confident working with?	NO. I feel confident.
Do you see any risks regarding these hazards (which you are not working with)? What are these risks?	There is a chance of respiratory exposure when some people work with highly volatile substances.
Would you like to have more support from your colleagues while working in the lab? Which kind of support?	No. I feel my colleagues are very supportive if I need
Do you feel that scientific publication pressure affects the attention you pay while performing your laboratory activities; group solidarity?	Yes, there is the publication pressure, however there is no unhealthy competition in the group.
Do you feel pressure or/and judgement if you make mistakes when working in the laboratory?	No. I feel that I can always discuss and resolve mistakes made.
Would you prefer working alone?	Sometimes. It is easier to organize your work and working space.

Table 50. Psycho-social climate. Perceived by the operator.

This process is conducted regularly by Ph.D. students. In this particular case, the student interviewed also played the role of CoSEC (Safety correspondents), which is the safety responsibility of the research group. Based on the working environment assessment, it can be classified as **Good (1.25)** , see Table 51 and Table 48.

Factor	Level
Level of light	Good
Comfort regarding noise condition	Medium
Temperature conditions	Good
Working space conditions	Good
Overall working environment conditions	***1.25 Good***

Table 51. Working Environment conditions.

Personal protective equipment is advised to improve the person's comfort regarding the noise level in the laboratory due to the sonification procedure. Noise-reducing earbuds/earplugs can be used during the process when the noise level is high. Contrary to the isolation of the noise source, this measure is reasonable, as it can be used temporarily and doesn't require changing the design of the experiment.

The safety climate in the laboratory can also be considered **Good**. The normalized value of the safety climate score corresponds to 0.76. The exact responses of the Ph.D. student can be found in Table 52. The final value is calculated as follows, according to the $SC = \sum_{i=1}^{3} \omega_{Fi} * V_{Fi} = 0.462 * V_{F1} + 0.167 * V_{F2} + 0.371 * V_{F3}$ Equation 31:

$$SC = \frac{0.462*F1+0.167*F2+0.371*F}{3} = 0.76 \quad \textit{Equation 42}$$

$$F1=\frac{0.318*2+0.136*1+0.15*2+0.227*3}{3}=0.69$$

$$F2=\frac{0.102*3+0.205*3+0.409*3+0.284*2}{3}=0.86$$

$$F3=\frac{0.144*3+0.16*3+0.122*3+0.086*3+0.141*2+0.204*2+0.144*2}{3}=0.79$$

N^O	Question	Answer	Score
1	How important do you think safety is in your lab? (P_1)	Equally important to laboratory main activities	2
2	How often do you work alone? (P_2)	Several times per week	**1**
3	How much time per week do you spend working in the lab performing experiments? (P_3)	Around 30 hour per week	2
4	Your laboratory is a safe environment (P_4)	Agree	3
5	What do you think about your level of safety training? (P_5)	I was trained specifically for Hazards I am working with	3
6	What is your primary affiliation? For how long are you at this university? (P_6)	EPFL, More than 1 year	3
7	How well does your previous experience help you to be integrated in your current lab? (P_7)	Really well	3
8	What is your current occupation? (P_8)	PhD student	2
9	What is your total lab working experience? (P_9)	More than 5 years	3
10	The research and safety equipment (fume hoods, biosafety cabinets, etc.) in your lab are safe and in good working order? (P_{10})	Neither agree nor disagree	3
11	In your lab, there is a sufficient supply of the appropriate PPE? (P_{11})	Agree	3
12	Does your supervisor encourage others to work safely, demonstrating with his/her own example? (P_{12})	He/she is always supportive and encourages safety initiative	3
13	Have you ever seen a colleague break a lab safety rule? (P_{13})	Yes, always corrected/commented	3
14	Are you aware about accident reporting system in your lab? (P_{14})	Yes, but don't know how to use	2
15	What do you think about information about safety rules and procedures in your laboratory? (P_{15})	There is only general information available	2
16	What do you think about safety rules and regulations you need to follow? (P_{16})	Majority are just common sense	2

Table 52. Safety climate questioner.

However, specific measures are suggested for implementation to improve the existing safety climate, see Table 53.

Factor	Measures
Frequency of working alone (P4)	Adjust working schedule
Frequency of working alone (P4)	Do not perform tasks that are not appropriate for working alone
Accident reporting system, ARS (P14)	Introduce team to ARS
Accident reporting system, ARS (P14)	Make a training on ARS

Table 53. Measures advised to improve safety climate.

3. Hazard Identification

This process is divided into main steps. This division is meant to ease assessment in case of complex and lengthy processes, make a separation from the time and activity type perspective, see Table 54.

Steps
1.Weight the powder (WSe_2)
2.Redisperse the powder in the liquid N-methylperillidon
3.Exfoliation
4.Transfer of WSe_2 suspension under fumehood

Table 54. Steps of the activity.

Afterward, hazards present during mentioned steps are identified. As chemicals often have more than one hazard statement and during handling, the user focuses on the complete hazardous portfolio of it, it is also important to focus on the substances. The following hazards are present in steps, see Table 55.

Step	Substance	Hazard
Weightthe powder	WSe_2	Oral Toxicity Respiratory Toxicity STOT RE Hazardous to aquatic life
Redisperse the powder in the liquid N-methylperillidon	N-methylperillidon	STOT SE Corrosive to eye or skin/ Irritant CMR, reproductive toxicity Flammable aerosol, liquid or solid Respiratory irritation
Exfoliation	N-methylperillidon	STOT SE Corrosive to eye or skin/ Irritant CMR, reproductive toxicity Flammable aerosol, liquid or solid Respiratory irritation
Transfer of WSe_2 suspension under fumehood	N-methylperillidon	STOT SE Corrosive to eye or skin/ Irritant CMR, reproductive toxicity Flammable aerosol, liquid or solid Respiratory irritation
	WSe_2	Oral Toxicity Respiratory Toxicity STOT RE Hazardous to aquatic life

Table 55. Process steps, substances and related hazards.

4. Risk analysis

In order to efficiently proceed with the risk assessment, it is important to set priorities and identify potentially the most problematic points of the process. The following questions are meant to set priorities for the analyst:

- Which product/ substance has maximum number of hazards?
- Which hazard appears in the maximum number of steps?
- Which hazard is the most severe?
- Which hazard appears in the most critical step?

Based on this pre-assessment N-methylperillidon appears to be the most hazardous substance, as it contains five hazard statements. It also appears in the majority of steps. The most critical step, according to the operator, is the transfer of suspension under fumehood. The design of the sonification bath requires certain efforts and time from the user to open the lid and transfer the bath under fumehood. Meanwhile, the user is exposed to accumulated vapors.

The risk analysis of CMR (reproductive toxicity) associated with this substance on step 4 reviewed in details. The factors used for calculation of the risk index (RiCS) are demonstrated in Figure 77.

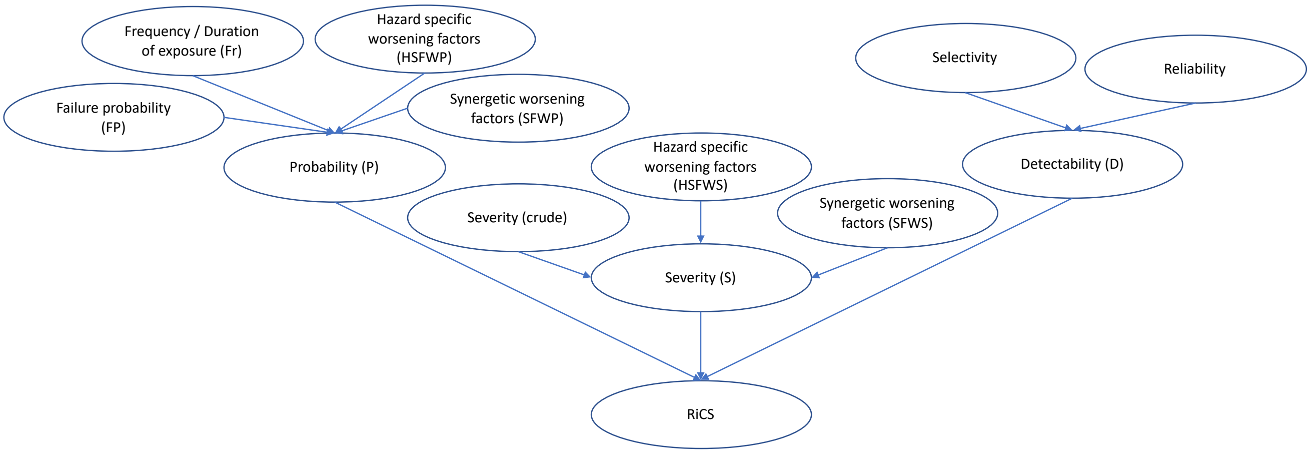


Figure 77. Factors used for calculation of RiCS.

Severity

The impact of this hazard is limited to human type of consequences. The impact is high, as the life of unborn child can be damaged, see Table 56.

	Qualitative description	Value	Specific qualitative description
Human	Very low	1	Wound without work interruption
	Low	2	Wound with work interruption
	Medium	3	Light handicap
	Serious	4	Serious handicap
	Very serious	5	Death

Table 56. Severity scales used in LARA+D for consequences.

Thus, the score for *Severity (crude)* is 4. This hazard has several *worsening factors*, that will aggravate the impact:

- Use of pure, not diluted chemicals
- Insufficient ventilation
- Inadequate PPE

These worsening factors will impact the final score of severity, see Table 58. These factors are chosen from LARA+D database, see Attachment D1.

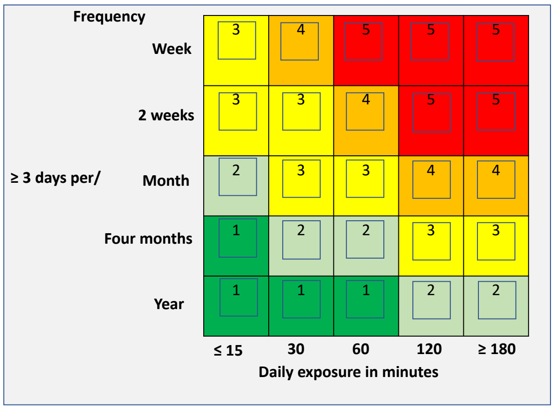
Probability

First of all, it is essential to determine potential failure. Traditionally, the problem of the accident assessment was a discrepancy between what exactly shall be assessed. Some experts were choosing between the worst-case scenario, which they were selected in the severity of an accident. Others were following the most probable. However, most experts kept in mind during this evaluation that the probability of outcome depends on the probability of certain failures or incidents happening. In LARA+D, we defined the list of generic failures that allow an analyst to keep the flexibility of the assessment without unnecessary vagueness. With this example, we also demonstrate that the risk index will be different depending on the selected failure scenario. During the transfer of WSe2 in N-methylperillidon suspension to the fumehood, two major failures can happen: Respiratory exposure to the hazard or Spill. After failures are defined, we need to select the list of potential failure contributing factors (FCF) that relate to these failures, see Table 57.

Failure	FCF
Respiratory exposure to the hazard	Set-up/equipment doesn't protect from hazard exposure Inappropriate equipment/material
Spill	Operator needs to move during the experiment with the hazard Set-up/equipment doesn't protect from hazard exposure

Table 57. Failures ad failure contributing factors for Step 4, N-methylperillidon.

It is essential to assess how often this person is involved in a hazardous activity and which percentage of the time they are exposed to this hazard. In this particular case, it is several days per month, around 30% of the time. Thus Frequency/Duration takes the value 3, see Figure 78.



Frequency ≥ 3 days per/	≤ 15	30	60	120	≥ 180
Week	3	4	5	5	5
2 weeks	3	3	4	5	5
Month	2	3	3	4	4
Four months	1	2	2	3	3
Year	1	1	1	2	2

Daily exposure in minutes

Figure 78. The risk matrix used for determination of frequency/duration of exposure.

During the last step, we determine whether hazard-specific and synergetic factors are present. The substance is *volatile and colorless,* and there is *insufficient ventilation*, which results in high HSFWP – 4, see Table 58. Risk analysis data sheet for CMR (reproductive toxicity).

All the factors are determined using LARA+D database. Relative contributions of worsening factors were established by the safety experts at EPFL. No synergetic factors were determined as worsening during this assessment.

Detectability

Human senses are the only available in this case type of detector. Solvent vapors can be easily detected as they have a specific amine-like odor. The performance of this detector cannot be considered ideal, as it depends on the person's physical condition. Thus, reliability is 3, and selectivity is 2. The risk analysis data sheet for the selected hazard is represented in Table 58.

It includes general information on the hazard, its appearance in the process, and the risk reduction effect of proposed safety measures.

CMR (Reproductive toxicity)

Substance: *N-methylperillidon*

Consequences: *Miscarriages, damage to unborn children's development, alteration of breastfeeding capability, or negative inherited developmental effects, affecting fertility*

Hazard statement: *May damage fertility or unborn child.*
Hazard: *Chemical hazard*
Hazard group: *CMR/STOT SE*
Presence in the steps: *2, 3, 4*

	Respiratory exposure				*Spill*		
Risk factors	Assigned value	Work under a fumehood	Cover the bath with a special lid	Respirator	Assigned value	Work under a fumehood	Cover the bath with a special lid
Severity	3	1	1	1	3	1	1
HSFWS	3	2	3	2	3	3	2
SFWS	1	1	1	1	1	1	1
Failure probability	2.9	1.2	1.9	1.9	2.1	1.9	1.2
Frequency/Duration	3	3	3	3	3	3	3
HSFWP	4	1	1	2	4	1	1
SFWP	1	1	1	1	1	1	1
Reliability	3	3	3	3	3	3	3
Selectivity	2	2	2	2	2	2	2
RiCS	4.4	3.0	3.7	3.7	4.1	3.7	3.0

Nr.	HSFWP	Score
1	Volatile substance	1.3
2	Colorless substance	1.3
3	Insufficient ventilation	2.6

Nr.	HSFWS	Score
1	Use of pure, not diluted chemicals	1
2	Inadequate PPE	1.3
3	Insufficient ventilation	2.0

Table 58. Risk analysis data sheet for CMR (reproductive toxicity).

The risk reduction effect of activity corrective measures (CM) advised for implementation is already considered. The impact of these measures constitutes ΔFP=0.5, reducing Failure Probability according to Equation 33:

$$\text{FP}=\left(\frac{\boldsymbol{WE}}{\boldsymbol{4}}\sum \boldsymbol{FCF}\right)^{SC}$$

Acceptability risk limits are set between 3.75 and 6.54, see Chapter 5.5. We can see that in the case of both failures, we are the ALARP zone. And additional measures are proposed to decrease the risk.

5. Risk treatment

After the risk reduction effect of the measures was evaluated. It is necessary to make their potential performance and financial evaluation, see Table 59. Acceptability (A) and Simplicity (S) are used for calculation of Human Reliability (HR) factor, according to equation 39:

$$HR=\frac{(A+S)^{SHF}}{10}$$

Where Sensitivity to human factors (SHF) determined according to STOP principle, see Table 44. Compatibility with process (CP) and environment (CE) contributes to Technical Reliability of the measure, according to equation 40:

$$TR=\frac{CP+CE}{10}$$

Corrective measure	A	S	CP	CE	Implementation costs, CHF	Running costs, CHF	HR	TR
Work under a fumehood	5	5	4	2	700	3000	0.42	0.6
Cover the bath with a lid	5	5	3	4	300	100	0.58	0.7
Use a respirator	5	4	5	5	500	200	0.51	1

Activity corrective measures

	Implementation cost	*Running cost*
Adjust working schedule	100	200
Do not perform dangerous tasks working alone	0	300
Introduce team to ARS	200	1000
Make a training on ARS	500	2000
Noise reducing earbuds	600	200

Table 59. Feasibility and costs of proposed measures.

6. Decision-making

A decision-making matrix is used to help the decision-maker select among different measures, see Table 60. Here, this table is represented only for respiratory exposure.

Corrective measure	RiCS	$\Delta RiCS$	HR	TR	Implementation costs, CHF	Running costs, CHF	Rank
Work under a fumehood	*3.0*	*1.4*	*0.42*	*0.6*	*700*	*3000*	*2*
Cover the bath with a lid	*3.7*	*0.7*	*0.58*	*0.7*	*300*	*100*	*3*
Use a respirator	*3.7*	*0.7*	*0.51*	*1*	*500*	*200*	*1*

Table 60. Decision-making matrix for CMR (Reproductive toxicity), step 4, respiratory exposure.

According to the decision-making algorithm, the preferable solution would be *the Use of a respirator*. *Work under a fumehood* is the second preferable option as it has the highest risk reduction potential. However, this measure can't be considered optimal due to lower technical compatibility. Looking at the actual risk reduction potential, see Figure 79 , the actual gain in safety when selecting fumehood becomes lower compared with other measures. Having information only on the potential risk reduction of these measures creates an impression that their risk reduction potential is higher than the actual one. The GRR (general risk reduction) takes into account human and technical reliability of the measure, demonstrating real capacity of measure to reduce the risk.

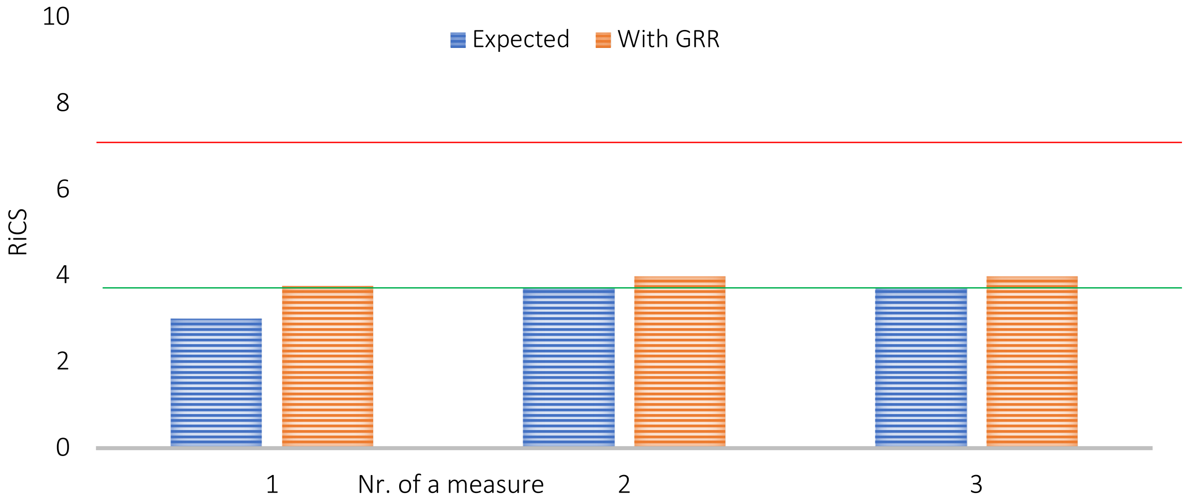


Figure 79. Expected and actual risk reduction capacity of the measures from table 61.

7. The focus of the analysis.

Any risk analysis has various limitations and assumptions that must be considered during the decision-making step. In the example mentioned above, the assessment was focused on the process user since the exposure of other individuals who could enter the room was minimal due to their time of exposure. It was also based on the assumption that there is only one user at the time.

Any assessment remains contextual. Thus, any significant modifications in the organization might impact focus of the analysis and the results of the decision-making, see Table 61 .

Corrective measure	RiCS	$\Delta RiCS$	HR	TR	Implementation costs, CHF	Running costs, CHF	Rank
Work under a fumehood	*3.0*	*1.4*	*0.42*	*0.6*	*700*	*3000*	*1*
Cover the bath with a lid	*3.7*	*0.7*	*0.58*	*0.7*	*300*	*100*	*2*
Use a respirator	*4.1*	*0.3*	*0.51*	*1*	*500*	*200*	*3*

Table 61. Decision-making matrix for CMR (Reproductive toxicity), step 4, respiratory exposure. Two users.

When the process user is not alone in the room, and other individuals are simultaneously working in the same space, the ranking of the measures will differ. In this case, respiratory exposure to the hazard will occur for the process user and other people in the room. Using a respirator by the user will not help reduce risk significantly, as different individuals will still be exposed. This measure will be the least preferential.

This method is flexible enough as it provides reliable results of the assessment with a change of the context. However, it is important to keep in mind what are the objects of the assessment, as it will significantly impact results as example above.

6.2. EPFL

The Ecole Polytechnique Fédérale de Lausanne (EPFL) is a part of the Swiss Federal Institutes of Technology (ETH). It also includes the Swiss Federal Institutes of Technology in Zurich (ETHZ), the Paul Scherrer Institute (PSI), the Swiss Federal Institute of Aquatic Science and Technology (EAWAG), the Swiss Federal Laboratories for Materials Sciences and Technology (EMPA), the

Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). EPFL can be represented as follows:

- 5 schools and two colleges, five campuses, 24 institutes, and over 500 laboratories
- 12'720 students (Bachelor, Master, Ph.D., MAS)
- 6'389 staff (administrative, scientific, technical)
- Over 1 billion CHF annual budget
- Around 32 startups

The evaluations represented in this chapter were conducted for the Faculty of Basic Sciences (SB). It includes chemistry, physics, and mathematical institutes. Safety Competence Center (SCC), which by the end of the project was reorganized into separate group of Occupational Health and Safety – Risk Prevention (OHS-PR), provides safety support to the laboratories, which includes:

- Assessment of the occupational exposure risks
- Provision of recommendations on the safety measures
- Validation and distribution of PPE
- Validation of the workspace ergonomics

This job is performed using different safety management tools, such as audit, quick audit, risk assessment methods, etc.

6.2.1 Laboratory of Catalysis and Organic Synthesis (LCSO)

The second application example of LARA+D was performed in the Laboratory of Catalysis and Organic Synthesis (LCSO) at EPFL. Currently, there are five main research directions in the group:

1. Electrophilic alkynylation with and without hypervalent iodine reagents
2. Transformations beyond alkynylation using hypervalent iodine reagents
3. Modification of peptides and proteins
4. Cyclization and annulation reactions initiated by the opening of small rings
5. In situ tethering strategies for the functionalization of olefins and alkynes

The group consists of 1 permanent scientist who is also a CoSEC, 4 Postdoctoral scholars, and 15 Ph.D. students. People from 10 different nationalities work in the group.

The process used for evaluation is the synthesis of Bisisobutyryl peroxide from isobutyril chloride and hydrogen peroxide in the presence of pyridine and diethyl ether, see Figure 80.

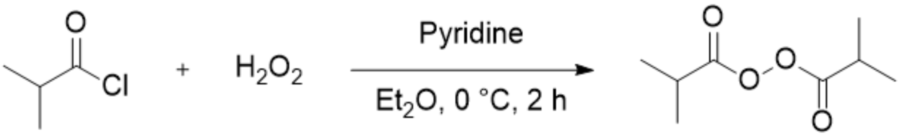


Figure 80. Synthesis of Isobutyryl peroxide.

A solution of pyridine in ether is cooled to -10 °C, and afterward, 30% hydrogen peroxide is added dropwise. The mixture is rapidly stirred for the two-phase system to disperse. Then acid chloride is added dropwise, maintaining the temperature between -5 and -10 °C. The mixture is stirred for 2 hours at 0 °C and neutralized with a chilled 10% sulfuric acid solution. Ether is added to extract the peroxide; the temperature should be maintained at 0 °C. Further, the aqueous layer is extracted with pentane. The ether and pentane extracts are combined and washed first with chilled 10% sulfuric acid, then with 10% aqueous sodium carbonate, and finally with brine. The solution is dried over anhydrous magnesium sulfate and concentrated on a rotary evaporator. Afterward, it is dried on a vacuum pump. The residue is purified by flash chromatography. The evaluation's objective is to identify the potentially most problematic moments in the synthesis. The process was chosen for the LARA+D assessment due to the hazardous nature of peroxides and widely spread accidents during their synthesis, use, and storage. This example is a typical synthesis conducted in an organic laboratory. However, it doesn't imply overnight reactions. No SOP (safety operating procedure) was given to the Ph.D. student. Even considering the high frequency of synthesis of this molecular in this laboratory, there is no such procedure available. The main hazardous component of this assessment is isobutyril peroxide due to its reactivity and explosive potential. The full results of the risk assessment of this process are included in Attachment C1.

LARA+D results

Before the risk assessment, a safety climate questionnaire was sent to the person involved in the hazardous process. According to the responses, the safety climate can be considered **good (0.86)**, and the working environment conditions are **medium** (2). Detailed responses can be found in Attachment C1. Measures advised, based on this assessment, are listed in Table 62.

Factor	Measures
Level of light	Adjust color temperature based on type of work Ensure adequate contrast between background and foreground
Level of noise	Maintain equipment (source of noise) properly Shut down equipment that is not required at the moment
Temperature conditions	Put local air conditioning
Time working in the laboratory (P5)	Organize working station for higher time efficiency
Accident reporting system (ARS) (P14)	Make a training on ARS

Table 62.Measures advised to improve working environment and safety climate.

This process can be separated into steps, represented in Table 63. Substances not considered hazardous are not included in this table, detailing the hazards contained in Attachment C1. This process is relatively simple and cannot be viewed as multistage; moreover, it is usually conducted in less than one day. However, peroxide represents a high threat. Thus, it was decided to analyze this process with a clear focus on each step.

Nr.	Steps	Hazardous substances	Nr. Of hazards
1	Cooling down solution of pyridine in ether	Pyridine	5
		Diethylether	3
2	Adding hydrogen peroxide and stirring the mixture	Hydrogen peroxide	5
		Pyridine	5
		Diethylether	3
3	Adding acid chloride and stirring for 2 h	Isobutyril chloride	3
4	Neutralizing mixture with the solution of 10% sulfuric acid	Sulfuric acid	1
5	Extracting aques layer with pentane	Pentane	5
		Diethylether	3
6	Combining pentane and ether extracts	Diethylether	3
		Pentane	5
		Isobutyril peroxide	5
7	Washing with 10% sulfuric acid	Sulfuric acid	1
8	Washing with sodium carbonate	Sodium carbonate	1
9	Washing with brine	Brine	-
10	Driying over anhydrous magnesium sulfate	Isobutyril peroxide	5
		Magnesium sulfate	-

11	Concentrating on a rotary evaporator	Isobutyril peroxide	5 Equipment under pressure
12	Drying on a vacuum pump	Isobutyril peroxide	5 Equipment under pressure
13	Purification of residue on a flash chromatography	Isobutyril peroxide	5
14	Checking the yield and moving to storage	Isobutyril peroxide	*5*

Table 63. Steps, substances and associated hazards present during synthesis.

Risks

Most of the risks arising from the use of the listed chemicals. Almost all substances can be considered very hazardous, see Attachment C1, which is always not only due to the number of associated hazards but also their harming potential and operation conditions. However, the risks which were considered the most hazardous are listed in Table 64.

Nr	Source	Hazard	RiCS
1	Isobutyril peroxide	Self reactive or peroxide	6.09
2	Diethylether	Oral toxicity	5.57
3	Diethylether	STOT-SE	5.57
4	Pyridine	Corrosive to eye or skin/ Irritant	5.42
5	Isobutyril chloride	Corrosive to eye or skin/ Irritant	5.26
6	Diethylether	Flammable aerosol, liquid or solid	5.25
7	Isobutyril peroxide	Respiratory irritation	5.22
8	Isobutyril peroxide	Oral irritation	5.22
9	Isobutyril peroxide	Corrosive to eye or skin/ Irritant	5.14

Table 64. The highest risks in synthesis of isobutyryl peroxide.

The location of these risks to the ALARP region is represented in Figure 81. No risks require obligatory treatment; but, some measures can be proposed. Worth to remember that the school management can modify acceptance limits which may vary in certain circumstances.

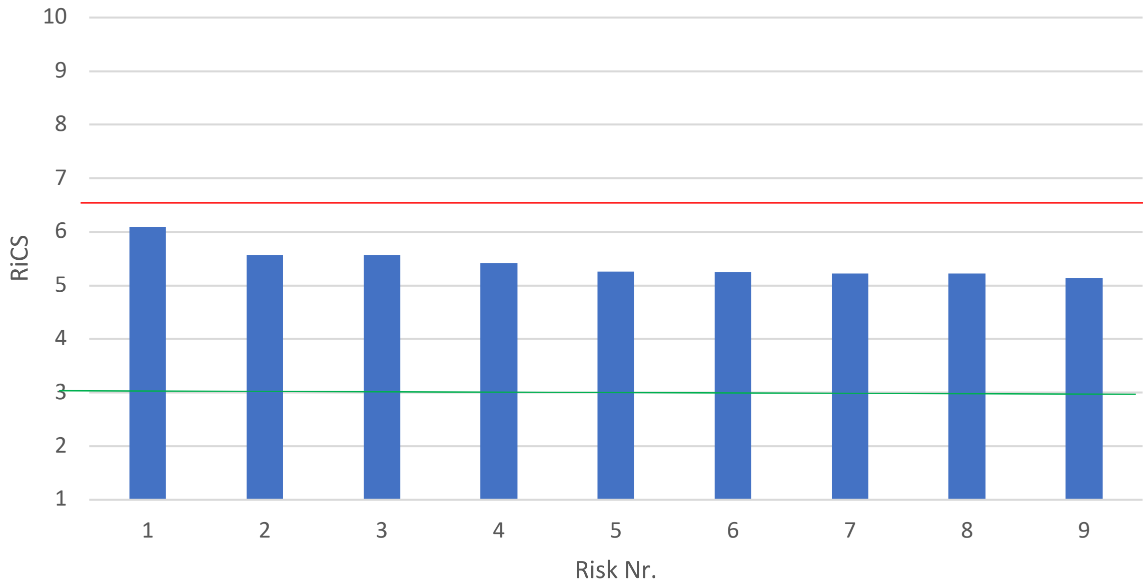


Figure 81. The most important risks in relation to ALARP region. All values above 6.54 are considered unacceptable and require treatment.

Risk treatment & decision-making

In contrary to Chapter 6.1, this assessment includes various risks, and due to the extent of the full evaluation, only accumulated results of risk treatment for the most important risks are presented here, see Table 64. These measures and the risks that they can potentially reduce are represented in Table 65.

Nr.	Safety measure	Affects risk Nr.	Rank
1	Use a face shield	2-5,9	4
2	Use safety glasses with the side protection	4,5,9	5
3	Use respirator	7	7
4	Use bigger flask for manipulations	1	8
5	Do not keep outside fridge longer than 10 minutes if it is hot	1	3
6	Use kevlar gloves	1	2
7	Use smaller quantities	1,6	6
8	Install a cooler outside of the lab	2,3,8	9
9	Separate office and lab zone with a shield	1-3,8	1

Table 65. Proposed safety measures.

Out of all the risks, risk Nr. 1 represents the highest threat. For the simplification purpose, the list of the measures and corresponding risk reduction is illustrated only for one risk. If the measure affects more than 1 risk, the one with the highest risk reduction is represented in Table 66. The complete list can be found in the Attachment C1. Ranking of the applicable safety measures is meant to ease the selection.

Nr.	Safety measure	Affects risk Nr.	Rank	RiCS after
1	Use bigger flask for manipulations	1	4	5.45
2	Do not keep outside fridge longer than 10 minutes if it is hot	1	3	5.04
3	Use kevlar gloves	1	2	4.87
4	Use smaller quantities	1,6	5	5.21
5	Separate office and lab zone with a shield	1,2,3,8	1	5.25

Table 66. Suggested measures, ranking and risk reduction potential.

The Decision-making matrix gives an overview of other factors which might influence the selection among listed measures, see Table 67.

Nr.		RiCS after	$\Delta RiCS$	HR	TR	Implementation cost, CHF	Running cost, CHF	Rank
1	Use bigger flask for manipulations	5.45	0.64	79	100	900	100	4
2	Do not keep outside fridge longer than 10 min	5.04	1.05	47	100	50	300	3
3	Use kevlar gloves	4.87	1.22	47	100	2000	200	2
4	Use smaller quantities	5.21	0.88	63	100	100	4000	5
5	Separate office and lab zone with a shield	5.25	0.84	79	90	3000	500	1

Table 67. Decision-making matrix for risk Nr. 1 according to Table 66.

Measure Nr. 5 is the most preferential according to the ranking algorithm. It reduces not only risk Nr.1 but has the potential to reduce other risks. The risk reduction potential of these measures for other risks is demonstrated in Figure 82.

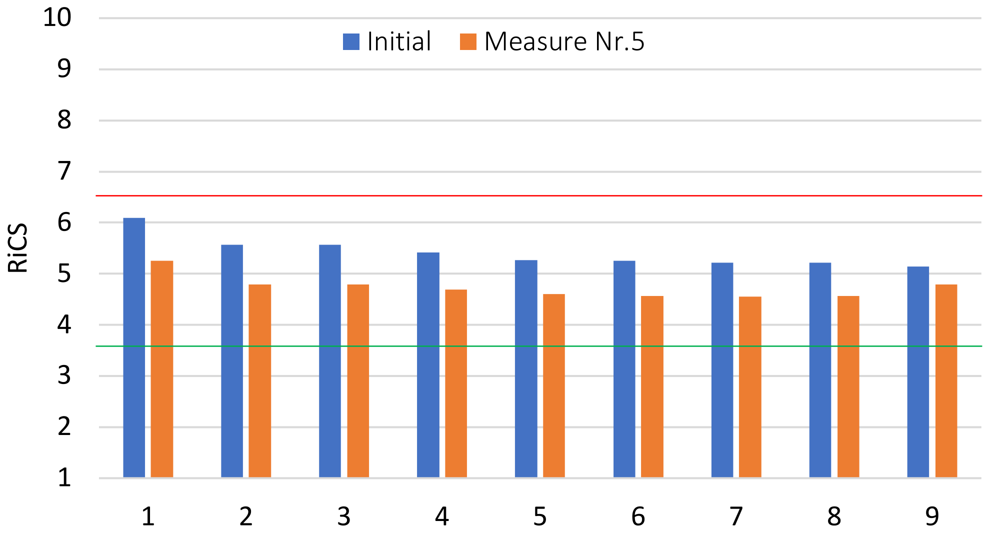


Figure 82. Risk reduction by measure Nr.5 for all the selected risks from Table 64.

Even though measure Nr. 5 is the most suitable according to the proposed ranking, its potential risk reduction capacity is lower than for measure Nr.2, and costs are significantly higher. To be able to judge the efficiency of this measure, it is essential to consider the actual risk reduction potential of all the measures, see Figure 83. The GRR (general risk reduction) considers human and technical reliability of the measure, demonstrating real capacity of measure to reduce the risk.

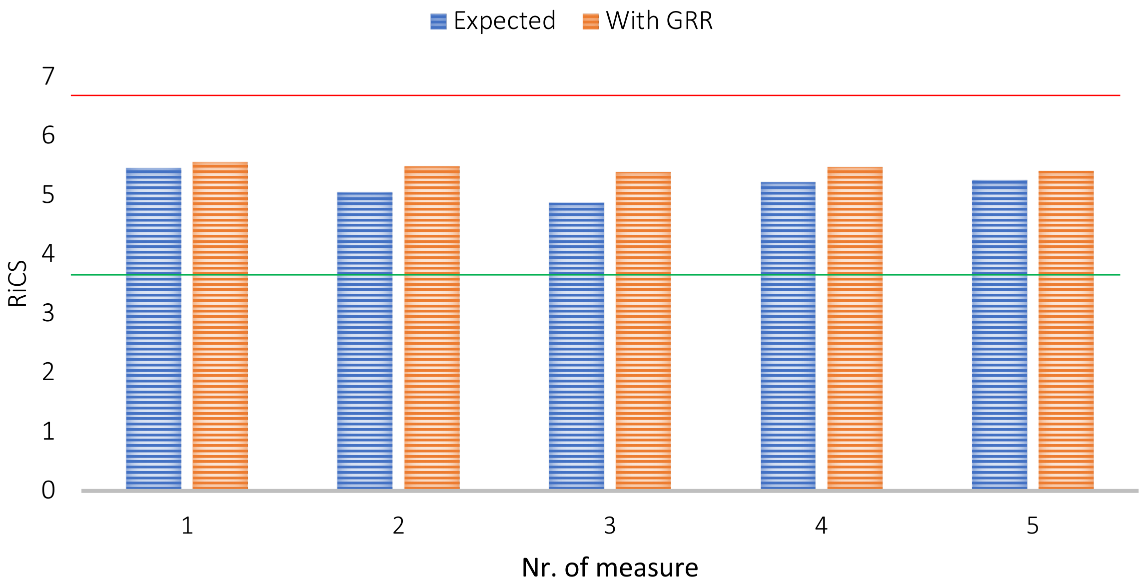


Figure 83. Expected and real risk reduction of the measures from the Table 67.

It is noticeable that measure Nr. 5 has the closest real and expected risk reduction potential, making it the most suitable, despite relatively higher costs. The effect of all the measures in the selected risks is detailed in the Attachment C1. The visual representation of the risk reduction potential of identified measures on the risks from Table 64 is illustrated in Figure 84.

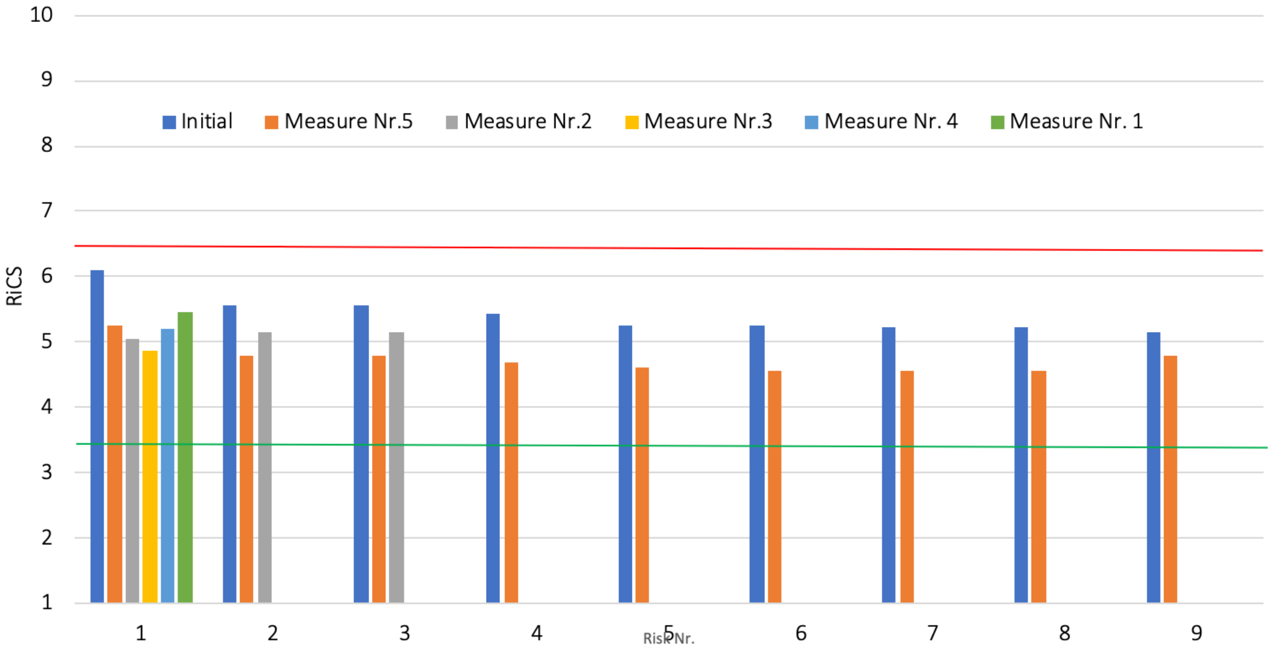


Figure 84. Risk reduction potential of all identified measures on different risks.

As we can observe from Figure 84 Measure Nr. 5 reduces the most significant number of risks. Its expected and real risk reduction potentials are very close as well. The second most versatile measure is Nr. 2, which efficiently reduces risks 1-3. Nevertheless, this measure is less preferential due to the lower HR (human reliability), see Table 67. As the risk Nr. 1 is the highest according to Table 64, and close to the unacceptable zone, it is essential to treat this risk first. Thus, the use of Kevlar gloves will be advised while manipulating peroxide. Meanwhile, to reduce other risks, store isobutyril peroxide in the fridge, especially when the room temperature is higher than 23ºC and manipulations take longer than 10 minutes. A protective shield between the office desk and laboratory is suggested as a general measure, as it will reduce the worsening factors of most handled chemicals.

6.2.2 Laboratory for Molecular Engineering of Optoelectronic Nanomaterials (LIMNO)

The third example of assessment was also conducted in LIMNO. Contrary to the first assessment, which analyzed a simple process designed to demonstrate the capacity of the proposed method to be very precise and detailed in the context of missing data, this process is more traditional as it consists of several steps.

This group is also rather big, including one postdoctoral fellow, five scientists, and 10 Ph.D. students. There are five main topics of research in this group:

- Solar fuels
- 2D semiconductors
- Organic semiconductors
- Oxide semiconductors
- Perovskite solar cells

As a part of his research, the process used as an example for evaluation is frequently performed by the Ph.D. student, see Figure 85.

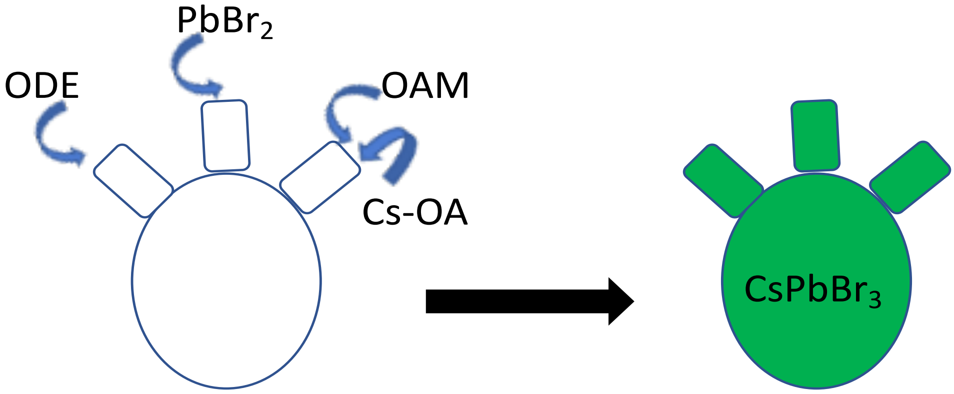


Figure 85. Synthesis of CsPbBr3 nanocrystals.

PbBr2 (55mg) is suspended in ODE (5mL) in a 25 ml 3-necked flask, then heated to 100 ^{o}C and dried for 30 minutes under vacuum. The reaction mixture was heated to 110 C under nitrogen, followed by the addition of dried oleylamine (OAM, 0.5 mL) and 0.5 mL of oleic acid. After PbBr2 was dissolved, the reaction mixture was heated to 180 ^{o}C. At this point, the mixture of Cs-OA solution (0.8mL) was injected into the reaction flask. After 15 s, the reaction mixture was cooled by a water-ice bath (Bodnarchuk *et al.*, 2019).

The process was chosen for LARA+D evaluation due to the hazardous nature of lead. This example is also a typical synthesis for chemical engineering. No SOP (safety operating procedure) was given to the Ph.D. student.

The main hazardous component of this assessment is PbBr2; however, some other hazardous substances were not perceived with the required attention and thus needed to be addressed. The full results of the risk assessment of this process are included in Attachment C2.

LARA+D results

Before the risk assessment, the safety climate questionnaire was sent to the person involved in the hazardous process. According to the responses, safety climate can be considered **good (0.79)**, and working environment conditions are **good** (1.25). Detailed responses can be found in Attachment C2. Advised measures are listed in Table 68.

Factor	Measures
Temperature conditions	Put local air conditioning
Previous experience (P7)	Assign a buddy
Years of lab experience (P9)	Share experience and accidents knowledge Assign a buddy
State of lab equipment	Announce the issue to OHS Increase frequency of maintainance
Accident reporting system (ARS) (P14)	Make a training on ARS

Table 68.Measures advised to improve working environment and safety climate.

The main steps of this process are represented in Table 69. Substances that don't represent any hazards are not included in this table, detailing the hazards in Attachment C2.

Nr.	Steps	Hazardous substances/Source	Nr. Of hazards
1	Making suspension	ODE	2
		$PbBr_2$	6
2	Heating suspension	Hot surfaces	1
3	Drying	Vacuum	1
4	Heating	Nitrogen	1
5	Adding ODA	Odeylamine	3
6	Adding OA	Oleic acid	
7	Heating	Hot surfaces	1
8	Adding Cs-OA	Cs-oleate	4
9	Cooling down mixture	$CsPbBr_3$	4

Table 69. Steps, substances/sources and associated hazards present during synthesis

Risks

Most of the risks arising from the use of the lead. However, some other substances can also be considered very hazardous, see Attachment C2. The highest risks which were considered are listed in Table 70.

Nr	Source	Hazard	RiCS
1	$PbBr_2$	CMR (Carcinogenic)	6.2
2	$PbBr_2$	CMR (Reproductive toxicity)	6.11
3	CsPbBr3	Corrosive to eye or skin/ Irritant	5.62
4	$PbBr_2$	STOT RE	5.48

Table 70. The highest risks in synthesis of $CsPbBr_3$.

The location of these risks concerning the ALARP region is represented in Figure 86. None of the measures are mandatory for risk reduction. Nevertheless, measures are advised for the identified list of risks, see Table 70.

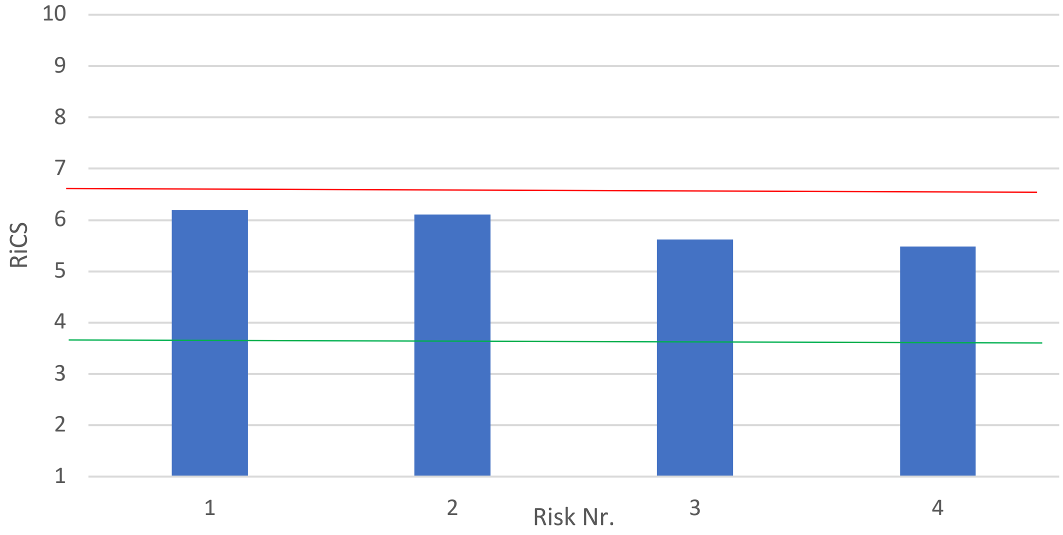


Figure 86. RiCS values; risks selected for the detailed evaluation and potential risk treatment; ALARP zone.

Risk treatment & decision-making

This risk assessment example represents an easy situation for the expert, where the most hazardous substances can be addressed in a similar manner and measures, as the list of the associated hazards is very close. Due to the extent of the full evaluation, only accumulated results of risk treatment for the most important risks are presented here. Seven measures were identified to decrease four of the most critical risks in this process. The majority of measures except, Nr. 2 can be easily applied to all the risks, see Table 71.

Nr.		Affects risk Nr.	Rank	RiCS after
1	Wear respiratory protective device	1,2,3,4	7	3.94
2	Store in a cool, dry place	3	1	5.12
3	Perform periodical medical test for lead in the blood	1,2,3,4	3	3.98
4	Install a warning sign where lead is manipulated and stored	1,2,3,4	2	5.35
5	Prepare a solution inside of a glovebox	1,2,3,4	5	4.57
6	Wear two pairs of nitrile gloves, change the outer layer frequently	1,2,3,4	6	5.48
7	PPE should not leave the room of the lab	1,2,3,4	4	5.52

Table 71. Proposed safety measures.

The Decision-making matrix gives an overview of other factors which might influence the selection among listed measures, see Table 72. Based on the color code of the decision-making matrix, measures Nr. 2 and 4 are the most optimal, while measures Nr. 5 and 6 are the least.

Nr.		RiCS after	$\Delta RiCS$	HR	TR	Implementation cost, CHF	Running cost, CHF	Rank
1	Wear respiratory protective device	3.94	2.26	43	100	500	50	6
2	Perform periodical medical test for lead in the blood	3.98	1.62	58	100	150	3500	2
3	Install a warning sign where lead is manipulated	5.35	0.85	63	100	40	200	1
4	Prepare a solution inside of a glovebox	4.57	1.63	53	100	50	1500	4
5	Wear two pairs of nitrile gloves, change the outer layer frequently	5.48	0.52	47	100	500	50	5
6	PPE should not leave the room of the lab	5.52	0.68	53	100	50	250	3

Table 72. Decision-making matrix for safety measures, excluding measure Nr.2 from the table above.

The comparison of the potential and actual risk reduction of these measures is illustrated in Figure 87. Measure Nr. 2 has the lowest level of risk comparing real risk reduction. The GRR (general risk reduction) takes into account human and technical reliability of the measure, demonstrating real capacity of measure to reduce the risk.

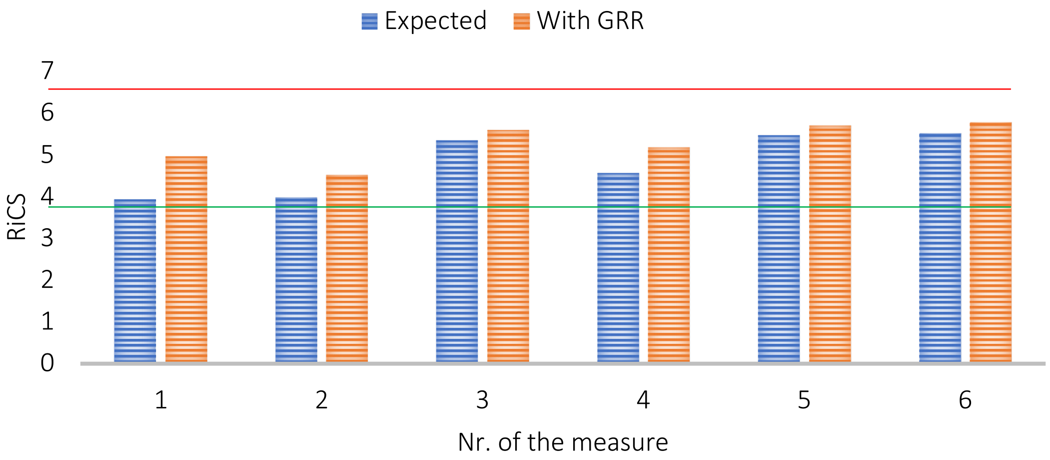


Figure 87. Expected and real risk reduction potential of the measures from the table 72.

Detailed representation of the risk reduction potential of all proposed measures on the identified risks can be found in the Attachment C2; its visual presentation is in Figure 88.

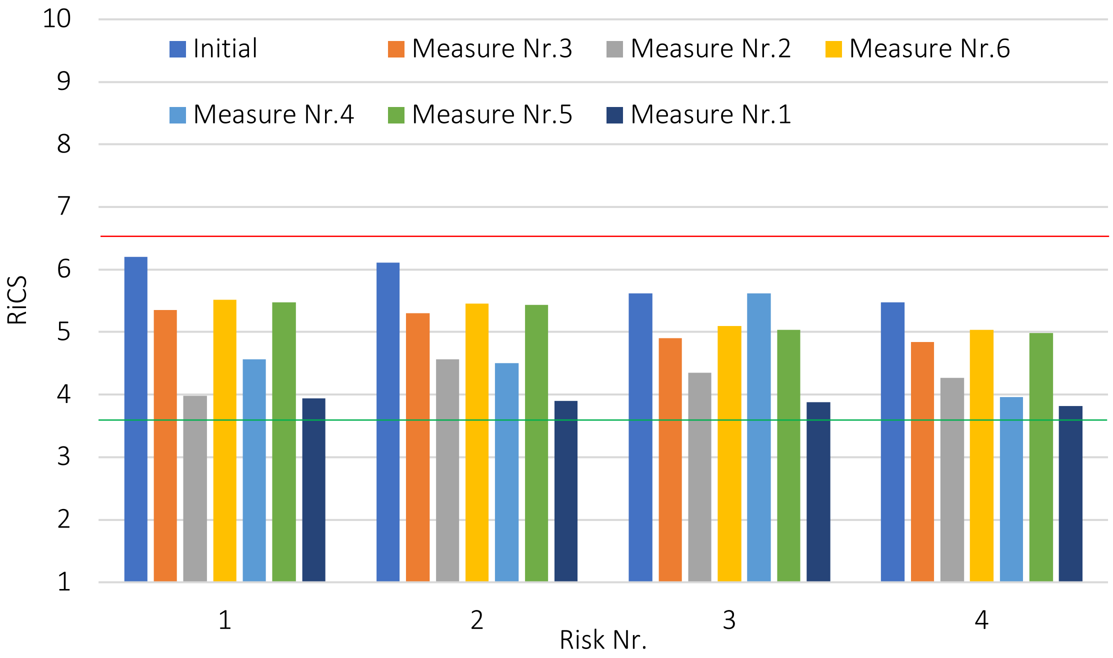


Figure 88. Risk reduction potential for all identified risks.

Measure Nr. 3, see Table 71, is suggested for its meager costs, easiness of implementation, and high suitability. It also has acceptable efficiency. Measure Nr. 1 is not preferential as it has a significant discrepancy between expected and actual risk reduction, see Figure 87 Measure Nr. 2 could be advised in case experiments with lead-based substances are performed regularly. This measure will effectively help prevent the negative consequences of exposure to such materials. Nevertheless, this measure is relatively costly. Even though the use of two pairs of gloves, as well as keeping PPE inside of the lab, are not the most efficient measures; they are advised as essential when working with lead-based materials, as they will help to reduce risks and are not resource-consuming.

6.2.3 Laboratory of Sustainable and Catalytic Processing (LDPC)

The second application example of LARA+D was performed in the Laboratory of Sustainable and Catalytic Processing (LDPC) at EPFL. Currently, there are six main research directions in the group:

- Biomass conversion
- Heterogeneous catalysis
- Lignin chemistry
- Biocatalysis
- Green solvents
- Bioplastics

The group consists of 2 Postdoctoral scholars and 13 Ph.D. students. People from different nationalities work in the group.

The process used for evaluation is the synthesis of Diformylxylose (DFX), see Figure 89. This process was conducted on two sites. The small scale is on the EPFL campus, while the big scale (in the 15L reactor) is in Fribourg. The purpose of this evaluation is to the second medium-scale process.

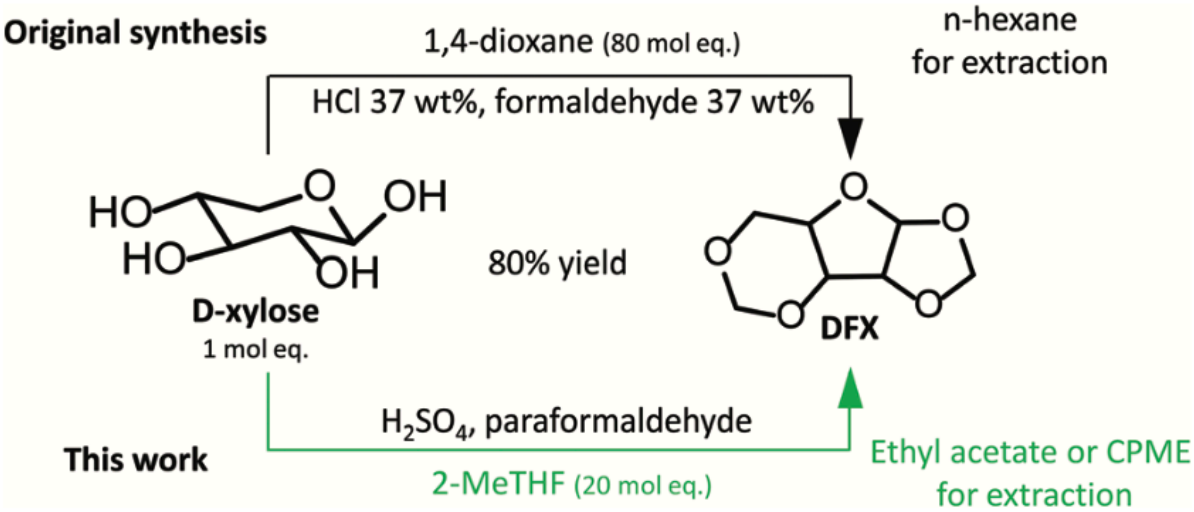


Figure 89. The scheme of the process used by (Komarova, Dick and Luterbacher, 2021).

A 15L-glass reactor equipped with an anchor stirrer is put under an inert atmosphere with a flow of nitrogen of 0.3 L/min through the reactor and then connected through the gas outlet to the 1st scrubber filled with the aqueous solution of sodium hydroxide (11 % (wt/wt)) for capturing possible HCl emissions.

The 1st scrubber is connected to the 2nd scrubber and filled with an aqueous solution of sodium bisulfite (10% (wt/wt) for capturing possible formaldehyde emissions. 5.1kg of 2-MeTHF was loaded into the reactor. Then, aqueous HCl (37 % (wt/wt), 1.8 kg, mol, eq.) is gradually added to the reaction mixture (approximate flow: 10ml/min) while keeping the temperature of the reaction mixture below 15°C.

Paraformaldehyde (kg, mol, eq.) and corn cobs (grinded, 1.50 kg) are added to the reaction mixture while keeping the inert atmosphere in the reactor. The resulting mixture is heated to 75°C (Tj=85°C) under constant stirring of 200rpm for 1 hour and then cooled to room temperature. The reaction mixture is filtered while washing with 2-Me-THF (3x1L) to ensure complete extraction of the cellulose solids and solubilization of acetalized sugars and lignin. After this, the filtrate is split into two equal portions and processed differently.

The 1st portion is distilled at 45°C and 225mbar to recover 2-MeTHF until the volume of the reaction mixture reaches about 2.5L. Toluene (3.0 L) is added to the mixture and stirred for 60 minutes to ensure complete lignin precipitation. The filtrate is distilled at 45°C and 225mbar to recover 2-MeTHF and then at 80°C and 20mbar to concentrate the mixture. The reactor returned to the atmospheric pressure by inserting nitrogen flow, and the resulting oil was removed and purified by SPD.

The 2nd portion is neutralized by gradually adding an aqueous solution of sodium hydroxide at 0°C (approximate flow: 10-20 ml/min) while keeping the temperature of the reaction mixture below 15°C. The reaction mixture was filtered while washing with water, and precipitated lignin was collected as a brown powder. The organic layer was distilled at 45°C and 225mbar to recover 2-MeTHF and then at 80°C and 20mbar to concentrate the mixture. The reactor returned to the atmospheric pressure by inserting nitrogen flow, and the resulting oil was removed and purified by SPD. The samples were characterized using NMR. This process is conducted regularly and provides the user with a detailed SOP.

LARA+D results

As in the examples above, in this case, a safety climate questionnaire was sent to the person before the risk assessment. According to the responses, safety climate can be considered **good (0.82)**, and working environment conditions are **good** (1.5). Detailed responses can be found in Attachment C3. Advised measures are listed in Table 73.

Factor	Measures
Temperature conditions	Put local air conditioning
Level of noise	Maintain equipment (source of noise) properly Shut down equipment that is not required
Level of safety training (P3)	Organize additional safety training
Quality and quantity of PPE (P11)	Express concerns to the OHS service Provide additional PPE
State of lab equipment (P13)	Announce the issue to OHS
Accident reporting system (ARS) (P14)	Make a training on ARS

Table 73.Measures advised to improve working environment and safety climate.

The main steps of this process are represented in Table 74. Substances that don't represent any hazards are not included in this table, details are included in Attachment. C3.

Nr.	Steps	Hazardous substances/Source	Nr. Of hazards
1	Initialization	Equipment under pressure	1
2	Inertization	Equipment under pressure	1
		Nitrogen	1
3	Scrubber set-up	Sodium hydroxide	3
		Sodium disulfite	3
4	Reactants and reagents loading	2-MeTHF	3
		Hydrochloric Acid	4
		Paraformaldehyde	6
		Corn cob	3
5	Reaction	Equipment under pressure	1
6	Work-up	2-MeTHF	3
		Cellulose	1
		Lignin	1
7	Work-up (1 portion)	Equipment under pressure	1
		2-MeTHF	3
		Toluene	7
		Formaldehyde	8
		Nitrogen	1
		Equipment under pressure	1
8	Work-up (2 portion)	Sodium hydroxide	3
		Formaldehyde	8
		2-MeTHF	3
		Equipment under pressure	1
9	Installation cleaning	Formaldehyde	8
		Sodium disulfite	3
10	Characterization	NMR	1

Table 74. Steps, substances/sources and associated hazards present during synthesis

Risks

Most of the risks arise from toluene, paraformaldehyde, and formaldehyde. The high level of risk is also associated with significant volumes of mentioned solvents, thus increasing impact. The most critical risks which were considered are listed in Table 75. A complete description of all hazards present in the process can be found in Attachment C3.

Nr	Source	Hazard	RiCS
1	Paraformaldehyde	CMR (Carcinogenic)	6.07
2	2-MeTHF	Corrosive to eye or skin/ Irritant	5.3
3	Toluene	CMR (Reproductive toxicity)	6.19
4	Toluene	Respiratory irritation	6.19
5	Toluene	Oral irritation	5.15
6	Formaldehyde	Respiratory toxicity	6.05
7	Formaldehyde	CMR (Carcinogenic)	5.97

Table 75. The highest risks in synthesis of DFX.

All the risks remain in the ALARP threshold. Thus, no risk that requires mandatory treatment, see Figure 90.

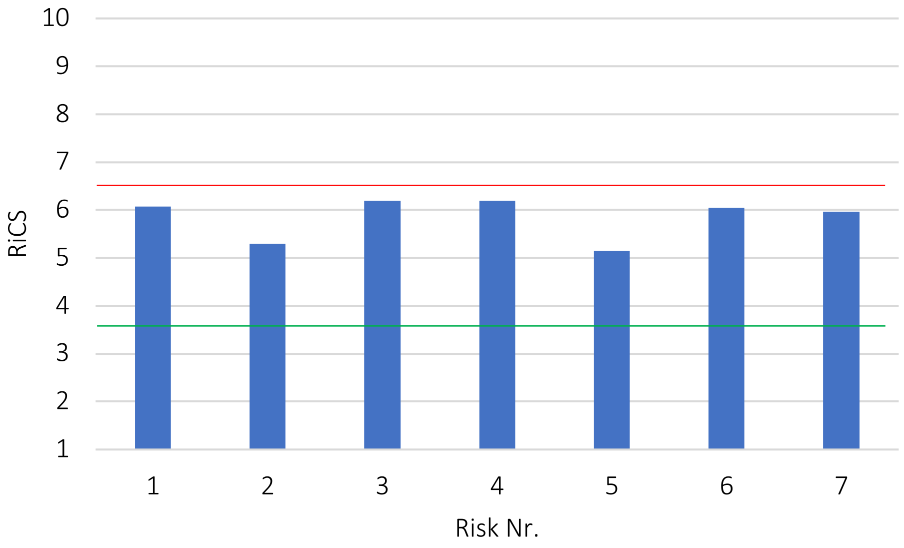


Figure 90. RiCS values;, risks selected for the detailed evaluation and potential risk treatment; ALARP zone.

Risk treatment & decision-making

This risk assessment example represents a long process that includes a limited number of hazardous substances but with a big hazard portfolio. The gravity of the risks is also more prominent than in the case of a small-scale reaction of the same type. Nevertheless, specifically designed equipment (15L reactor) reduces the risk level associated with the conducted process. The most problematic and potentially dangerous points are connected with the user's manipulation of reagents (loading, transfer, work-up, etc.). Due to the extent of the full evaluation, only accumulated results of risk treatment for the most important risks are presented here, see Table 75.

Four main measures were identified to decrease the most critical risks in this process. The majority of them except, measure Nr. 2 can be easily applied to all the risks, see Table 76.

Nr.	Safety measures	Affects risk Nr.	Rank	RiCS after
1	Use the help of a second person for manipulation	1-7	1	4.73
2	Use gas mask/respirator	3-5	4	5.08
3	Wear full body suit	1,2,6	3	4.41
4	Install automatization for loading	1-7	2	4.2

Table 76. Proposed safety measures.

Measures 1 and 4 can apply to all the selected risks from Table 75. The decision-making matrix for all the measures proposed in this assessment is represented in Table 77. The matrix overviews other factors influencing the selection among listed measures.

Nr.		Rank	RiCS after	$\Delta RiCS$	HR	TR	Implementation cost, CHF	Running cost, CHF
1	Use the help of a second person for manipulation	1	3.73	2.46	63	100	1000	5000
2	Use gas mask/respirator	4	4.08	2.11	43	100	1000	100
3	Wear full body suit	3	3.41	2.78	39	100	2000	200
4	Install automatization for loading	2	3.2	2.99	79	70	10000	5000

Table 77. Decision-making matrix.

Based on the decision-making matrix, the least optimal measure is Nr.2, and the most optimal is Nr.1 and 4. These measures are not only the most favorable but allow to mitigate all the risks. The comparison between real and expected risk reduction for all the measures is represented in Figure 91.

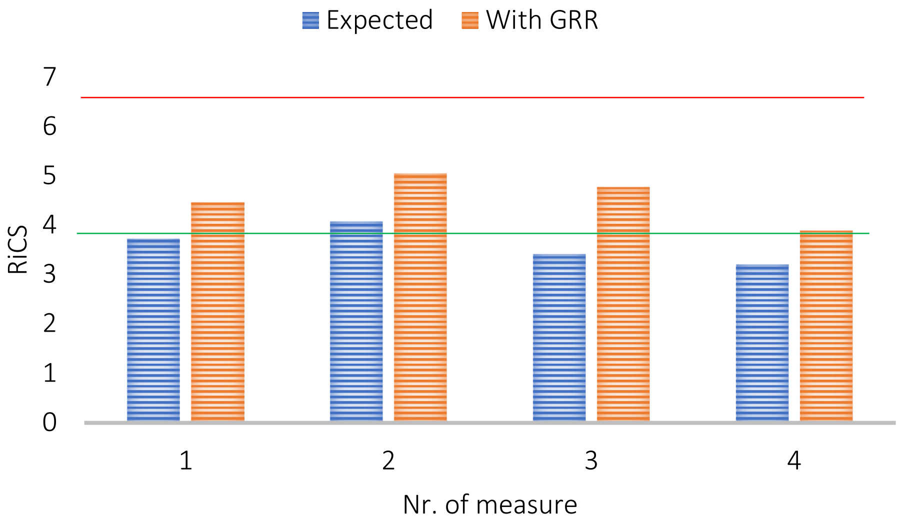


Figure 91. Expected and real risk reduction by the measures.

Measure Nr. 1 demonstrates actual risk reduction closest to expected out of all proposed measures. The highest discrepancy is demonstrated for measure Nr. 3. Risk reduction effect of measure Nr.1 on other risks showed in Figure 92.

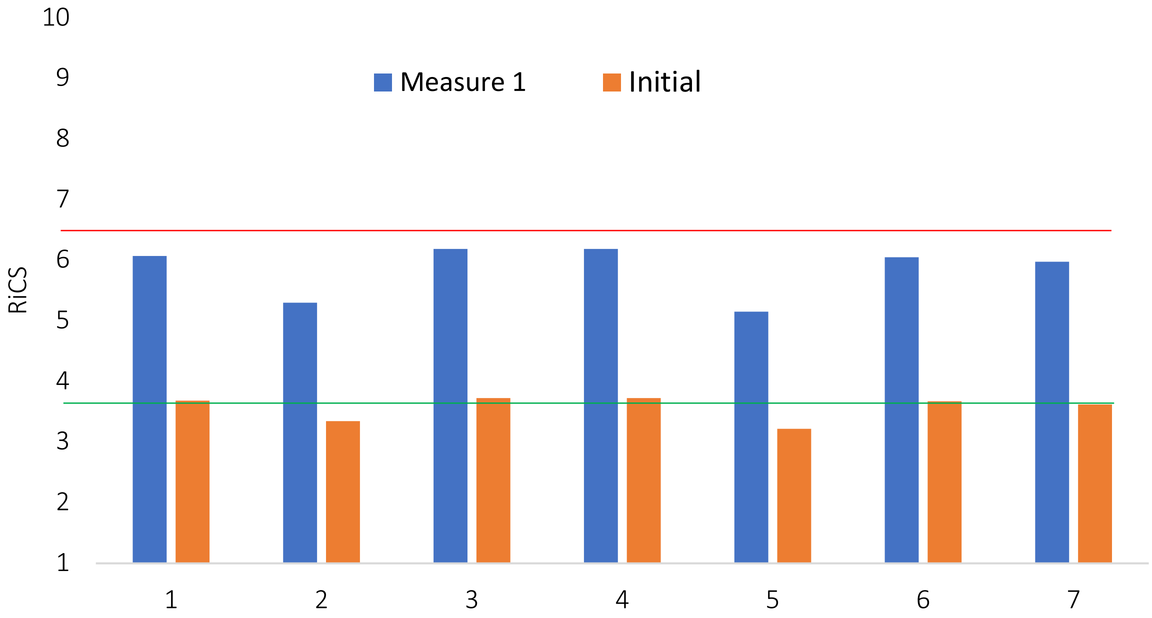


Figure 92. Risk reduction by measure Nr.1 for all the selected risks from Table 75.

Detailed representation of the risk reduction potential of all proposed measures on the identified risks can be found in the Attachment C3, its visual presentation is in Figure 93.

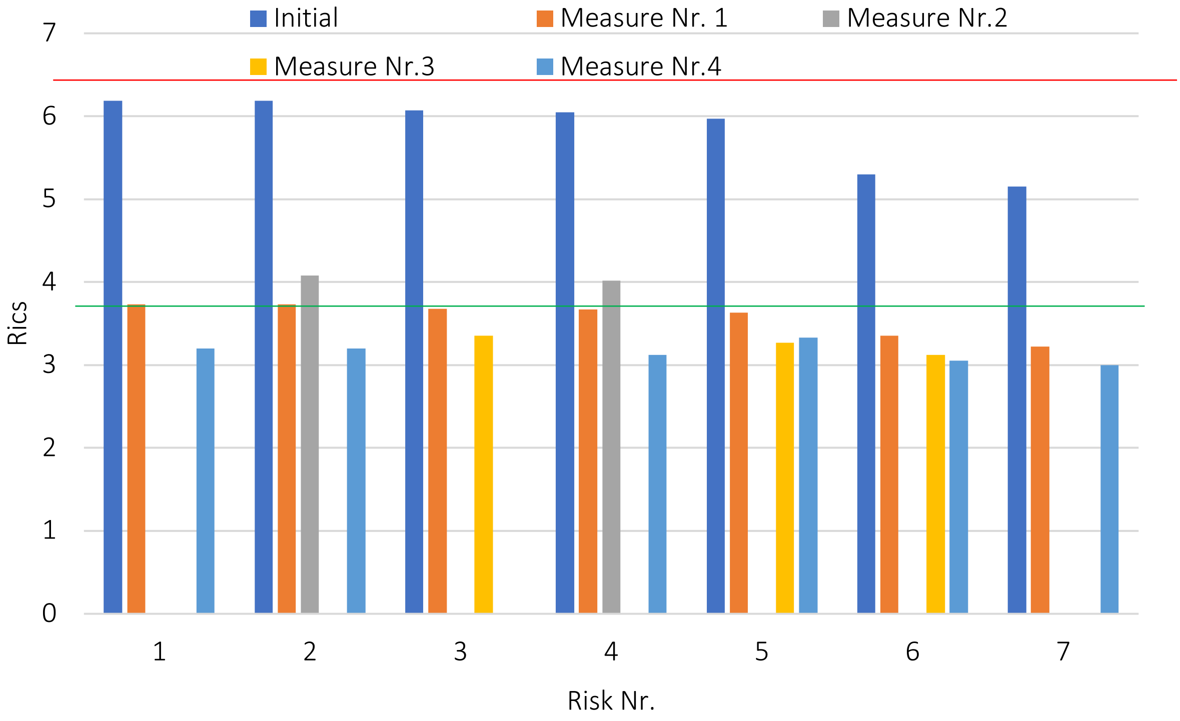


Figure 93. Risk reduction potential of all proposed measures.

Measures Nr.1 and Nr.4 are the most versatile as they can efficiently reduce all selected risks, see Table 75. More than twice the higher cost of the robotic arm and lower efficiency, Figure 91; thus, actual risk reduction makes this measure less favorable. Nevertheless, if the conditions of the set-up would allow, this measure in the long-term would be recommended above all other alternatives.

The main limitations of this assessment are a big-scale process and the high importance of safety to lab management. Thus, even despite potentially risky processes, all necessary precautions as preliminary safety assessment and implementation of safety measures (Nr.1), are taken.

6.2.4 Concluding remarks

The practical examples of the LARA+D application demonstrated that this method could be used for different types of processes. It can be applied to analyze the process depending on the requested level of detail, specifics of the process, potential problematic points, hazard portfolio, and dynamics.

The assessment results provide the user and decision-maker with the vision of which risks must be addressed with the highest priority. Depending on the process structure decision-aiding tool can be used to decide on the most suitable safety measures either for a particular step and hazard, as was demonstrated in chapter 6.1, or for the list of identified risks, as was demonstrated in the following examples. The combination of the ranking of the measures, along with a demonstration of the actual risk reduction potential, provides the decision-maker with various perspectives on the "optimality" of the selection. As was demonstrated with applicational examples, this tool is meant to guide and assists decision-maker in the risk management process and maintain their flexibility of choice.

6.3. Comparison of LARA+D with other methods.

To perform a complete test of the validity of the proposed method, it was compared to existing and tested methods. To accomplish this comparison, the risk assessment reports performed by the safety experts at EPFL were taken.

The joint tests are performed under conditions for which LARA+D is intended. The risk evaluation by LARA+D was conducted under the guidance of safety experts and with the support of the process user. The information missing in the initial assessments was completed to perform the LARA+D evaluation. All involved parties were introduced to the method and given an overview of the principles of the method and expected outcomes.

The test results highlighted the differences between techniques already used by the safety experts at EPFL and the newly developed LARA+D method. The results of the test serve as a demonstration of the validity, applicability, suitability, and usefulness of the proposed method. The earlier versions of LARA+D were compared to HAZOP and FMECA, which illustrated better suitability of LARA+D for research environment than those methods. This work compares modified LARA+D to the technique more frequently used for the risk analysis at EPFL than the abovementioned methods.

6.3.1 Depolymerization of aldehyde-stabilized lignin by hydrogenation.

Description of the process. Depolymerization of aldehyde-stabilized lignin by hydrogenation. Lignin is extracted from wood as a source of biomass. The extracted lignin is then reduced to various aromatic compounds through a Ni/SiO2-catalyzed hydrogenation reaction. The hydrogenation process is well-known, even though constantly modified since the 1980ies (Kasakov, 2015).

The reaction takes place in a 2 m3 Parr reactor. The box is opened on the front, and the door has two holes for protected access to the reactor. The box is connected to the fume hood ventilation system through flexible tubing. The air renewal rate in the Plexiglass box is 2 m3/h. The hydrogen gas line is drawn from a gas bottle (50L at 200 bar) stored outside the laboratory.

Reaction. Lignin and Ni/SiO2 (25 g) were suspended in n-propanol (700 mL). The reactor was sealed and filled with H2 (g) (0.3 L). The reaction was set to 120 bars at a temperature of 110°C. The reaction was heated for 4 hours. During one optimization reaction, the safety rupture disc of the reactor burst, and the reaction mixture sprayed out of the reactor into the Plexiglass box, the fumes from the reaction spread in the early laboratories and the hallway.

SUVA results. Safety experts followed by accident assessment, which was performed using the SUVA method. Risk was calculated as a combination of probability and severity of injury as described in Méthode Suva d'appréciation des risques à des postes de travail et lors de processus de travail "(SUVA, 2008). The severity was estimated as the most severe probable consequence of an accident. The probability was assessed by looking at the frequency and duration of the experiment (e), the possibility of limiting the damage (PO), and a probability index (L). The different hazard entries were then placed in a risk matrix. For the risks that were found in the red zone (high risk), or orange zone (medium risk), mitigation measures were proposed to reduce them to the blue zone (low risk).

The results of the assessment, risks, and their magnitude associated with the set-up are presented in Table 78.

Nr.	Hazard	Specifics	Hazard potential	e+2po+L	Probability
1	Mechanical hazard	Equipment under pressure.	III	2+2*4+3=13	D (improbable)
2	Harmful chemicals	1-propanol (700 ml), Ni/SiO_2 (25g), Unknown aromatic lignin products	IV	4+2*3+1=11	D (improbable)
3	Flammable substances, explosion hazard	1-propanol (700 ml)	I	4+2*4+3=15	C (rare)
4	Flammable substances, explosion hazard	Hydrogen (g)	I	-	Impossible (E)

Table 78. Most important risks according to SUVA methodology.

Figure 94 reports the risk matrix for the different risks identified above. The single entry applies for the Harmful chemicals, as they are assessed cumulatively.

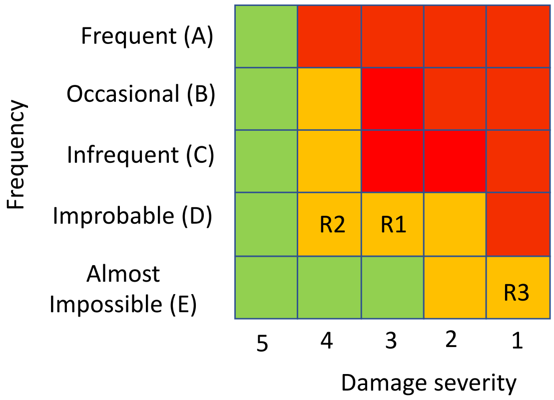


Figure 94. Risk matrix that represents the potential injury and probability of an accident.

LARA+D results. LARA+D assessment is performed accordingly to the procedure demonstrated in the chapters above. The safety climate assessment highlighted that the safety climate had a **medium** level **(0.67)**. The accident happened while the start-up team was experimenting. The level of integration of the start-up members in the group life is low, as they are present occasionally on the site. Thus, there is no sufficient control over equipment state or communication between start-up and group teams. The results of the assessment, risks, and their magnitude associated with the set-up conducted by LARA+D are presented in Table 79.

Nr.	Hazard	Source	Severity	Probability	Detectability	RiCS
1	Mechanical hazard	Equipment under pressure.	3	1.2	5	4.47
2	Flammable aerosol, liquid or solid	1-propanol	4	3.4	3.8	5.48
3	Corrosive to eye or skin/ Irritant		3	1.4	3.8	4.52
4	STOT SE		2	3.4	3.8	4.98
5	Flammable aerosol, liquid or solid	Ni/SiO_2	1	1.4	5	4.12
6	CMR (Carcinogenic)		3	1.4	5	4.79
7	Skin toxicity		1	1.4	5	4.22
8	Hazardous to aquatic life		2	1.4	5	4.44
9	Corrosive to eye or skin/ Irritant	Aromatic components, lignin based	1	1.2	5	4.02
10	Flammable compressed gas	Hydrogen	4	1.0	1	4.67

Table 79. The most important risks according to LARA+D.

As the working temperature of the reactor is above 100 degrees ^{0}C, there is a high risk of explosion; as a consequence, propanol can escape into the environment, which will result in the users' intoxication if the user is close by. On the other hand, there is a high chance of equipment failure due to the low level of maintenance and check-up of the equipment, which needs to be frequently checked.

Comparison. Based on the risk matrix provided by the SUVA, it is complicated to judge the priority of the risks. All three risks are located in similar zones, and some measures can be advised. Comparing the priority of risks between LARA+D and SUVA, the risk of propanol explosion during the reaction is the highest, and the potential intoxication of a person represents the second risk that needs to be addressed.

The SUVA method is often used for this kind of accident analysis. The technique's benefits are its accuracy and consideration of different aspects of the risk, such as existing preventive measures and the duration of the experiment. On the other hand, this method is very resource-consuming, and detailed analysis requires a significant time investment. It is simple and can be performed by non-experts. Assessment results also demonstrate that it is complicated to make prioritization the risks, see Table 80.

Hazard	Source	LARA+D	SUVA
Mechanical hazard	Equipment under pressure.	6	1/2/3
Flammable aerosol, liquid or solid	1-propanol	1	1/2/3
Corrosive to eye or skin/ Irritant		5	1/2/3
STOT SE		2	1/2/3
Flammable aerosol, liquid or solid	Ni/SiO_2	9	4/5/6
CMR (Carcinogenic)		3	4/5/6
Skin toxicity		8	4/5/6
Hazardous to aquatic life		7	4/5/6
Corrosive to eye or skin/ Irritant	Aromatic components, lignin based	10	4/5/6
Flammable compressed gas	Hydrogen	4	4/5/6

Table 80. Comparison of risk priorities by LARA+D and SUVA.

LARA+D demonstrated its suitability and similar results in that all risks identified by the SUVA were assessed and evaluated. Contrary to the SUVA method, which gives a somewhat limited assessment of the "possibility of risk," failure probability used in LARA+D provides better guidance for the user and helps to discriminate between risks, setting treatment priorities.

Evaluation of results. The results of this study demonstrate that LARA+D can be used as a risk analysis method in the research laboratory setting. Earlier versions of LARA were compared to FMECA and HAZOP (Plüss, 2015). Even though the method was modified, the logic and structure of the assessment remain similar. Thus, this work decided to compare the modified method with another widely used technique in Switzerland, which SUVA developed.

LARA+D can identify not only scenarios relevant for the risk assessment, as it is done by the SUVA method. But, it allows more precise calculations when historical data on accidents is absent. This higher precision helps to distinguish among different risks and set priorities on the risk treatment strategies.

On the other hand, the effort needed to perform a risk analysis is relatively low and can be done by a non-expert user if a sufficient introduction to the method is made. Compared with the SUVA method, which is time-consuming and requires specific expertise from the user, this is an absolute benefit in terms of the applicability of the technique in research laboratories, where resources are minimal, see Table 81.

Requirements			Approach		
	LARA+D	SUVA		LARA+D	SUVA
Data	Low-moderate		Form	Semi-quantitative	
Difficulty	Low	Moderate	Level of detail	Moderate	Detailed
Complexity	Low	Moderate	Direction	Hybrid	Deductive
Expertise	Low-moderate	High	Focus	Variable	
Time	Low	Moderate	Phase	Operation	

Table 81. Specifications of the LARA+D and SUVA methods.

The main limitation of LARA+D is its database. The existing database should be complete and straightforward for this method to be suitable for all assessments, precise, and not confusing. Practical tests of the tool and software can help to overcome this drawback, improving and clarifying the existing database, see Table 82.

Method	Advantages	Disadvantages
LARA+D	Very flexible for level of details Compares and prioritizes risks Considers human and organizational factors	The database needs to be detailed and clear The established level of details needs to persistent during the whole assessment
SUVA	Structured and clearly established guidance Consideration of existing safety measures Relatively easy to learn and train	Focus only on determined scenarios Probability determination is vague for non-statistical approach Difficult to compare risks Limited consideration of human factors

Table 82. Advantages and disadvantages of the compared methods.

6.4 Discussions

The application of LARA+D with the example mentioned above intends to analyze the workflow of the method and compare not only outputs but the resource investments necessary for the assessment.

Definition of the context. As discussed in chapters 3 and 5, the setting of the analysis and the main mechanisms of assessment is defined by context. Differences in interpretation, personal attitude, and safety culture can affect judgment, especially when it concerns evaluating certain parameters.

The organizational context is more factual, as it defines the roles and responsibilities of the stakeholders of the analysis. This may vary depending on the structural and administrative changes happening in Academia. For example, EPFL underwent such changes in 2022, which modified the operation and roles of the OHS department.

The technical context of LARA+D sets how hazards are identified and risks are evaluated. It requires correct identification of the primary object of the study, split of the processes, and grouping of similar activities or projects. For the examples illustrated in this chapter, structural divisions of the processes might have been different depending on the process and types of hazards involved. It allows flexibility necessary for the method to be applicable and suitable for diverse processes present in academia.

Hazard identification. Hazard identification is one of the main elements of a risk assessment. The main challenge of the research environment is the presence of different hazards and the frequent synergetic effect of such. Chemical synthesis usually involves a wide range of hazardous substances. They might often have similar hazard portfolios, varying by several hazards or their severity. Previous versions of LARA were utterly relying on the GHS classification for chemicals. However, it was often increasing the time required for assessment. The drawback of such a hazard database was the low applicability of LARA when risk analysis for the chemical process was needed. The new classification of Hazards is based on the principles of the primary target, route of exposure, and type of protection. For example, in most cases, substances that appear corrosive to the skin will show the same effect on the eyes. The precautionary principle is used in this case; the most severe category is considered as the main for classification. Apart from that, the usual practice in the laboratories implies the use not only of gloves and lab coats but requires some eye protection. Classification of other hazards, such as physical or mechanical, is also based on source type, destructing mechanism, and target principle. The existing database of the hazards was verified by the safety experts working at EPFL. However, in order for the method to remain valid and suitable, this database should be constantly monitored and modified, in case new knowledge becomes available.

Risk analysis. In the abovementioned examples, a high number of risks were identified. To be able to address risks correctly, risk management tools should be able to prioritize them, focusing on the most important. In LARA+D, it is done using the risk index RiCS which is composed of three subfactors. To allow certain flexibility of the method, keeping at the same time sufficient precision majority of the factors are scaled from 1 to 5. Those factors that don't imply the use of such a scale are still converted to it. For example, for the detectability factor, there are only three levels, for calculation purposes, they are coded as 1,3, and 5. Undoubtedly, it creates certain empty gaps in the values, which don't impact risk evaluation and prioritization of compared values.

The main challenges for the risk assessment are insignificant risks, represented by diluted chemicals. Another problem is highly hazardous substances that are both odorless, volatile, and colorless. In this case, even though the gravity and probability can be low due to existing safety measures, aggravating factors will still be present, keeping the risk level relatively high, though not unacceptable.

Enhancement of the existing database by practical application, adjustments of factors coefficients can help to overcome this problem.

Risk treatment. The approach used for resource allocation includes consideration of not only financial factors but other factors related to the potential performance of the measure. Despite their location in or above the ALARP zone, all the measures in LARA+D are evaluated from their human and technical reliability perspectives.

LARA+D uses the STOP principle, where the hierarchy of the measures and their expected efficiency depends on the type of the measure. Using a coefficient, which helps to calculate the efficiency of the measure based on its sensitivity to human behavior, not only helps to set the hierarchy for different classes of measures but to take into account their actual suitability for the particular setting. The main drawback is lowered levels of human reliability of any measures, except strategical. However, these factors are mainly used to compare and select the measures. Thus, values are compensated.

Decision-making. LARA+D allows users to conduct risk analysis efficiently and reliably and proposes an assisted selection of suitable safety solutions for the user and decision-maker. The referential approach provides the user with a relatively objective ranking of proposed alternatives.

Considering that any decision-making method won’t be capable of simulating real decision-maker preferences, the risk matrix is meant to give another angle of the preferential selection among different measures. A comparison of expected and real risk reduction is shown to provide the decision-maker with a rough estimation of the risk reduction potential of the measure when such is in place. The main limitation of such comparison is that it is based on the assessed by the analyst quality of man-safety measure interaction, and thus can be biased. However, it gives a first estimation of the actual situation. Clear guidance on how to assess these values, with practical examples for the user, can help to reduce such expert bias.

Risk communication, risk documentation, and risk treatment. LARA+D is expected to be a part of the safety management framework existing at EPFL. The Filemaker platform is decided based on the fact that another tool for safety management is already implemented using this software. Contrary to safety audits, risk analysis is a more detailed and process-oriented approach that requires more time. It means that not all the processes existing at EPFL should be analyzed using this tool. It won't be feasible either from man a time perspective. But it can be used for two occasions: for planned highly risky or new processes or on the local level by the users in the lab. In the second case, it will serve as guidance for the necessary safety actions in the lab and a reference level for further investigation if safety issues can't be resolved locally.

Applicational examples of LARA+D were examined on a hypothetical level, and it is difficult to judge the place of this tool in the safety management framework. Technical aspects of the software were tested only to a limited extent due to delays caused by the reorganization of OHS at EPFL and the developmental delays caused by the contracted software company.

Evaluation of LARA+D method.

The LARA+D project intends to provide universities and research institutes with a safety management tool, which will be suitable for the mentioned risk analysis and decision-aiding tool. This tool was expected to:

- Easy to use, without particular long training
- Time-efficient and detailed if necessary
- Reliable in the context of absent statistical data
- Flexible as it supposes to analyze processes with diverse hazard portfolio
- Take into account the influence of human, organizational and environmental factors
- Compare and prioritize risks
- The support decision-making process, serving users as a negotiation point
- Be integrated into the existing safety management framework at EPFL

The results of the application demonstrated that LARA+D fits these requirements. Semi-quantitative approach and existing database also allow non-experts users to conduct necessary risk assessments in a complete cycle, not only identifying unacceptable risks but helping compare, prioritize and address all problematic points of the process. There is no absolute requirement on the level of detail in analysis; it depends on the process and existing circumstances. Expertise in risk analysis is not required to perform this method; however, knowledge of the process is essential. The deliverables match the expectations of the project. Despite the semi-quantitive character, accurate results are generated and demonstrated with applicational examples. The limitation of the method is not known substances and materials, which are difficult to assess without knowledge of their harming potential. This drawback is a frequent weak point for most existing risk analysis techniques. In the applicational examples, the precautionary principle was used, and hazardous properties of initial substances were used as a reference point for the synthesized component.

The applicational results suggest that the LARA+D project reaches the goal of this thesis, providing Universities and research laboratories with an efficient risk management tool suitable for the process analysis. The software makes this method more time and resource-efficient in terms of application, helping users collect safety knowledge. This tool also considers all the peculiarities of the research environment, not only the direct safety aspects of the proposed alternatives.

Conclusions

A detailed methodological study on the applicability of existing risk management review of their advantages and disadvantages demonstrated that most of these methods are unsuitable for a holistic risk management approach in academia. Some other approaches specifically designed for this setting showed their applicational limitations in a term of a risk management process. The comprehensive risk management process also includes the decision-making step. While most decision-making approaches are based on the idea that the decision-makers know well what they want and their priorities, it is not always suitable for academia. In this dissertation, the evaluation of possible decision-making approaches was performed to provide the final user with an appropriate tool.

To fill the existing gap and design a process risk management tool for the research laboratories, the LARA+D method was developed and tested at EPFL. The results of these tests suggest that the newly developed method overcomes the limitations of existing methods and can serve as a holistic method for the described setting. Compared to other methods, LARA+D can remain sufficiently precise and flexible even without statistical data on the accidents; it is also far less resource-consuming which is crucial for the academic environment.

Various elements achieved this. The novel method of the failure probability calculation, which uses a hybrid model between human error and safety climate approach, not only allows a more precise and less biased evaluation of probability but considers the human element in the risk assessment. The latter is essential for the environment where the role of the individual is so high that each particular user of the process becomes indirectly involved in the decision-making process. Consideration of possible worsening factors that can aggravate the risk allows not only more precise calculations but help not to omit important aspects of the risk. Even though the structure of the method was designed to decrease possible misinterpretation of the factors, the uncertainty of the evaluation remains a weak point of the majority of semi-quantitative methods. The application of Bayesian networks is intended to take this uncertainty into account, thus reflecting a more realistic situation for each risk analysis. Filemaker software is aimed to make this method more user-friendly and increase its applicability, as it provides access to the developed database, generates risk-evaluating reports, and allows communication and feedback to key stakeholders.

However, particular limitations during the application of LARA+D were revealed. It is difficult to make judgments for diluted chemicals using the severity scale of LARA+D. Nevertheless, this limitation is not only typical to LARA+D; the identical drawback can be found, especially in official organizations' methods, such as the SUVA method. The second problematic point is the acceptability scale. They were established without consultation with the University board and used the same scale approach for all types of hazards. However, as demonstrated, most existing risks are situated in the ALARP zone since all feasible precautionary measures were taken. Still, the risk potential of the hazard remains high. This limitation needs to be considered during the application. The least problematic aspect of LARA+D is its database; even though major elements were developed as extensively as possible at the design stage, they will constantly require monitoring and modifications. These modifications may include the addition or correction of the worsening factors and their relative impact; failure contributing factors, amplification of the list; and list of corrective measures, their costs, type, and legal status.

In academia, the impact of accidents is unlikely to reach disastrous scales as in the industry. However, from the perceptional point of view, academic accidents strongly influence public opinion. These accidents pose not only direct financial harm to the institutions. Still, they can result in reputational damages, financial claims from third parties, limited resources and loss of funding, etc. Thus, it is in the interest of any institution to do its best to provide people working and studying in Universities with an environment that is as safe as reasonably practical. To achieve this, various safety management tools can be applied, such as audits or risk assessments. Each tool serves its specific purpose. LARA+D is a tool that helps to achieve this purpose as a tool focused on the process risk assessment. Being more accessible ad resource efficient than traditional methods, LARA+D allows for conducting an extensive risk assessment in the field where it is rarely used. Extensive use of this method in academia could help raise awareness of the risks faced during the experiments and allocate resources most practically. Thus efficiently reducing academic accidents despite existing limitations requires further improvements and additional studies. This method can contribute to safety improvement in the research environment.

Perspectives and recommendations. The LARA+D method developed in the frame of this dissertation is holistic and suitable for the research environment risk management method. Nevertheless, as with all freshly developed methods, it has not only benefits but some limitations. To improve this tool, these limitations need to be tackled. The following recommendations on further work are suggested to enhance the method.

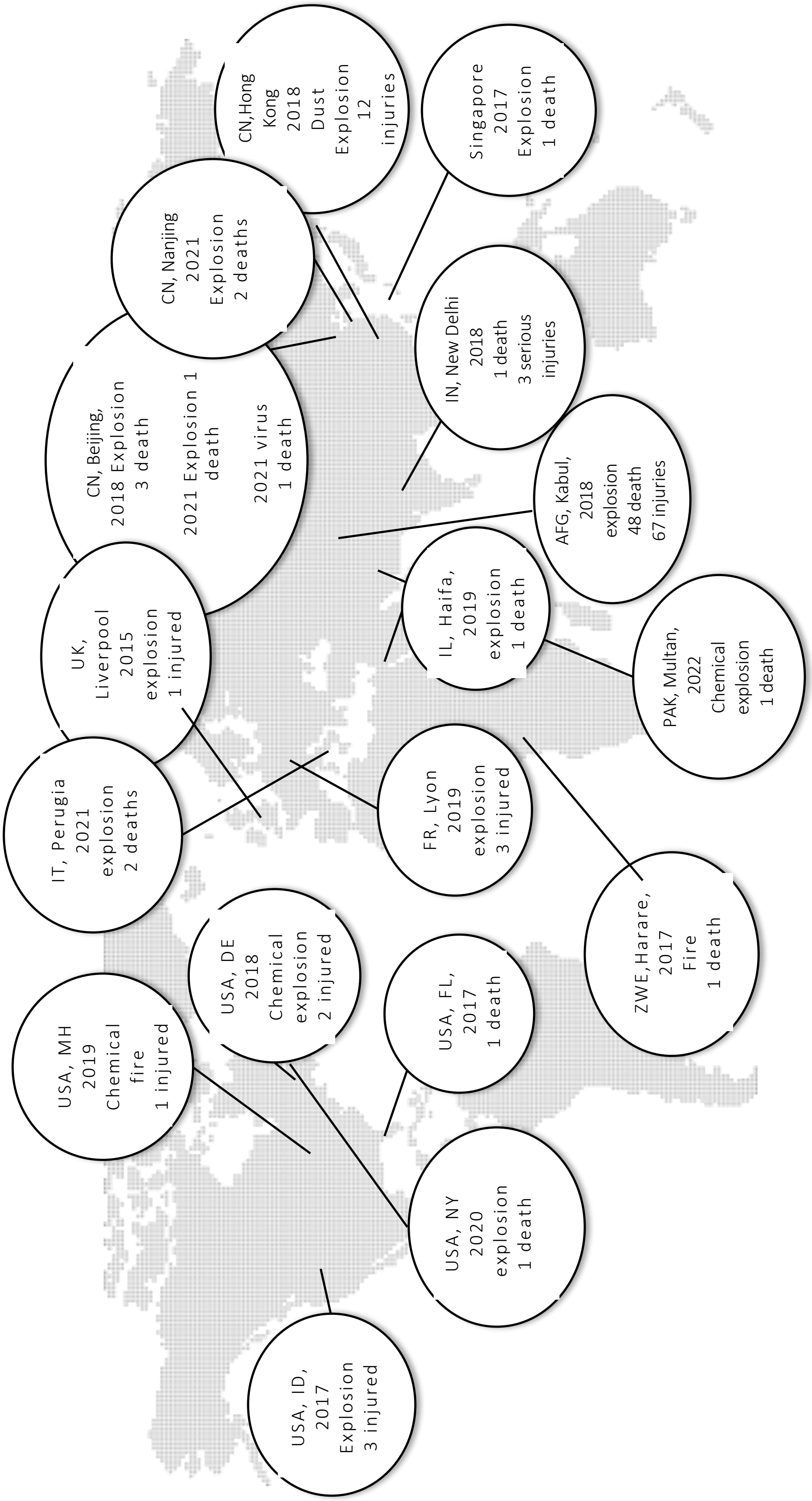
Safety framework integration. LARA+D is intended to be integrated into the safety management framework of EPFL. Along with the quick audit that already exists on the Filemaker platform, LARA+D is meant to enhance the portfolio of safety management tools available for OHS service. Using two instruments on the same platform could ease connectivity between them. Quick audits can also be used to identify processes that will require further assessment by LARA+D; information collected during this kind of audit can be further used for risk assessment. Another approach for the integration of LARA+D is for educational and preventive purposes. In this case, the OHS experts will not perform risk assessments but conduct them by the process users and students. Such integration can help to improve safety awareness in the institution and establish a good practice of a preliminary risk assessment during routine operations.

Improvement of calculations. The calculations used in LARA+D are partially based on the Bayesian approach. Currently, the first assumption made is the equal importance of the factors. However, such can result in a non-balanced calculation, giving too much weight to the elements with lower levels, as in the case of detectability. Nevertheless, to identify whether all contributing factors are weighted correctly, only a significant number of practical applications can help to identify and improve it. Secondly, since Bayesian networks are based on probability distributions, these can be modified if statistically relevant data of expert judgments are developed. Another modification that can be made regarding calculations concerns the decision-aiding block. This version of LARA+D is based on the assumption that decisions are made individually, and each decision-maker is presented with relatively objective information. However, some complex situations may require collective decision-making when other influences one decision-maker's opinion. In this case, it is worth considering the implementation of a quantum-based approach that can simulate the natural decision-making process and consider interferences.

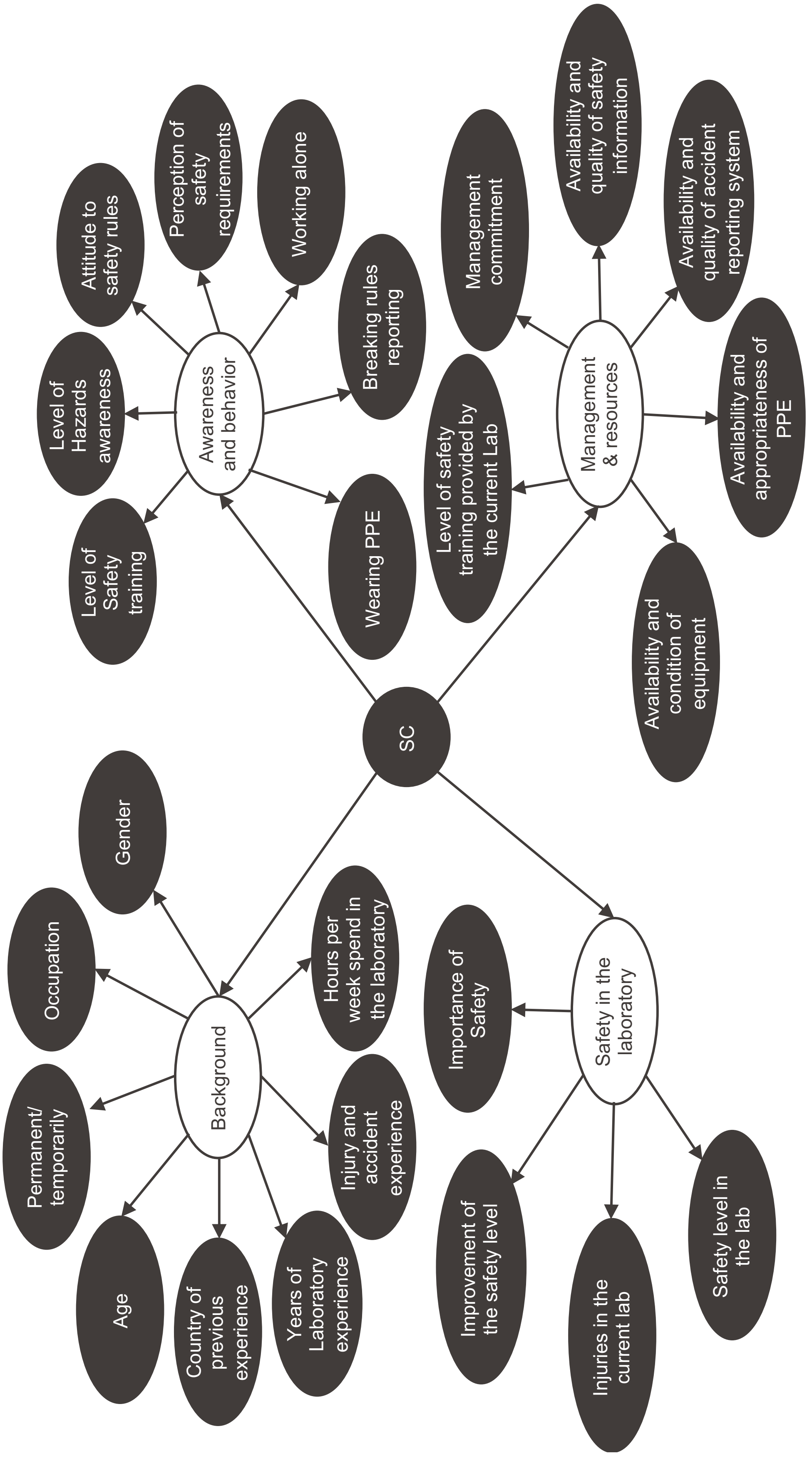
Corrective measures. The decision-aiding block is meant to ease the selection of corrective measures. The current database provides a classification of the measures based on the analyzed hazard, STOP approach, and legal status of the measure and suggests users with information on which factor this measure affects. However, the existing database is not extensive, and analysts frequently need to propose new measures. Another problem is that the costs are not always known and require some investigation to be determined automatically. Guidelines on the used suppliers and access to their catalogs can improve this drawback.

In overall, for this method to be more efficient and performant higher transparency between different structural units at EPFL should be established. The exchange of the information could help to improve the database and make risk assessment more time-efficient and reliable.

Attachment A1.



Attachment A2



Attachment A3

FAHP Questionnaire

Simplicity (S) describes the laboratory staff's ease of operation and use of the measure. If the safety measure is difficult to use, most likely, it will affect its acceptability. However, simplicity will depend on the activity, and generally, a well-accepted measure can be challenging to use in the analyzed process.

Value	Level
1	Very complicated
2	Complicated
3	Average
4	Simple
5	Very simple

Acceptability (A) describes the extent to which the safety measure is accepted for usage by the individual directly affected and potentially using it. If the acceptability of the measure is low, a person(s) will always evade its usage. Thus it will impact the overall effectiveness of the measure. There can be objective and subjective reasons for the low acceptability of the measure. Knowledge about such can improve the acceptability of the measure.

Value	Level
1	Absolutely Unacceptable
2	Very Low Acceptability
3	Average
4	Acceptable
5	Well Accepted

Compatibility with the environment (CE) defines the extent to which safety measure is compatible with the surrounding environment. Contrary to CP, the process is not relevant here, but the "ergonomics" or organization of the physical space of the room.

Value	Level
1	Not Compatible, can’t be used
2	Low Compatibility
3	Compatible, can be used with some modifications (room, environment reorganizations)
4	Good Compatibility
5	Absolutely Compatible

Process Compatibility (CP) describes how well a particular measure is compatible with the process. It means that this measure needs to be compatible with the process and equipment used during it. Low process compatibility will significantly affect the effectiveness of the measure.

Value	Level
1	Not Compatible, can't be used
2	Low Compatibility
3	Compatible, can be used with some modifications of the measure or process
4	Good Compatibility
5	Absolutely Compatible

1. How important is it that chosen measure is suitable for the process than the use doesn't cause any complications for the employees? (CP max than S max)

Process compatibility — Simplicity

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

2. How important that the measure will be well accepted for use by employees than it fits in the space of the room and correlates with the working conditions (ex.: lightning, sound level, temperature)? (A max than CE max)

Acceptability — Compatibility with working environment

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

3. How important is that measure is well accepted by the users, than it won't require additional efforts from them to use it? (A max than S max)

Acceptability — Simplicity

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

4. How important that the employees do not need additional efforts when using the measure than it is compatible with the surrounding environment (room space, equipment location, etc.) and working conditions (ex.: lightning, sound level, temperature)? (S max than CE max)

Simplicity — Compatibility with working environment

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

5. How important is that measure well compatible with the analyzed process than it suits the surrounding environment (room space, equipment location, etc.) and working conditions (ex.: lightning, sound level, temperature)? (Ce max than CP max)

Compatibility with working environment Process compatibility

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

6. How important that the employees well accept the proposed measure than it is well compatible with the analyzed process? (A max than CP max)

Acceptability Process compatibility

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

7. How important is that measure is **badly** compatible with the analyzed process than it is **complicated** to use this measure? (CP min than S min)

Process compatibility Simplicity

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

8. How important is the employees **not** to accept that measure than it is incompatible with the surrounding environment (room space, equipment location, etc.) and working conditions (ex.: lightning, sound level, temperature)? (A min than CS min)

Acceptability Compatibility with working environment

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

9. How important is that measure is **not** accepted by the users than it will be **complicated** for them to use it? (A min than SU min)

Acceptability Simplicity

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

10. How important that it will be **complicated** for employees to use proposed measures than **won't** be compatible with the surrounding environment (room space, equipment location, etc.) and working conditions (ex.: lightning, sound level, temperature)? (S min than CS min)

Simplicity Compatibility with working environment

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

11. How important is that the proposed measure **won't** be compatible with the surrounding environment (room space, equipment location, etc.) and working conditions (ex.: lightning, sound level, temperature) than is **poorly** compatible with the analyzed process? (CS min than CP min)

Process compatibility — Compatibility with working environment

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

12. How important do the employees **not** to accept that proposed measure than it is incompatible with the analyzed process? (A min than CP min)

Acceptability — Process compatibility

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Attachment B1.

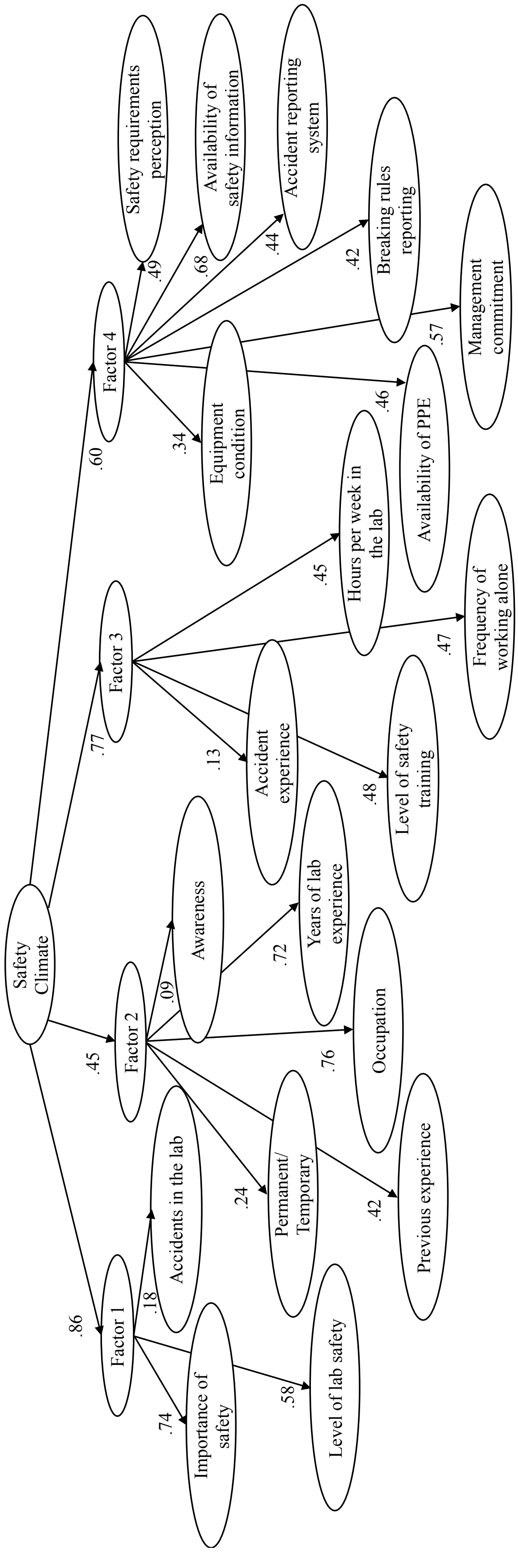
Spearman's correlations coefficients

Items	Mean	SD	I1	I2	I3	I4	I5	I6	I7
Availability of safety info (I1)	*2.55*	*0.859*	*1.000*	.466**	.399**	.296**	0.420*	.096**	.205**
Accident reporting (I2)	2.52	.901	.466**	*1.000*	.312**	.221**	.359**	.046	.145**
Perception of safety requirements (I3)	2.65	.656	.399**	.312**	*1.000*	.212**	.321**	.148**	.130**
Equipment Condition (I4)	2.5	.881	.296**	.221**	.212**	*1.000*	.489**	.011	.122**
Availability of PPE (I5)	1.11	.596	0.420*	.359**	.321**	.489**	*1.000*	.021	.147**
Working alone (I6)	2.33	.803	.096	.046	.148**	.011	.021	*1.000*	.131**
Breaking rules reporting (I7)	1.9	1.098	.205**	.145**	.130**	.122**	.147**	.131**	*1.000*
Occupation (I8)	2.3	1.064	.012	.135**	-.014	.156**	.120**	-.239**	-.076
Permanent/Temporary (I9)	1.07	.253	.057	.041	.008	-.110**	-.047	.021	.051
Previous experience (I10)	2.32	1.030	.135**	.155**	.090	-.262**	.030	.001	.167**
Awareness (I11)	2.33	.756	.256**	.295**	.145**	.197**	.252**	-.118**	.017
Y. of lab work experience (I12)	2.04	.743	.078	.125**	.056	.151**	.136**	-.202**	-.122**
H/week working in the lab (I13)	1.90	.781	.002	.084	-.038	.069	.077	-.345**	-.077
Accident experience (I14)	2.40	1.195	.129**	.178**	.085	-.120**	.112**	-.048	-.043
Accidents in the lab (I15)	2.34	1.026	-.005	-.002	.059	.053	.025	.064	.019
Level of lab safety (I16)	2.60	.731	.129**	.125**	.043	.115**	.085	.155**	.135**
Importance of safety (I17)	2.20	.768	.271**	.215**	.233**	.063	.189**	.186**	.138**
Management commitment (I18)	2.30	1.092	.466**	.290**	.294**	.185**	.261**	.110**	.205**
Level of safety training (I19)	2.49	.713	.283**	.278**	.239**	.157**	.197**	.072	.107**
Age (I20)	2.17	1.044	-.083	-.166**	-.067	.074	.012	-.125**	-.067
Attitude to Safety rules (I21)	2.59	1.014	.065	.153**	.057	-.151**	.033	.007	.036
Improvement of lab safety (I22)	2.37	1.068	0.15	.133**	.072	-.142**	.067	-.077	-.106**
Time when safety training was provided	2.74	1.086	.293**	.253**	.290**	.140**	.262**	.142**	.087**
Type of accident (I2)	1.91	.874	.056	.133**	.092**	-.071	.071	-.028	-.007
Safety training background (I25)	2.24	.731	.304**	.252**	.193**	.195**	.311**	.015	.045

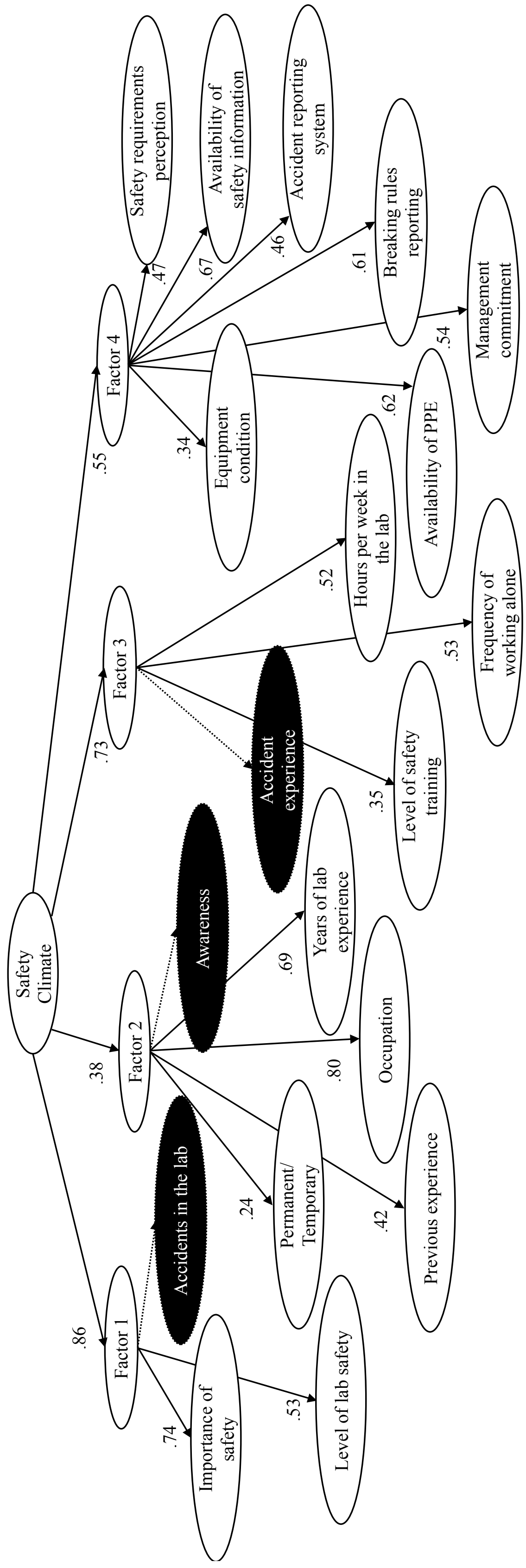
I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19	I20
.012	.057	.135**	.256**	.078	.002	.129**	-.005	.129**	.271**	.448**	.283**	-.083
.135**	.041	.155**	.295	.125	.084	.178**	-.002	.125**	.215**	.290**	.278**	-.166**
-.014	.008	.090	.145**	.056	-.038	.085**	.059	.043	.233**	.294**	.239**	-.067
.156**	-.110**	-.262**	.197**	.151**	.069	-.120**	.053	.115**	.063	.185**	.157**	.074
.120**	-.047	.030	.252**	.136**	.077	.112**	.025	.085	.189**	.261**	.197**	.012
-.239**	.021	.001	-.118**	-.202	-.345	-.048	-.064	.155**	.186**	.110**	.072	-.125**
-.076	0.51	0.167**	.017	-.122**	-.077	-.043	-.019	.135**	.138**	.205	.107	-.067
1.000	-.110**	-.117**	.230**	.624**	.301**	.061	-.012	-.112**	-.164**	-.086**	.131**	.221**
-.110**	*1.000*	.232**	.027	-.080	-.101**	.069	-.032	.023	.101**	.055	.011	-.084**
-.117**	.232**	*1.000*	-.013	-.038	.012	.284**	-.041	.074	.229**	.153**	.060	-.166**
.230**	.027	-.013	*1.000*	.259**	.205**	.174**	-.078	-.014	.049	.122**	.255**	-.026
.624**	-.080	-.038	.259	*1.000*	.240**	.171**	-.067	-.182**	-.166**	-.057	.099**	-.084**
.301**	-.101**	.012	.205	.240	*1.000*	.166	.018	-.133**	-.189**	-.035	-.034	.065
.061	.069	.284**	.174**	.171**	.166**	*1.000*	-.122**	-.061	.052	.059	.108**	-.118**
-.012	-.032	-.041	-.078	-.067	.018	-.122**	*1.000*	.199**	.071	.056	-.007	.014
-.112**	.023	.074	-.014	-.182**	-.133**	-.061	.199**	*1.000*	.388**	.149**	.134**	-.212**
-.164**	.101**	.229**	.049	-.166**	-.189**	.052	.071	.388**	*1.000*	.312**	.205**	-.177**
-.086**	.055	.153**	.122**	-.057	-.035	.059	.056	.149**	.312**	*1.000*	.170**	-.099**
.131**	.011	.060	.255**	.099**	-.034	.108**	-.007	.134**	.205**	-.019	*1.000*	-.022
.221**	-.084**	-.166**	-.026	-.084**	.065	-.118**	.014	-.212**	-.177**	-.099**	-.022	*1.000*
-.070	.088**	.210**	.053	.065	-.010	.181**	-.021	.104**	.159**	.113**	.016	-.170**
-.012	.075	.215**	.016	-.025	.094**	.188**	-.045	-.067	.173**	.079	-.005	-.068
-.181**	.068	.055	.099**	-.129**	-.102**	.064	.097**	.204**	.275**	.250**	.212**	-.099**
.103**	-.01	.110**	.159**	.189**	.084**	.403**	-.041	.13**	-.01	.021	.084**	.059
.054	-.029	.099**	.227**	-.007	.097**	.116**	.016	.145**	.191**	.262**	.25**	.005

I21	I22	I23	I24	I25
.065	.015	.293**	.056	.304**
.153**	.113**	.253**	.133**	.252**
.057	.072	.290**	.092**	.193**
-.151**	-.142**	.140**	-.071	.195**
.033	.067	.262**	.071	.311**
.007	-.077	.142**	-.028	.015
.036	-.106**	.087**	-.007	.045
-.070	-.012	-.181**	.103**	.054
.088**	.075	.068	-.010	-.029
.210**	.215**	.055	.110**	.099**
.053	.016	.099**	.159**	.227**
.065	-.025	-.129**	.189**	-.007
-.010	-.094**	-.102**	.084**	.097**
.181**	.188**	.064	.403**	.116**
-.021	-.045	.097**	-.041	.016
.104**	-.067	.204**	-.130**	.145**
.159**	.173**	.275**	-.010	.191**
.113**	.079	.250**	.021	.262**
.016	-.005	.212**	.084**	.250**
-.170**	-.068	-.099**	.059	.005
1.000	.122**	.067	-.009	.018
.122*	*1.000*	.047	.138**	.037
.067	.047	*1.000*	-.001	.336**
-.009	.138**	-.001	*1.000*	0.076
.018	-037	.336**	0.076	*1.000*

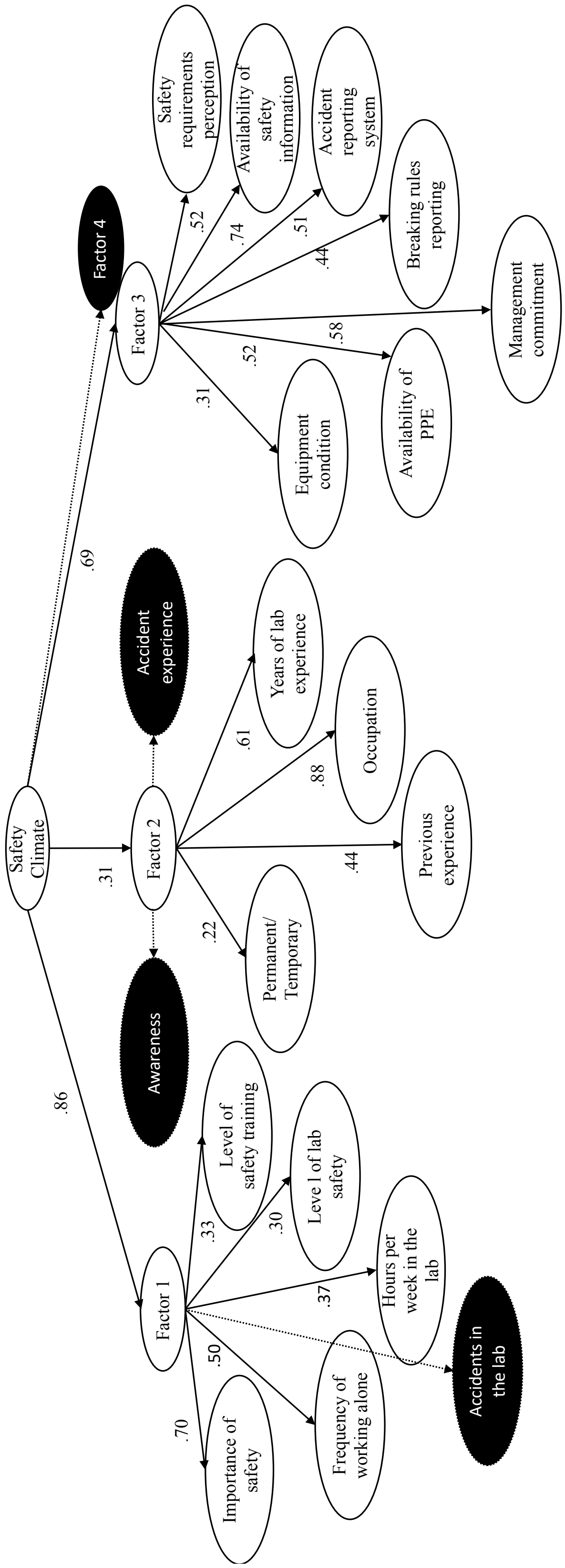
Attachment B2.



Attachment B3.



Attachment B4.



Attachment B5.

Questionnaire for the safety climate assessment with relevant scores for calculation of the Safety Climate (SC).

P1. How important do you think safety is in your laboratory?

Not really important	Less important than laboratory main activities	Equally important to laboratory main activities	Very important	More important than laboratory main activities
1	1	2	3	3

P2. Your laboratory a safe environment.

Disagree	Neither agree nor disagree	Agree
1	2	3

P3. What do you think about your level of safety training?

I had just a basic training	Sometimes I don't remember how to work with certain hazards	I would like to have an additional training to better perform my work in the laboratory	I was trained specifically for hazards I am working with	My training helps me efficiently to decrease risk
1	1	2	3	3

P4. How often do you work alone?

Almost every day	Several times per week	Several times per month	Once per couple of months	Couple of times per year
1	1	2	3	3

P5. How much time per week do you spend working in the lab performing experiments?

More than 40 hours per week	Between 30 and 40 hours per week	Between 20 and 30 hours per week	Around 20 hours per week
1	1	2	3

P6. For how long have you been working at this university?

I'm not this university affiliate	For about 1 year	More than 1 year
1	2	3

P7. How well your previous experience helps you to be integrated in your current lab?

Not really well	Average	Really well
1	2	3

P8. What is your current occupation?

Bachelor/Master	PhD	Postdoc/Research Scientist	Technician/Engineer
1	2	3	3

P9. What is your total lab experience?

Less than 1 year	Less than 3 years	Between 3-5 years	More than 5 years	More than 10 years
1	1	2	3	3

P10. Have you ever seen a colleague break a lab safety rule?

Yes, but never commented/corrected	Yes, sometimes corrected/commented	Yes, always corrected/commented	Never
1	2	3	3

P11. In your lab, there is a sufficient supply of the appropriate PPE?

Disagree	Neither agree nor disagree	Agree
1	2	3

P12. Does your supervisor encourage others to work safely, demonstrating with his/her own example?

No, he/she is not interested in safety	No, he/she is just interested in compliance	He/she only encourages others	He/she encourages us and tries to demonstrate with own example	He/she is always supportive and encourages safety initiative
1	1	2	3	3

P13. The research and safety equipment (fume hoods, biosafety cabinets, etc.) in your lab are safe and in good working order?

Disagree	Neither agree nor disagree	Agree
1	2	3

P14. Are you aware about accident reporting system in your lab?

No	Yes, but don't know how to use it	It is not very clear how to use it	I know how to use it
1	1	2	3

P15. What do you think about information about safety rules and procedures in your laboratory?

There is no any	There is only general information available	Specific safety information on hazards and equipment is easily available
1	2	3

P16. What do you think about safety rules and regulations you need to follow?

They are not appropriate for my work	They slow down my work	Majority are just common sense	It is important to follow majority of safety rules and procedures	It is important to follow safety rules and procedures
1	1	2	3	3

Attachment C0.

Key topics discussed during interview with decision-makers.

I. **Risk assessment. Specific features of the risk analysis tool which would benefit the laboratory.**
   A. The process, materials used, and frequency of modification requirements to the risk assessment might differ. Laboratories working with specific and new materials, whose properties may vary widely, will benefit from detailed risk assessment and possible collaboration with other expert groups working with similar materials. General hazard assessment, in this case, is not sufficient, as the properties of a material may change during manipulation.
   B. On the other hand, groups with frequently modified processes will need a more general assessment, which allows them to modify the experiment conditions without modification of the entire assessment. For example, the chemical substitution with the following change of the hazard portfolio shall be done without the complete reassessment of the process. It also needs to be done fast, allowing users to manipulate already created by the safety expert assessment, and adapt his/her safety behavior, implementing additional safety measures if needed. This means that the tool needs to propose measures automatically with the connection to a Hazard/substance.
   C. Another type of group with several rarely modified processes will benefit from the risk assessment, which also pursues educational purpose and will ensure good safety behavior within the group.
   D. Some laboratories have a high portfolio of various hazardous processes, which change daily. Considering that lab journals with a minimal risk evaluation conducted by the individual is already a comprehensive spread practice, integrating a risk assessment tool with a tablet-based lab journal will profit some labs. Open data protocols can help improve the research quality, secure all information about the experiment, and increase individuals' safety awareness. It means that risk analysis will be less detailed than in cases when a safety expert conducts such, but it will increase the safety involvement of the individual.
   E. Keeping in mind that many processes will be performed using non-standardized equipment and materials, sometimes implementing the compulsory measures can be

complicated. The main accent needs to be paid to the specific characteristics of the setup. Such focus will most likely create a more trustworthy relationship between safety experts and laboratory personnel, increasing the reliability of proposed safety solutions.

II. **Decision-making. Way of communication and information are considered significant during the selection process.**
   A. Safety often can be compromised due to ambitious individual research objectives. The main reason for such a biased choice of research success over personal safety is in perceived consequences by the individual. The possibility of not delivery of expected results and professional failure outranks the distant probability of an accident. Experienced individuals might feel confident in their skills and knowledge to avoid accidents, not taking other possible factors that are not always predicted. Quantitative communication of the risk level will not improve safety awareness; on the other hand, clear communication of the possible consequences, also from the lens of the research activity impact, will help an individual to set priority more objectively.
   B. The same concerns the laboratory in general. Even costly, time-demanding safety modifications can be done by shifting research priorities to the second place when there is an apparent gain in terms of safety. Such added value needs to be demonstrated qualitatively.
   C. Time is almost always a crucial element in research. It can be a decisive factor in determining whether the measure will be accepted. On the other hand, approximate time estimation for measure implementation will allow laboratories to reorganize their time planning for the processes, optimizing available time and increasing acceptance of time-consuming installation measures.

1. **Educational objectives of PI’s**
   A. Even though teaching objectives are often underestimated in Academia, in comparison with research activities, some PI's determine educational goals as primary for themselves. Safety education of the students and transfer of the knowledge to less experienced is essential, as it also creates a particular personal brand image. Teaching

modern practices of working with hazardous materials and equipment, which are also used in industry, results in the generation of young expert graduates. In the long run, such output helps create collaboration between individual labs and companies.

B. The educational approach towards subordinates also creates a positive impression about lab and PI in the case of an academic career. It benefits both laboratory and PI – improving inter-laboratory collaboration and brand image, and students – increasing their chances of a successful career. In the long run, it can also benefit University, increasing its collaboration and reputation nationally and internationally.

C. Available online courses will help people working with materials and equipment to update and refresh existing knowledge. Each half-one year, periodical online testing can be used to control the level of safety knowledge and eliminate knowledge-based errors.

2. Research objectives of the group

A. The high quality of the research is undoubtedly crucial to any laboratory. Reliable results of the experiments, reproducibility of the data, and conditions of the experiment are highly affected by the safety conditions. It includes ergonomics, state of equipment, safety behavior, and culture in the group. The quality of the research will also affect the publication capacities of the laboratory and the value of its research. Minor incidents and near misses can jeopardize these objectives.

B. On the other hand, accidents, despite their severity, will affect the time frame of the research, resulting in pushing other deadlines or dropping the quality of the research, degrading the laboratory's reputation.

3. Social objectives of the group

A. Sharing of knowledge, both positive and negative, will improve the research performance of the laboratory. Laboratories can be a very competitive environment, where team members compete again each other in order to fulfill their research objectives. In the majority of cases, is publication pressure, especially when several members are working on the same topic. Individual performance in the short run can benefit particular individuals, but in the long perspective, the overall performance of the laboratory will be more critical. Sharing experience and working practices between team members will improve the performance of all the members. Mentoring new and less experienced team members with more experienced will help avoid possible incidents/accidents, improve laboratory research performance, and create a trustworthy relationship within the laboratory.

B. Sharing the negative experience, personal or non-direct incident/accident experiences, improves hazard perception among laboratory members. Connecting their working habits, conditions of the experiment, or environment with real situations experienced by their colleague will make it more accurate, increasing awareness.

C. COSEC can be one of the vital connecting elements, transferring concerns and issues from the group to PI and vice versa. Having less imposing power and not having an employee role can serve as a mediator, resolving some issues before they escalate. On the other hand, in Academia, individuals frequently do not feel confident to ask questions, as it puts their expertise at stake. These questions could be asked easier when there is no explicit subordination between individuals and another individual is specifically assigned a task to provide safety advice.

4. Safety expectations from other safety management tools

A. Some laboratories suffer from a lack of communication among the members. In the case of the big labs, when there is no awareness about research projects and hazards handled by others, it is difficult to keep control over hazard handling and associated responsibility. These laboratories can use a COSEC as a connecting element or an anonymous reporting tool. Reporting tool shall indicate existing safety issues, bring the attention of the responsible person(s) to the existing problem, or notify COSEC or PI in case of repeated and unsolved issues.

B. Such a tool can also be used on another level, allowing labs to report issues outside the laboratory (shared equipment, space, etc.). At the first step, such reporting shall serve as a signal to involved parties, and in case the issue is not solved, inform Safety Competence Center.

C. The position of the COSEC shall also depend on the type and needs of the laboratory. A permanent role will be more desirable in some bigger laboratories with a significant hazard portfolio. In the case of less hazardous laboratories, COSEC can perform its functions simultaneously in several laboratories, or a temporary position will be sufficient. In both cases, COSEC shall be selected, paying attention to the characteristics of the individual. The main requirement is a specific (responsible) attitude towards safety and the ability to impose rules on others.

5. Communication

A. Communication between Safety Competence Center and laboratories shall be more supportive and educational, creating a trustworthy relationship and improving the exchange of information.

B. Communication between the laboratory – human resources/academic affairs – safety competence center is necessary to provide timely training for new personnel in the laboratory and to avoid long delays of practical work or work without prior training.

C. Individual discussions between lab members and PI are necessary when unsafe behavior or attitude is repeatedly observed. It is essential to conduct this type of discussion educationally, explaining possible consequences for the individual, colleagues, project, and laboratory.

6. Individual responsibility

A. There is a need for formal regulation of safety behavior at the school level. It includes written rules for both students and employees.

B. Specific rules shall be supported by the general guidance indicating possible consequences in case of violation of such rules.

C. Safety requirements need to be supported by both positive and negative stimuli.

D. The safety performance of the individual working in the laboratory must be a part of individual performance evaluation.

E. Laboratories shall undergo yearly safety performance evaluation, which the stimuli can support, influencing the evaluation of PI individual performance.

Apart from the information necessary for designing a decision-aiding tool, much information was gained on the overall vision of safety at EPFL, possible improvements, and sharing positive experiences.

Attachment C1

N^O	Question	Answer	Score
1	How important do you think safety is in your lab? (P_1)	Very important	3
2	How often do you work alone? (P_2)	Several times per month	2
3	How much time per week do you spend working in the lab performing experiments? (P_3)	Between 40 and 30 hours per week	1
4	Your laboratory is a safe environment (P_4)	Agree	3
5	What do you think about your level of safety training? (P_5)	I was trained specifically for Hazards I am working with	3
6	What is your primary affiliation? For how long are you at this university? (P_6)	EPFL, More than 1 year	3
7	How well does your previous experience help you to be integrated in your current lab? (P_7)	Really well	3
8	What is your current occupation? (P_8)	PhD student	2
9	What is your total lab working experience? (P_9)	Between 3-5 years	2
10	The research and safety equipment (fume hoods, biosafety cabinets, etc.) in your lab are safe and in good working order? (P_{10})	Neither agree nor disagree	3
11	In your lab, there is a sufficient supply of the appropriate PPE? (P_{11})	Agree	3
12	Does your supervisor encourage others to work safely, demonstrating with his/her own example? (P_{12})	He/she is always supportive and encourages safety initiative	3
13	Have you ever seen a colleague break a lab safety rule? (P_{13})	Yes, always corrected/commented	3
14	Are you aware about accident reporting system in your lab? (P_{14})	Yes, but don't know how to use	2
15	What do you think about information about safety rules and procedures in your laboratory? (P_{15})	Specific safety information and hazards is easily available	3
16	What do you think about safety rules and regulations you need to follow? (P_{16})	It is important to follow majority of safety rules and procedures	3

N^O		Answer	Score
1	Level of light	Medium	2
2	Level of noise	Poor	3
3	Temperature condition	Medium	2
4	Working space condition	Good	1

		Presence in steps													
Source	Hazards	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Pyridine	Flammable aerosol, liquid or solid	X	X												
	Oral toxicity	X	X												
	Respiratory toxicity	X	X												
	Skin toxicity	X	X												
	Corrosive to eye or skin/ Irritant	X	X												
Diethylether	Flammable aerosol, liquid or solid	X	X			X	X								
	Oral toxicity	X	X			X	X								
	STOT-SE	X	X			X	X								
Hydrogen peroxide	Corrosive to eye or skin/ Irritant		X												
	Oral toxicity		X												
	Respiratory toxicity		X												
	STOT SE		X												
	Hazardous to aquatic life		X												
Isobutyril chloride	Flammable aerosol, liquid or solid			X											
	Corrosive to eye or skin/ Irritant			X											
	Hazardous to aquatic life			X											
Sulfuric acid	Corrosive to eye or skin/ Irritant				X			X							
Pentane	Respiratory irritation					X	X								
	Oral irritation					X	X								
	STOT SE					X	X								
	Flammable aerosol, liquid or solid					X	X								
	Hazardous to aquatic life					X	X								
Isobutyril peroxide	Self reactive or peroxide										X	X	X	X	X
	Corrosive to eye or skin/ Irritant										X	X	X	X	X
	Skin toxicity										X	X	X	X	X
	Respiratory irritation										X	X	X	X	X
	Oral irritation										X	X	X	X	X
Sodium carbonate	Corrosive to eye or skin/ Irritant								X						
Equipment under pressure	-											X	X		

Nr	Hazard	FP	HSFWP	SFWP	FDA	Severity (Crude)	HSFWS	SFWS	Reliability	Selectivity	RiCS
1	Flammable aerosol, liquid or solid	3.2	3	1	2	2	2	1	3	2	4.19
2	Oral toxicity	3.2	5	1	2	2	4	1	3	2	4.51
3	Respiratory toxicity	4.0	3	1	2	1	4	1	3	2	4.04
4	Skin toxicity	3.2	4	1	2	1	4	1	3	2	3.85
5	Corrosive to eye or skin/ Irritant	3.2	4	1	2	3	3	1	3	2	4.99
6	Flammable aerosol, liquid or solid	3.2	3	1	2	3	2	1	3	2	4.83
7	Oral toxicity	3.2	5	1	2	3	4	1	3	2	4.99
8	STOT-SE	3.2	5	1	2	3	4	1	3	2	4.99
9	Corrosive to eye or skin/ Irritant	3.2	4	1	2	3	3	1	3	2	4.99
10	Oral toxicity	3.2	5	1	2	2	4	1	3	2	4.51
11	Respiratory toxicity	3.2	5	1	2	2	4	1	3	2	4.51
12	STOT SE	3.2	5	1	2	2	4	1	3	2	4.51
13	Hazardous to aquatic life	1.2	4	1	1	2	§	1	3	2	3.9
14	Flammable aerosol, liquid or solid	3.0	3	1	3	2	2	1	3	2	4.62
15	Oral toxicity	3.5	5	1	3	2	4	1	3	2	4.93
16	Respiratory toxicity	3.6	3	1	3	1	4	1	3	2	4.35
17	Skin toxicity	3.2	4	1	3	1	4	1	3	2	4.27
18	Corrosive to eye or skin/ Irritant	4.1	4	1	3	3	3	1	3	2	5.42
19	Flammable aerosol, liquid or solid	4.1	3	1	3	3	2	1	3	2	5.25
20	Oral toxicity	3.1	5	1	3	3	4	1	3	2	4.65
21	STOT-SE	3.1	5	1	3	3	4	1	3	2	4.65
22	Flammable aerosol, liquid or solid	3.0	3	1	3	2	2	1	3	2	4.62
23	Corrosive to eye or skin/ Irritant	3.6	4	1	3	3	3	1	3	2	5.26
24	Hazardous to aquatic life	1.2	3	1	3	2	3	1	3	2	3.85
25	Corrosive to eye or skin/ Irritant	3.2	3	1	1	1	1	1	3	3	4.11
26	Respiratory irritation	4.1	5	1	3	2	4	1	3	2	5.1
27	Oral irritation	4.1	3	1	3	2	4	1	3	2	4.78
28	STOT SE	4.0	5	1	3	3	4	1	3	2	5.1
29	Flammable aerosol, liquid or solid	4.1	4	1	3	3	3	1	3	2	5.26
30	Hazardous to aquatic life	1.2	3	1	3	2	3	1	3	2	3.85
31	Flammable aerosol, liquid or solid	4.2	3	1	3	3	2	1	3	2	5.1
32	Oral toxicity	4.4	5	1	3	3	4	1	3	2	5.57
33	STOT-SE	4.4	5	1	3	3	4	1	3	2	5.57
34	Self reactive or peroxide	4.7	5	1	3	3	4	1	3	3	6.09
35	Corrosive to eye or skin/ Irritant	3.8	4	1	3	2	5	1	3	3	5.14
36	Skin toxicity	4.1	5	1	3	1	5	1	3	3	4.61
37	Respiratory irritation	4.4	5	1	3	2	5	1	3	3	5.22
38	Oral irritation	4.4	5	1	3	2	5	1	3	3	5.22
39	Corrosive to eye or skin/ Irritant	3.2	3	1	1	2	1	1	3	3	4.11
40	Corrosive to eye or skin/ Irritant	2.8	3	1	1	1	1	1	3	3	3.61
41	Self reactive or peroxide	4.7	5	1	3	3	4	1	3	3	6.09
42	Corrosive to eye or skin/ Irritant	3.8	4	1	3	2	5	1	3	3	5.14
43	Skin toxicity	4.1	5	1	3	1	5	1	3	3	4.61
44	Respiratory irritation	4.4	5	1	3	2	5	1	3	3	5.22
45	Oral irritation	4.4	5	1	3	2	5	1	3	3	5.22
46	Self reactive or peroxide	4.7	5	1	3	3	4	1	3	3	6.09
47	Corrosive to eye or skin/ Irritant	3.8	4	1	3	2	5	1	3	3	5.14
48	Skin toxicity	4.1	5	1	3	1	5	1	3	3	4.61
49	Respiratory irritation	4.4	5	1	3	2	5	1	3	3	5.22

50	Oral irritation	4.4	5	1	3	2	5	1	3	3	5.22
51	Equipment under pressure	1.2	1	1	4	2	1	1	1	1	3.35
52	Self reactive or peroxide	4.7	5	1	3	3	4	1	3	3	6.09
53	Corrosive to eye or skin/ Irritant	3.8	4	1	3	2	5	1	3	3	5.14
54	Skin toxicity	4.1	5	1	3	1	5	1	3	3	4.61
55	Respiratory irritation	4.4	5	1	3	2	5	1	3	3	5.22
56	Oral irritation	4.4	5	1	3	2	5	1	3	3	5.22
57	Equipment under pressure	1.2	1	1	4	2	1	1	1	1	3.35
58	Self reactive or peroxide	4.7	5	1	3	3	4	1	3	3	6.09
59	Corrosive to eye or skin/ Irritant	3.8	4	1	3	2	5	1	3	3	5.14
60	Skin toxicity	4.1	5	1	3	1	5	1	3	3	4.61
61	Respiratory irritation	4.4	5	1	3	2	5	1	3	3	5.22
62	Oral irritation	4.4	5	1	3	2	5	1	3	3	5.22
63	Self reactive or peroxide	4.7	5	1	3	3	4	1	3	3	6.09
64	Corrosive to eye or skin/ Irritant	3.8	4	1	3	2	5	1	3	3	5.14
65	Skin toxicity	4.1	5	1	3	1	5	1	3	3	4.61
66	Respiratory irritation	4.4	5	1	3	2	5	1	3	3	5.22
67	Oral irritation	4.4	5	1	3	2	5	1	3	3	5.22

	Refering Nr	Corrective Measure	RiCS before	RiCS after	$\Delta RiCS$	Installation Cost	Running cost	A	S	CP	CE
Pyridine	5	Use a face shield	4.99	3.74	1.14	1000	100	4	4	5	4
Hydrogen peroxide	9		4.99	3.74	1.14	1000	100	4	4	5	4
Pyridine	18		5.42	3.74	1.68	1000	100	5	4	5	4
Isobutyril chlor	23		5.26	3.74	1.52	1000	100	5	4	5	4
Isobutyril peroxide	35		5.14	4.16	0.98	1000	100	5	4	5	4
Sulfuric acid	39		4.11	3.29	0.82	1000	100	3	4	4	4
Sodium carbonate	40		3.61	3.25	0.36	1000	100	3	4	4	4
Diethylether	20		5.57	5.15	0.32	1000	100	4	4	4	4
Diethylether	21		5.57	5.15	0.32	1000	100	4	4	4	4
Pyridine	5	Use safety glasses with side protection	5.99	3.98	1.01	2000	200	5	5	5	5
Hydrogen peroxide	9		5.99	3.98	1.01	2000	200	5	5	5	5
Pyridine	18		6.42	3.98	1.44	2000	200	5	5	5	5
Isobutyril chlor	23		6.26	4.30	0.96	2000	200	5	5	5	5
Isobutyril peroxide	35		6.14	4.44	0.7	2000	200	5	5	5	5
Sulfuric acid	39		5.11	3.29	0.82	2000	200	5	5	5	5
Sodium carbonate	40		4.61	3.25	0.36	2000	200	5	5	5	5
Pentane	26	Respirator	5.1	3.81	1.29	500	50	3	4	5	5
Isobutyril peroxide	37		5.22	3.68	1.54	500	50	3	4	5	5
Isobutyril peroxide	36	Bigger flask	6.09	5.45	0.64	900	100	5	5	5	5
Isobutyril peroxide	36	Do not keep outside fridge longer than 10 min	6.09	5.04	1.05	50	300	3	4	5	5
Isobutyril peroxide	36	Use Kevlar gloves and face shield during manipulation	6.09	4.87	1.22	2000	200	5	4	5	5
Isobutyril peroxide	36	Smaller quantities	6.09	5.21	0.88	100	4000	5	5	5	5
Diethylether	19		5.25	4.43	0.82	100	4000	5	5	5	5
Pyridine	5	Install a cooler outside of the lab	4.99	4.51	0.48	5000	1000	5	5	5	5
Hydrogen peroxide	9		4.99	4.51	0.48	5000	1000	5	5	5	5
Pyridine	18		5.42	4.87	0.55	5000	1000	5	5	5	5
Isobutyril chlor	23		5.26	4.74	0.52	5000	1000	5	5	5	5
Isobutyril peroxide	35		5.14	4.64	0.5	5000	1000	5	5	5	5
Sulfuric acid	39		4.11	3.74	0.38	5000	1000	5	5	5	5
Sodium carbonate	40		3.61	3.37	0.24	5000	200	5	5	5	5
Diethylether	20		5.57	4.01	0.56	5000	1000	5	5	5	5
Diethylether	21		5.57	4.01	0.56	5000	1000	5	5	5	5
Pyridine	5	Separate lab from the office space with a protective shield	4.99	4.41	0.58	5000	1000	5	5	5	5
Hydrogen peroxide	9		4.99	4.41	0.58	5000	1000	5	5	5	5
Pyridine	18		5.42	4.69	0.73	3000	500	5	4	5	4
Isobutyril chlor	23		5.26	4.6	0.66	3000	500	5	4	5	4
Isobutyril peroxide	35		5.14	4.52	0.62	3000	500	5	4	5	4
Sulfuric acid	39		4.11	3.61	0.50	3000	500	5	4	5	4
Sodium carbonate	40		3.61	3.19	0.42	3000	500	5	4	5	4
Diethylether	20		5.57	4.79	0.78	3000	500	5	4	5	4
Diethylether	21		5.57	4.79	0.78	3000	500	5	4	5	4
Pentane	26		5.1	4.5	0.60	300	500	5	4	5	4
Isobutyril peroxide	37		5.22	4.57	0.65	300	500	5	4	5	4
Isobutyril peroxide	36		6.09	5.25	0.84	300	500	5	4	5	4

Attachment C2

N^{O}	Question	Answer	Score
1	How important do you think safety is in your lab? (P_1)	Equally important to laboratory main activities	2
2	How often do you work alone? (P_2)	Couple of times per year	3
3	How much time per week do you spend working in the lab performing experiments? (P_3)	Around 30, but more than 20 h per week	2
4	Your laboratory is a safe environment (P_4)	Neither agree nor disagree	2
5	What do you think about your level of safety training? (P_5)	I was trained specifically for Hazards I am working with	3
6	What is your primary affiliation? For how long are you at this university? (P_6)	EPFL, More than 1 year	3
7	How well does your previous experience help you to be integrated in your current lab? (P_7)	Average	2
8	What is your current occupation? (P_8)	PhD student	2
9	What is your total lab working experience? (P_9)	Less than 3 years	1
10	The research and safety equipment (fume hoods, biosafety cabinets, etc.) in your lab are safe and in good working order? (P_{10})	Neither agree nor disagree	3
11	In your lab, there is a sufficient supply of the appropriate PPE? (P_{11})	Agree	3
12	Does your supervisor encourage others to work safely, demonstrating with his/her own example? (P_{12})	He encourages us and tries to demonstrate with his own example	3
13	Have you ever seen a colleague break a lab safety rule? (P_{13})	Yes, sometimes corrected/commented	2
14	Are you aware about accident reporting system in your lab? (P_{14})	Yes, but it is not clear how to use it	2
15	What do you think about information about safety rules and procedures in your laboratory? (P_{15})	Specific safety information and hazards is easily available	3
16	What do you think about safety rules and regulations you need to follow? (P_{16})	It is important to follow majority of safety rules and procedures	3

N^{O}		Answer	Score
1	Level of light	Good	1
2	Level of noise	Good	1
3	Temperature condition	Medium	2
4	Working space condition	Good	1

Source	Hazards	1	2	3	4	5	6	7	8	9
ODE	Respiratory irritation	X	X	X	X	X				
	Oral irritation	X	X	X	X	X				
$PbBr_2$	Respiratory irritation	X	X	X	X	X				
	Oral irritation	X	X	X	X	X				
	CMR (reproductive)	X	X	X	X	X				
	STOT RE	X	X	X	X	X				
	Hazardous to aquatic life	X	X	X	X	X				
	CMR (cancirogenic)	X	X	X	X	X				
Heater	Hot substace/surface		X					X		
Equipment under pressure	Equipment under pressure			X						
Nitrogen	Compressed gas				X			X		
Dried oleylamine	Corrosive to eye or skin/ Irritant					X				
	Respiratory irritation									
	STOT RE									
Cs-OA	Corrosive to eye or skin/ Irritant								X	
	CMR (reproductive)								X	
	STOT RE								X	
	Oral toxicity								X	
$CsPbBr_3$	CMR (reproductive)									X
	STOT RE									X
	Oral toxicity									X
	Hazardous to aquatic life									X

Nr	Hazard	FP	HSFWP	SFWP	FDA	Severity (Crude)	HSFWS	SFWS	Reliability	Selectivity	RiCS
1	Respiratory irritation	3.3	3	1	3	2	3	1	3	3	4.79
2	Oral irritation	2.7	3	1	3	2	3	1	3	3	4.58
3	Respiratory irritation	3.3	4	1	3	1	3	1	3	3	4.31
4	Oral irritation	2.7	4	1	3	1	3	1	3	3	4.02
5	CMR (Reproductive toxicity)	3.5	4	1	3	4	2	1	3	3	6.11
6	STOT RE	3.5	4	1	3	3	2	1	3	3	5.48
7	Hazardous to aquatic life	1.9	4	1	3	3	2	1	3	3	4.78
8	CMR (Cancerogenic)	3.5	5	1	3	4	2	1	3	3	6.2
9	Hot substance or surface	1.7	1	1	3	1	3	1	1	1	3.23
10	Equipment under pressure	1.2	1	1	3	2	1	1	3	3	3.35
11	Compressed gas	1.2	2	1	4	3	1	1	3	3	4.87
12	Corrosive to eye or skin/ Irritant	2.4	5	1	3	2	3	1	3	3	4.68
13	Respiratory irritation	3.5	5	1	3	2	3	1	3	3	5
14	STOT RE	3.5	5	1	3	2	2	1	3	3	4.93
15	Hot substance or surface	1.7	1	1	3	1	3	1	1	1	3.23
16	Corrosive to eye or skin/ Irritant	3.8	5	1	3	3	3	1	3	3	4.18
17	CMR (Reproductive toxicity)	3.8	5	1	3	3	2	1	3	3	4.13
18	STOT RE	3.5	5	1	3	3	2	1	3	3	4.06
19	Oral toxicity	2.9	4	1	3	2	3	1	3	3	4.46
20	CMR (Reproductive toxicity)	3.8	4	1	3	4	2	1	3	2	5.62
21	STOT RE	3.5	4	1	3	2	2	1	3	2	4.61
22	Oral toxicity	2.9	4	1	3	2	3	1	3	2	4.38
23	Hazardous to aquatic life	1.9	4	1	3	3	3	1	3	2	4.78

	Refering Nr	Corrective Measure	RiCS before	RiCS after	$\Delta RiCS$	Implementation cost	Running cost	A	S	CP	CE
$PbBr_2$	5	Wear respiratory protective device	6.11	3.90	2.21	500	50	4	4	5	5
$PbBr_2$	6		5.48	3.82	1.66	500	50	4	4	5	5
$PbBr_2$	8		5.2	3.94	2.26	500	50	4	4	5	5
$CsPbBr_3$	20		5.62	3.88	1.72	500	50	2	4	5	5
$CsPbBr_3$	20	Store in a cool, dry place	5.62	5.12	0.50	50	50	4	5	5	5
$PbBr_2$	5	Perform periodical medical test for lead in the blood	6.11	4.56	1.55	150	3500	4	5	5	5
$PbBr_2$	6		5.48	4.27	1.21	150	3500	4	5	5	5
$PbBr_2$	8		6.2	3.98	1.62	150	3500	4	5	5	5
$CsPbBr_3$	20		5.62	4.35	1.27	150	3500	4	5	5	5
$PbBr_2$	5	Install a warning sign where lead is manipulated and stored	6.11	5.3	0.81	40	200	5	5	5	5
$PbBr_2$	6		5.48	4.84	0.64	40	200	5	5	5	5
$PbBr_2$	8		6.2	5.35	0.85	40	200	5	5	5	5
$CsPbBr_3$	20		5.62	4.9	0.72	40	200	5	5	5	5
$PbBr_2$	5	Prepare a solution inside of a glovebox	6.11	4.5	1.61	50	1500	4	4	5	5
$PbBr_2$	6		5.48	3.96	1.52	50	1500	4	4	5	5
$PbBr_2$	8		6.2	4.57	1.63	50	1500	4	4	5	5
$PbBr_2$	5	Wear two pairs of nitrile gloves, change the outer layer frequently	6.11	5.43	0.68	500	50	5	4	5	5
$PbBr_2$	6		5.48	4.98	0.5	500	50	5	4	5	5
$PbBr_2$	8		6.2	5.48	0.52	500	50	5	4	5	5
$CsPbBr_3$	20		5.62	5.04	0.64	500	50	5	4	5	5
$PbBr_2$	5	PPE should not leave the room of the lab	6.11	5.46	0.65	50	250	3	5	5	5
$PbBr_2$	6		5.48	5.04	0.44	50	250	3	5	5	5
$PbBr_2$	8		6.2	5.52	0.68	50	250	3	5	5	5
$CsPbBr_3$	20		5.62	5.1	0.52	50	250	3	5	5	5

Attachment C3

N^{O}	Question	Answer	Score
1	How important do you think safety is in your lab? (P_1)	More important than laboratory main activities	3
2	How often do you work alone? (P_2)	Once per couple of months	3
3	How much time per week do you spend working in the lab performing experiments? (P_3)	Around 20 h per week	3
4	Your laboratory is a safe environment (P_4)	Neither agree nor disagree	2
5	What do you think about your level of safety training? (P_5)	I had a training, but sometimes I don't remember how to work with certain hazards	1
6	What is your primary affiliation? For how long are you at this university? (P_6)	EPFL, More than 1 year	3
7	How well does your previous experience help you to be integrated in your current lab? (P_7)	Really well	3
8	What is your current occupation? (P_8)	PhD student	2
9	What is your total lab working experience? (P_9)	More than 3 years	3
10	The research and safety equipment (fume hoods, biosafety cabinets, etc.) in your lab are safe and in good working order? (P_{10})	Neither agree nor disagree	2
11	In your lab, there is a sufficient supply of the appropriate PPE? (P_{11})	Neither agree nor disagree	2
12	Does your supervisor encourage others to work safely, demonstrating with his/her own example? (P_{12})	He/she is always supportive and encourages safety initiative	3
13	Have you ever seen a colleague break a lab safety rule? (P_{13})	Yes, sometimes corrected/commented	2
14	Are you aware about accident reporting system in your lab? (P_{14})	Yes, but don't know how to use it	1
15	What do you think about information about safety rules and procedures in your laboratory? (P_{15})	There is only general information available	2
16	What do you think about safety rules and regulations you need to follow? (P_{16})	It is important to follow majority of safety rules and procedures	3

N^{O}		Answer	Score
1	Level of light	Good	1
2	Level of noise	Medium	2
3	Temperature condition	Medium	2
4	Working space condition	Good	1

Source	Hazards	1	2	3	4	5	6	7	8	9	10
Equipment under pressure	Equipment under pressure	X	X			X		X	X		
Nitrogen	Compressed gas		X					X	X		
Sodium hydroxide	Corrosive to eye or skin/ Irritant			X						X	
	Respiratory irritation			X						X	
	Oral irritation			X						X	
Sodium disulfite	Oral toxicity			X					X		
	Skin toxicity			X					X		
	Corrosive to eye or skin/ Irritant			X					X		
2-MeTHF	Flammable aerosol, liquid or solid				X	X		X	X		
	Oral toxicity				X	X		X	X		
	Corrosive to eye or skin/ Irritant				X	X		X	X		
Hydrochloric Acid	Oral toxicity				X						
	Corrosive to eye or skin/ Irritant				X						
	STOT SE				X						
	Hazardous to aquatic life				X						
Paraformaldehyde	flammable aerosol, liquid or solid				X						
	Oral toxicity				X						
	Respiratory toxicity				X						
	Corrosive to eye or skin/ Irritant				X						
	CMR (Mutagenic)				X						
	CMR (Carcinogenic)				X						
Corn cob	Corrosive to eye or skin/ Irritant				X						
	Respiratory irritation				X						
	Flammable aerosol, liquid or solid				X						
Cellulose	Corrosive to eye or skin/ Irritant						X				
Lignin	Corrosive to eye or skin/ Irritant						X	X	X		
Toluene	Flammable aerosol, liquid or solid							X			
	Corrosive to eye or skin/ Irritant							X			
	CMR (Reproductive toxicity)							X			
	STOT SE							X			
	Respiratory irritation							X			
	Oral irritation							X			
	Hazardous to aquatic life							X			
Formaldehyde	Flammable aerosol, liquid or solid							X	X	X	
	Oral toxicity							X	X	X	
	Respiratory toxicity							X	X	X	
	Skin toxicity							X	X	X	
	Corrosive to eye or skin/ Irritant							X	X	X	
	CMR (Carcinogenici)							X	X	X	
	CMR (Mutagenic)							X	X	X	
	STOT SE							X	X	X	
NMR	Static magnetic field										X

Nr	Hazard	FP	HSFWP	SFWP	FDA	Severity (Crude)	HSFWS	SFWS	Reliability	Selectivity	RiCS
1	Equipment under pressure	2.6	1	1	4	2	1	1	1	1	3.26
2	Equipment under pressure	2.6	1	1	4	2	1	1	1	1	3.26
3	Compressed gases	1.4	1	1	4	2	1	1	1	1	2.95
4	Corrosive to eye or skin/ Irritant	3.8	3	1	2	3	3	1	3	3	5.22
5	Respiratory irritation	3.8	3	1	2	2	3	1	3	3	4.58
6	Oral irritation	2.9	3	1	2	2	3	1	3	3	4.36
7	Oral toxicity	2.9	3	1	2	2	3	1	3	3	4.36
8	Skin toxicity	3.8	3	1	2	1	3	1	3	3	4.02
9	Corrosive to eye or skin/ Irritant	3.8	3	1	2	2	3	1	3	3	4.58
10	Flammable aerosol, liquid or solid	3.5	3	1	2	3	2	1	3	3	4.88
11	Oral toxicity	2.5	4	1	2	2	3	1	3	3	4.29
12	Corrosive to eye or skin/ Irritant	4.8	4	1	2	3	3	1	3	3	5.3
13	Oral toxicity	3.5	4	1	2	2	3	1	3	3	4.6
14	Corrosive to eye or skin/ Irritant	4.1	4	1	2	3	3	1	3	3	4.9
15	STOT SE	4.1	4	1	2	2	3	1	3	3	4.97
16	Hazardous to aquatic life	2.8	4	1	2	1	3	1	3	3	3.78
17	Flammable aerosol, liquid or solid	3.5	3	1	2	3	2	1	3	3	4.88
18	Oral toxicity	2.8	3	1	2	2	2	1	3	3	4.18
19	Respiratory toxicity	4	3	1	2	2	2	1	3	3	4.71
20	Corrosive to eye or skin/ Irritant	4	4	1	2	3	2	1	3	3	5.07
21	CMR (Mutagenic)	3.7	4	1	2	3	2	1	3	3	5.07
22	CMR (Carcinogenic)	4.5	4	1	2	4	2	1	3	3	6.07
23	Corrosive to eye or skin/ Irritant	1.5	2	1	2	1	1	1	3	3	3.18
24	Respiratory irritation	1.5	2	1	2	1	1	1	3	3	3.18
25	Flammable aerosol, liquid or solid	1.5	2	1	2	1	1	1	3	3	3.18
26	Equipment under pressure	2.6	1	1	4	2	1	1	1	1	3.26
27	Flammable aerosol, liquid or solid	3.5	3	1	2	3	2	1	3	3	4.88
28	Oral toxicity	2.5	4	1	2	2	3	1	3	3	4.29
29	Corrosive to eye or skin/ Irritant	4.8	4	1	2	3	3	1	3	3	5.3
30	Corrosive to eye or skin/ Irritant	2.5	2	1	1	1	1	1	3	3	3.18
31	Equipment under pressure	2.6	1	1	4	2	1	1	1	1	3.26
32	Flammable aerosol, liquid or solid	3.5	3	1	2	3	2	1	3	3	4.88
33	Oral toxicity	2.5	4	1	2	2	3	1	3	3	4.29
34	Corrosive to eye or skin/ Irritant	3.8	4	1	2	3	3	1	3	3	5.02
35	Flammable aerosol, liquid or solid	3.5	3	1	2	3	2	1	3	3	4.88
36	Corrosive to eye or skin/ Irritant	4.8	3	1	3	2	3	1	3	2	4.9
37	CMR (Reproductive toxicity)	4.8	3	1	3	4	3	1	3	2	6.19
38	STOT SE	4.8	3	1	3	2	3	1	3	2	4.9
39	Respiratory irritation	4.8	3	1	3	4	3	1	3	2	6.19
40	Oral irritation	2.6	3	1	3	4	3	1	3	2	5.5
41	Hazardous to aquatic life	2.6	3	1	3	2	3	1	3	2	4.22
42	Corrosive to eye or skin/ Irritant	2.5	2	1	1	1	1	1	3	3	3.18

43	Flammable aerosol, liquid or solid	3.7	3	1	2	3	2	1	3	3	4.96
44	Oral toxicity	2.5	3	1	3	3	2	1	3	2	4.78
45	Respiratory toxicity	4.5	3	1	3	4	2	1	3	2	6.05
46	Skin toxicity	3	4	1	3	3	2	1	3	2	4.7
47	Corrosive to eye or skin/ Irritant	3	4	1	3	3	2	1	3	2	4.7
48	CMR (Carcinogenic)	4.5	4	1	3	4	2	1	3	2	5.97
49	CMR (Mutagenic)	3.7	4	1	3	3	2	1	3	2	4.95
50	STOT SE	3.7	4	1	3	3	2	1	3	2	4.95
51	Compressed gases	1.4	1	1	4	2	1	1	1	1	2.95
52	Equipment under pressure	2.6	1	1	4	2	1	1	1	1	3.26
53	Corrosive to eye or skin/ Irritant	3	3	1	2	3	3	1	3	3	5.05
54	Respiratory irritation	3.5	3	1	2	2	3	1	3	3	4.95
55	Oral irritation	2.9	3	1	2	2	3	1	3	3	4.7
56	Corrosive to eye or skin/ Irritant	3.5	2	1	3	1	2	1	3	3	5
57	Flammable aerosol, liquid or solid	3.7	3	1	2	3	2	1	3	3	4.96
58	Oral toxicity	2.5	3	1	3	3	2	1	3	2	4.78
59	Respiratory toxicity	4.5	3	1	3	4	2	1	3	2	6.05
60	Skin toxicity	3	4	1	3	3	2	1	3	2	4.7
61	Corrosive to eye or skin/ Irritant	3	4	1	3	3	2	1	3	2	4.7
62	CMR (Carcinogenic)	4	4	1	3	4	2	1	3	2	4.9
63	CMR (Mutagenic)	4	4	1	3	3	2	1	3	2	4.7
64	STOT SE	3	4	1	3	3	2	1	3	2	4.7
65	Equipment under pressure	2.6	1	1	4	2	1	1	1	1	3.26
66	Flammable aerosol, liquid or solid	3	3	1	2	3	2	1	3	3	4.68
67	Oral toxicity	2.5	4	1	3	2	3	1	3	3	4.6
68	Corrosive to eye or skin/ Irritant	3	4	1	3	3	3	1	3	3	4.9
69	Compressed gases	1.4	1	1	4	2	1	1	1	1	2.95
70	Corrosive to eye or skin/ Irritant	1.4	2	1	3	1	1	1	3	3	3.48
71	Respiratory irritation	1.4	2	1	3	1	1	1	3	3	3.48
72	Oral irritation	1.4	2	1	3	1	1	1	3	3	3.48
73	Flammable aerosol, liquid or solid	1.2	2	1	3	1	2	1	3	2	3.17
74	Oral toxicity	1.2	2	1	3	1	2	1	3	2	3.17
75	Respiratory toxicity	1.2	2	1	3	1	2	1	3	2	3.17
76	Skin toxicity	2	2	1	3	1	2	1	3	2	3.42
77	Corrosive to eye or skin/ Irritant	2.5	2	1	3	1	2	1	3	2	3.53
78	CMR (Carcinogenic)	4	2	1	3	1	2	1	3	2	4
79	CMR (Mutagenic)	4	2	1	3	1	2	1	3	2	4
80	STOT SE	2.5	2	1	3	1	2	1	3	2	3.53
81	Oral toxicity	1.2	3	1	2	1	3	1	3	3	3.29
82	Skin toxicity	2	3	1	2	1	3	1	3	3	3.49
83	STOT SE	2	3	1	2	1	3	1	3	3	3.49
84	Static magnetic fields	3	2	1	2	3	1	1	3	3	4.76

	Refering Nr	Corrective Measure	RiCS before	RiCS after	$\Delta RiCS$	Installation cost	Running cost	A	S	CP	CE
Paraformaldehyde	22	Use help of a second person	6.07	3.68	2.39	1000	7000	5	5	5	5
2-MeTHF	29		5.3	3.35	1.95	1000	7000	5	5	5	5
Toluene	37,39		6.19	3.73	2.46	1000	7000	5	5	5	5
Toluene	40		5.15	3.22	1.93	1000	7000	5	5	5	5
Formaldehyde	48		5.97	3.62	1.53	1000	7000	5	5	5	5
Formaldehyde	45		6.05	3.67	2.36	1000	7000	5	5	5	5
Toluene	37,39	Use gas mask/respirator	6.19	4.08	2.11	1000	100	5	3	5	5
Formaldehyde	49		6.05	4.01	2.04	1000	100	5	3	5	5
Paraformaldehyde	22	Wear full body suit	6.07	3.35	2.72	2000	200	4	3	5	5
2-MeTHF	29		5.3	3.12	2.18	2000	200	4	3	5	5
Formaldehyde	48		5.97	3.27	2.7	2000	200	4	3	5	5
Toluene	37,39	Install automatization for loading	6.19	3.2	2.99	10’000	5000	5	5	4	3
Formaldehyde	45		6.05	3.12	2.93	10’000	5000	5	5	4	3
Paraformaldehyde	22		6.07	3.13	2.94	10’000	5000	5	5	4	3
2-MeTHF	29		5.3	3.05	2.25	10’000	5000	5	5	4	3
Formaldehyde	48		5.97	3.33	2.64	10’000	5000	5	5	4	3
Toluene	40		5.15	3.0	2.15	10’000	5000	5	5	4	3

Attachment D1. LARA+D Database. Extracts.

Hazard Category	Hazard Group	Hazard
Biological Hazards refer to biological substances that pose a threat to the health of humans.	Biological organisms	Group 1 organisms
	Biological organisms	Group 2 organisms
	Biological organisms	Group 3 organisms
Mechanical Hazards refer to moving machine parts and objects, dangerous surfaces and work in height	Sharp objects	Blades
	Sharp objects	Needles
	Moving Objects	Moving objects
	Surfaces	Uneven surfaces
	Surfaces	Holes
	Surfaces	Slippery surfaces
	Surfaces	Sharp edges
	Work at height	Work at height
Physical Hazards refer to noise, pressure and electricity, Electromagnetic fields and radiations refer to static magnetic fields, ionizing and nonionizing radiations	Sounds and vibrations	Vibrations transmitted to all body
	Sounds and vibrations	Vibrations transmitted to arm-hand
	Sounds and vibrations	Audible noise
	Sounds and vibrations	Ultrasound >20kHz
	Sounds and vibrations	Infrasound <20Hz
	Electricity	Low voltage (AC 0-50V, DC 0-120V, I>2A)
	Electricity	High voltage (AC > 50V, DC > 120V)
	Thermic Hazards	Cold substance or surface
	Thermic Hazards	Work environment at T>33 C
	Thermic Hazards	Work environment at T<15 C
	Thermic Hazards	Hot substance or surface
	Pressure Hazards	Compressed Gas (not toxic or flammable)
	Pressure Hazards	Toxic Compressed Gas
	Pressure Hazards	Flammable Compressed Gas
	Pressure Hazards	Equipment under pressure
	Pressure Hazards	Hypobaric environment
	Pressure Hazards	Hyperbaric environment
	Laser	Laser class 1M or 2M
	Laser	Laser class 2
	Laser	Laser class 3R visible beam
	Laser	Laser class 3R invisible beam
	Laser	Laser class 3B
	Laser	Laser class 4
	Electromagnetic fields	Time-varying electromagnetic field
	Electromagnetic fields	Static magnetic fields
	UV / IR incoherent radiation	Incoherent UV
	UV / IR incoherent radiation	Incoherent IR
	Ionizing Radiation	Open radioactive sources
	Ionizing Radiation	Closed radioactive sources
	Ionizing Radiation	Ionizing radiation generators

Continued from previous page		
Category of acute or chronic hazards to the musculoskeletal system	Hazards for the musculoskeletal system	Imposed posture
	Hazards for the musculoskeletal system	Lifting and handling heavy weight
	Hazards for the musculoskeletal system	Repetitive movement
Chemical Hazards refer to substances that can cause harm to people or environment.	Nanomaterials	Nanomaterial hazard
	Oxidizer	Oxidizing liquid or solid
	CMR / STOT	CMR or STOT RE
	CMR / STOT	STOT SE
	Corrosives	Corrosive to metals
	Corrosives	Corrosive to eye or skin/ Irritant
	Corrosives	Oral irritation
	Corrosives	Respiratory irritation
	Explosives	Explosive
	Flammables	Flammable aerosol, liquid or solid
	Flammables	Flammable gas
	Self-reactive and Organic Peroxides	Pyrophoric
	Self-reactive and Organic Peroxides	Self-heating
	Self-reactive and Organic Peroxides	Water reactive
	Self-reactive and Organic Peroxides	Self-reactive or peroxide
	Acute Toxics	Oral toxicity
	Acute Toxics	Respiratory toxicity
	Acute Toxics	Skin toxicity
	Hazardous to the Environment	Hazardous to aquatic life
	Hazardous to the Environment	Hazardous to ozone

Hazard specific worsening factors
Aerosol production
Breastfeeding
Built-in pressure due to natural decomposition
Change of the plane of the laser beam
Chemical stored in food container
Chemical undergoes shock or friction
Colorless chemical
Crack/holes on the laboratory surfaces
Cross contamination
Damaged or wrong label (inadequate or missing information)
Direct contact with the source of ultrasound
Drug induced photosensitivity
Eating or drinking in the laboratory
Experimental setup with beams oriented vertically
Exposed skin
Exposure to the sunlight
Ferromagnetic objects present near strong static fields
Free access to the laser beam
Frequent laser alignment necessary
Frequently accessed area
Heat accumulation /release during activity/reaction
Heat-sensitive chemicals
High pathogenicity GM organisms
Home-made equipment
Home-made setup
Inadequate cleaning procedure/organization
Inadequate conditioning of chemical waste
Inadequate containment
Inadequate or damaged container
Inadequate PPE
Inadequate storage conditions
Inadequate waste disposal
Increased pathogenicity GM organisms
Indirect contact with the source of ultrasound via solid medium
Inhibitor completely consumed
Insufficient ventilation
Invisible laser beam
Laser beam at the eyes' height of a sitting or standing person
Leak of grease or other lubrificant from equipment
Long communicability of the pathogen (long infectious period)
Made of toxic chemical elements
Nano below 4 nm
Nano between 20 and 45 nm
Nano between 4 and 20 nm

Non-conductive apparatus

Continued from previous page

Odorless chemical
Office spaces shared with lab spaces
Open-circuit
Outdated equipment
Pathogen is resistant to inactivation
Pathogen survives outside the host
Persistent nanomaterials
Poor eyesight
Porous surfaces of floors/walls
Powder form (disperse easily)
Powder form only (cannot be used in suspension)
Presence of catalytic impurities (heavy metal, acid or base)
Presence of heat sources
Presence of ignition sources
Presence of large metallic structures
Presence of liquid on floor
Presence of reflective surfaces on the optical table
Presence of sound alarms
Quantities above 1 mg
Sequence with hazard potential (ex. oncogene, cytokine encoding sequence, integrase, defined si/mi/shRNA)
Significant quantities
Size below 50 nm
Slippery surface on stairs
Smoking
Spore formation
Spore formation of GM organisms
Strong absorption in mucous
Strong oxidant
Substance has another(s) intrinsic hazard(s)
Substance is completely dry
Tasteless chemical
Temperature above 66 degree Celsius
Temperature sensitivity impaired
The user was subject to back surgery
Toxin production possible
Transmission route
Uneven surface on stairs
Unknown/unreported material
User is smoking
Use of a non-adequate decontamination solution
Use of highly concentrated solution
Use of laser goggles with wrong optical density
Use of lasers of various wavelengths in parallel
Use of metallic retention tray

Use of optical instruments
Continued from previous page
Use of strong mineral acids
User pregnant
User subject to vertigo
User wears a passive implanted medical device
User wear metallic prosthesis
Vapours / Gas lighter than air
Violation of the SOP
Volatile substance/ chemical
Wet floor
Work done outside clean room environment
Work in darkness or semidarkness
Work in vacuum
Work on bench
Work requiring great physical strength
Work requiring torso twisting
Work with animals
Work with infected animals
Work with invasive species
Worker had cataract surgery
Working outside of containment with GM organisms
Wrong electrical connection
Wrong handling procedure

Synergetic worsening factors
Dye laser with flammable chemical
Dye laser with toxic chemical
Laser is functioning using high voltage
Lifting and handling heavy weight
Machining/cutting of a CMR substance
Machining/cutting of a toxic substance
Moving objects
Nearby presence of an incompatible substance
Presence of equipment under pressure
Presence of electrical hazard
Presence of flammable aerosol, liquid or solid
Presence of flammable gasses
Presence of flammable liquids
Presence of flammable solids
Presence of hazardous chemical
Presence of heat-sensitive chemicals
Presence of holes
Presence of hot substances
Presence of laser class 4
Presence of lasers
Presence of magnetic fields
Presence of moving objects
Presence of Oxygen
Presence of slippery surfaces
Presence of uneven surfaces
Presence of unshielded source of infrared light
Presence of unshielded source of UV light
Stored with flammable products
Use of needles / sharps
Work at height
Work environment at T<15 C

Attachment D2. Bayesian calculation of RiCS.

```
"""
import numpy as np
import scipy as sp
from sys import exit #used to exit the script
from scipy.stats import truncnorm #for the truncated gaussian distribution
import math #for the truncated gaussian distribution
 #truncated gaussian distribution
#https://stackoverflow.com/questions/36894191/how-to-get-a-normal-distribution-within-a-range-in-numpy
#redefine truncnorm
def get_truncated_normal(mean=0, sd=1, low=0, upp=10):
    return sp.stats.truncnorm((low - mean) / sd, (upp - mean) / sd, loc=mean, scale=sd)


##################################################
#Function to normalize a vector
##################################################
def normalizeV(vector):
    #initialisation of the variable containing the sum of the vector components
    sumComponents=0
    #size of the vector
    size=vector.size
    #loop to normalize the vector
    for i in range(size):
        sumComponents=sumComponents+vector[i]
    for i in range(size):
        vector[i]=vector[i]/sumComponents

    return vector

#####################################################
#Function  to calculate the CPT in case of 2 parents
#based on Fenton's method
#####################################################
def CPT2parents(niv,weights,sigma):

    #rename the levels
    nivP1=niv[0]
    nivP2=niv[1]

    #rename the weights
    wP1=weights[0]
    wP2=weights[1]

    #size of the CPT
    sizeCPT=nivP1*nivP2

    #create the CPT table (considering 5 possible states:very low, low, medium,high,very high)
    CPT2P=np.ndarray(shape=((sizeCPT),5))

    #table filled with zero
    for ii in range (sizeCPT):
        for jj in range(5): # 5 possible states
                CPT2P[ii,jj] = (0)

    ##########
    #loop on the levels
    for i1 in range(nivP1):
        for i2 in range(nivP2):
            i = i1*nivP2+i2 #table row
            moy1 = (i1+0.5)/nivP1 #center of the inetrval
            moy2 = (i2+0.5)/nivP2
            moy = (moy1*wP1+moy2*wP2) / (wP1+wP2)
            TN = get_truncated_normal(mean=moy, sd=sigma, low=0, upp=1) #truncated normal distribution
            aux = TN.cdf(1)-TN.cdf(0)
            for j in range(5): # 5 possible states
                CPT2P[i,j] = (TN.cdf((j+1)/5)-TN.cdf(j/5.))/aux #probability table
    return CPT2P


####################################################################
#function to calculate the weighted average of the 2 parents'vectors
```

```
######################################################################
def weights2P(vectorA,vectorB):

    #normalize the vectors
    vectorA=normalizeV(vectorA)
    print('vectorA',vectorA)
    vectorB=normalizeV(vectorB)
    print('vectorB',vectorB)
    ################################
    #performing the weighted average
    ##################################

    #size of the vectors
    sizeA=vectorA.size
    #print('sizeA',sizeA)
    sizeB=vectorB.size
    #print('sizeB',sizeB)
    #size of the resulting vector
    sizeVResult=sizeA*sizeB
    #print('sizeVResult', sizeVResult)

    #create the vector result
    VResult=np.ndarray(shape=(sizeVResult))
    for i in range(sizeA):
        for j in range(sizeB):

            VResult[(i*sizeB+j)]=vectorA[i]*vectorB[j]


    return VResult

######################################################
#Function  to calculate the CPT in case of 3 parents
#based on Fenton's method
######################################################
def CPT3parents(niv,weights,sigma):

    #rename the levels
    nivP1=niv[0]
    nivP2=niv[1]
    nivP3=niv[2]


    #rename the weights
    wP1=weights[0]
    wP2=weights[1]
    wP3=weights[2]

    #size of the CPT
    sizeCPT=nivP1*nivP2*nivP3

    #create the CPT table (considering 5 possible states:very low, low, medium,high,very high)
    CPT3P=np.ndarray(shape=((sizeCPT),5))

    #table filled with zero
    for ii in range (sizeCPT):
        for jj in range(5): # 5 possible states
                  CPT3P[ii,jj] = (0)

    ##########
    #loop on the levels
    for i1 in range(nivP1):
        for i2 in range(nivP2):
            for i3 in range(nivP3):
                i = (i1*nivP2+i2)*nivP3+i3
                moy1 = (i1+0.5)/nivP1
                moy2 = (i2+0.5)/nivP2
                moy3 = (i3+0.5)/nivP3
                moy = (moy1*wP1+moy2*wP2+moy3*wP3) / (wP1+wP2+wP3)
                TN = get_truncated_normal(mean=moy, sd=sigma, low=0, upp=1) #truncated normal distribution
                aux = TN.cdf(1)-TN.cdf(0)
                for j in range(5): # 5 possible states
                    CPT3P[i,j] = (TN.cdf((j+1)/5)-TN.cdf(j/5.))/aux #probability table
    return CPT3P

######################################################################
```

```
#function to calculate the weighted average of the 3 parents'vectors
#####################################################################
def weights3P(vectorA,vectorB,vectorC):
    print('vectorA',vectorA)
    print('vectorB',vectorB)
    print('vectorC',vectorC)
    #normalize the vectors
    vectorA=normalizeV(vectorA)
    vectorB=normalizeV(vectorB)
    vectorC=normalizeV(vectorC)
    ###############################
    #performing the weighted average
    #################################

    #size of the vectors
    sizeA=vectorA.size
    sizeB=vectorB.size
    sizeC=vectorC.size
    #size of the resulting vector
    sizeVResult=sizeA*sizeB*sizeC
    print('sizeVresult',sizeVResult)
    #create the vector result
    VResult=np.ndarray(shape=(sizeVResult))
    for i in range(sizeA):
        for j in range(sizeB):
            for k in range(sizeC):

                VResult[(i*sizeB+j)*sizeC+k]= vectorA[i]*vectorB[j]*vectorC[k]
    print('VResult',VResult)
    return VResult

#####################################################
#Function  to calculate the CPT in case of 4 parents
#based on Fenton's method
#####################################################
def CPT4parents(niv,weights,sigma):

    #rename the levels
    nivP1=niv[0]
    nivP2=niv[1]
    nivP3=niv[2]
    nivP4=niv[3]


    #rename the weights
    wP1=weights[0]
    wP2=weights[1]
    wP3=weights[2]
    wP4=weights[3]

    #size of the CPT
    sizeCPT=nivP1*nivP2*nivP3*nivP4

    #create the CPT table (considering 5 possible states:very low, low, medium,high,very high)
    CPT4P=np.ndarray(shape=((sizeCPT),5))

    #table filled with zero
    for ii in range (sizeCPT):
        for jj in range(5): # 5 possible states
                CPT4P[ii,jj] = (0)

    ##########
    #loop on the levels
    for i1 in range(nivP1):
        for i2 in range(nivP2):
            for i3 in range(nivP3):
                for i4 in range(nivP4):
                    i = ((i1*nivP2+i2)*nivP3+i3)*nivP4+i4
                    moy1 = (i1+0.5)/nivP1
                    moy2 = (i2+0.5)/nivP2
                    moy3 = (i3+0.5)/nivP3
                    moy4 = (i4+0.5)/nivP4
                    moy = (moy1*wP1+moy2*wP2+moy3*wP3+moy4*wP4) / (wP1+wP2+wP3+wP4)
                    TN = get_truncated_normal(mean=moy, sd=sigma, low=0, upp=1) #truncated normal distribution
                    aux = TN.cdf(1)-TN.cdf(0)
                    for j in range(5): # 5 possible states
```

```
                    CPT4P[i,j] = (TN.cdf((j+1)/5)-TN.cdf(j/5.))/aux #probability table
    return CPT4P

########################################################################
#function to calculate the weighted average of the 4 parents'vectors
########################################################################
def weights4P(vectorA,vectorB,vectorC, vectorD):

    #normalize the vectors
    vectorA=normalizeV(vectorA)
    vectorB=normalizeV(vectorB)
    vectorC=normalizeV(vectorC)
    vectorD=normalizeV(vectorD)
    ################################
    #performing the weighted average
    ##################################

    #size of the vectors
    sizeA=vectorA.size
    sizeB=vectorB.size
    sizeC=vectorC.size
    sizeD=vectorD.size
    #size of the resulting vector
    sizeVResult=sizeA*sizeB*sizeC*sizeD

    #create the vector result
    VResult=np.ndarray(shape=(sizeVResult))
    for i in range(sizeA):
        for j in range(sizeB):
            for k in range(sizeC):
                for z in range(sizeD):

                    VResult[((i*sizeB+j)*sizeC+k)*sizeD+z]= vectorA[i]*vectorB[j]*vectorC[k]*vectorD[z]

    return VResult

########################################################################
#function to include the user's error
########################################################################
def UserError (vectorMoy, vectorSize, sigmaUser):
    vectorVariable = np.zeros(vectorSize)
    TNuser = get_truncated_normal(mean=vectorMoy, sd=sigmaUser, low=0, upp=1) #truncated normal distribution
    auxUser = TNuser.cdf(1)-TNuser.cdf(0)
    for i in range (vectorSize):
        vectorVariable[i]=(TNuser.cdf((i+1)/5.)-TNuser.cdf(i/5.))/auxUser
    return vectorVariable
############################################################################################################
#@@@@@@@@@@@@@@@@@@@@@@@@@     MAIN PROGRAM
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
############################################################################################################

#################################################
#INPUTS for Severity##############################
#################################################

#parents of severity (!remember to introduce the number with the point-notation, otherwise they are considered integer)
#HSFWS= hazard specific factor worsening severity
#sev = severity of consequence
specificWFseverity = 1.        #@@@@@@@@@input from LARA
var_hsfws = 0.1  #@@@@@@@@@input from LARA
synergeticWFseverity =1.        #@@@@@@@@@input from LARA
var_sfws = 0.1  #@@@@@@@@@input from LARA
sevir = 1.    #@@@@@@@@@input from LARA
var_sevir= 0.1    #@@@@@@@@@input from LARA

#adding the user's error
HSFWS=UserError((specificWFseverity-0.5)/5.,5,var_hsfws) #first parameter: center of the interval
print('HSFWS =', HSFWS)
print( 'somma', HSFWS[0]+HSFWS[1]+HSFWS[2]+HSFWS[3]+HSFWS[4])

#adding the user's error
SFWS=UserError((synergeticWFseverity-0.5)/5.,5,var_sfws) #first parameter: center of the interval
print('SFWS =', SFWS)
print( 'somma', SFWS[0]+SFWS[1]+SFWS[2]+SFWS[3]+SFWS[4])

sev=UserError((sevir-0.5)/5.,5,var_sevir) #first parameter: center of the interval
```

```
print('sev=',sev)
print('sev', sev[0]+sev[1]+sev[2]+sev[3]+sev[4])

#number of levels for severity's parents (P=parents)
#[nlevel_HSFWS, nlevel_SFWS nlevel_sev]

nlevel_Pseverity = np.array([HSFWS.size,SFWS.size, sev.size])

#weights of probability's parents
#[weights_HSFWS, weight_SFWS, weight_sev]
weight_Pseverity = np.array([1.,1., 1.])        #@@@@@@@@@input from LARA
#sigma of the truncated Gaussian distribution to build the severity-CPT
sigma_severityTPC = 0.1                   #@@@@@@@@@input from LARA

##################################################
#Building the probability table
##################################################
severityCPT = CPT3parents(nlevel_Pseverity, weight_Pseverity, sigma_severityTPC)

##################################################
#Forward inference
##################################################
#vector containing the combination of HSFWS,SFWS,sev (row vectors, 125 components)
wSeverityParents = weights3P(HSFWS,SFWS,sev)
print ('wSeverityParents',wSeverityParents)
#vector Severity
vSeverity = np.matmul(wSeverityParents, severityCPT)

# checking if the sum of all probabilities is different than 1:
# if equal to 1 : print the vector Severity
# if not  : give an error value
sumSeverity = vSeverity[0]+vSeverity[1]+vSeverity[2]+vSeverity[3]+vSeverity[4]
sumSeverity = sumSeverity.tolist() # otherwise only double precision float
print ('Sum Severity',sumSeverity)

if sumSeverity < 1.000000001 and sumSeverity > 0.999999999:
    print('Severity', vSeverity)

else:
    print ("Error: sum of probabilities higher than 1 for Severity") #@@@@@@@@@ this error should come out in LARA. In any case the calculation
is stopped
    exit()


###################################################
#INPUTS for probability###########################
###################################################

#parents of probability (!remember to introduce the number with the point-notation, otherwise they are considered integer)
#FDE = Frequency Duration and Exposure to Hazard
#FP = Failure probability
#HSFWP = hazard specific factor worsening probability
#SFWP = hazard specific factor worsening probability
duration = 4.             #@@@@@@@@@input from LARA
var_duration = 0.1             #@@@@@@@@@input from LARA
failure = 3.             #@@@@@@@@@input from LARA
var_failure = 0.1             #@@@@@@@@@input from LARA
specificWFprobability = 2.            #@@@@@@@@@input from LARA
var_hsfwp = 0.1            #@@@@@@@@@input from LARA
synergeticWFprobability = 2.               #@@@@@@@@@input from LARA
var_sfwp = 0.1           #@@@@@@@@@input from LARA

#adding the user's error
FDE = UserError((duration-0.5)/5.,5,var_duration) #first parameter: center of the interval
print('FDE =', FDE)
print( 'somma', FDE[0]+FDE[1]+FDE[2]+FDE[3]+FDE[4])

FP = UserError((failure-0.5)/5.,5,var_failure) #first parameter: center of the interval
print('FP =', FP)
print( 'somma', FP[0]+FP[1]+FP[2]+FP[3]+FP[4])

HSFWP = UserError((specificWFprobability-0.5)/5.,5,var_hsfwp) #first parameter: center of the interval
print('HSFWP =', HSFWP)
print( 'somma', HSFWP[0]+HSFWP[1]+HSFWP[2]+HSFWP[3]+HSFWP[4])

SFWP=UserError((synergeticWFprobability-0.5)/5.,5,var_sfwp) #first parameter: center of the interval
```

```
print('SFWP =', SFWP)
print( 'somma', SFWP[0]+SFWP[1]+SFWP[2]+SFWP[3]+SFWP[4])
#number of levels for probability's parents
 #[nlevel_FDE, nlevel_FP, nlevel_HSFWP, nlevel_SFWP]
nlevel_Pprobability = np.array([FDE.size, FP.size, HSFWP.size., SFWP.size, ])

#weights of probability's parents
#[weights_accident, weight_exposure, weight_frequency, weight_HSWFP]

weight_Pprobability = np.array([1,1,1,1])         #@@@@@@@@@input from LARA

#sigma of the truncated Gaussian distribution to build the probability's CPT

sigma_probabilityCPT = 0.1                        #@@@@@@@@@input from LARA

####################################################
#Building the probability table
####################################################
probabilityCPT = CPT4parents(nlevel_Pprobability,weight_Pprobability,sigma_probabilityCPT)

####################################################
#Forward inference
####################################################
#vector containing the combination of accident freq. rate,exposure to hazard,frequency duration of activity, HSWFP (row vectors, 625 components)
wProbabilityParents = weights4P(FDE,FP,HSFWP,SFWP)
#print('wProbabilityParents',wProbabilityParents)
#vector Probability
vProbability = np.matmul(wProbabilityParents, probabilityCPT)


# checking if the sum of all probabilities is different than 1:
# if equal to 1 : print the vector Probability
# if not  : give an error value
sumProbability = vProbability[0]+vProbability[1]+vProbability[2]+vProbability[3]+vProbability[4]
sumProbability = sumProbability.tolist() # otherwise only double precision float
print ('Sum Probability',sumProbability)
if sumProbability < 1.000000001 and sumProbability > 0.999999999:
    print('Probability', vProbability)

else:
    print ("Error: sum of probabilities higher than 1 for Probability") #@@@@@@@@@ this error should come out in LARA. In any case the
calculation is stopped
    exit()

#####################################################
#INPUTS for detectability##########################
#####################################################

#parents of detectability (!remember to introduce the number with the point-notation, otherwise they are considered integer)
select= 1.                #@@@@@@@@@input from LARA
var_select= 0.1                              #@@@@@@@@@input from LARA
reliabil = 1.                #@@@@@@@@@input from LARA
var_reliabil = 0.1                              #@@@@@@@@@input from LARA


#adding the user's error
Selectivity = UserError((select-0.5)/3.,3,var_select) #first parameter: center of the interval
print('Selectivity =', Selectivity)
print( 'tot selectivity', selectivity[0]+selectivity[1]+selectivity[2])

Reliability = UserError((reliabil-0.5)/3.,3,var_reliabil) #first parameter: center of the interval
print('Reliability =', Reliability)
print( 'tot Reliability', Reliability[0]+Reliability[1]+Reliability[2])



#number of levels for detectability's parents (P=parents)
#[nlevel_selectivity, nlevel_reliability]
nlevel_Pdetectability = np.array([Selectivity.size,Reliability.size])

#weights of detectability's parents
 #[weights_usitability, weight_reliability, weight_selectivity]
weight_Pdetectability = np.array([1,1])         #@@@@@@@@@input from LARA

#sigma of the truncated Gaussian distribution to build the detectability's CPT
sigma_detectabilityCPT = 0.1                       #@@@@@@@@@input from LARA
```

```
##################################################
#Building the probability table
##################################################
detectabilityCPT = CPT2parents(nlevel_Pdetectability,weight_Pdetectability,sigma_detectabilityCPT)

##################################################
#Forward inference
##################################################
#vector containing teh combination of availability,reliability,selectivity (row vectors, 9 components)
wDetectabilityParents = weights2P(Selectivity,Reliability)
print('wDetectabilityParents',wDetectabilityParents)
#vector Detectbility
vDetectability = np.matmul(wDetectabilityParents, detectabilityCPT)

# checking if the sum of all probabilities is different than 1:
# if equal to 1 : print the vector Severity
# if not  : give an error value
sumDetectability = vDetectability[0]+vDetectability[1]+vDetectability[2]+vDetectability[3]+vDetectability[4]
sumDetectability = sumDetectability.tolist() # otherwise only double precision float
print ('Sum Detectability',sumDetectability)
if sumDetectability < 1.000000001 and sumDetectability > 0.999999999:
    print('Detectability', vDetectability)

else:
    print ("Error: sum of probabilities higher than 1 for Detectability") #@@@@@@@@@ this error should come out in LARA. In any case the calculation is stopped
    exit()


#################################################################
#                      RiCS                                  #
#################################################################

#parents of RiCS (previously calculated)
#severity = vSeverity
#Probability = vProbability
#Detectability = vDetectability

#number of levels for probability's parents
 #[nlevel_vSeverity, nlevel_vProbability, nlevel_vDetectability]
nlevel_P_RiCS = np.array([vSeverity.size, vProbability.size, vDetectability.size])

#weights of RiCS's parents
#[weights_vSeverity, weight_vProbability, weight_vDetectability]

weight_P_RiCS = np.array([2,2,1])           #@@@@@@@@@input from LARA

#sigma of the truncated Gaussian distribution to build the RiCS's CPT

sigma_RiCS_CPT = 0.1                        #@@@@@@@@@input from LARA

##################################################
#Building the probability table
##################################################
RiCS_CPT = CPT4parents(nlevel_P_RiCS,weight_P_RiCS,sigma_RiCS_CPT)

##################################################
#Forward inference
##################################################
#vector containing the combination of Severity, Probability, Detectability (row vectors, 125 components)
wRiCSParents = weights3P(vSeverity, vProbability, vDetectability)

#vector RiCs
vRiCS = np.matmul(wRiCSParents, RiCS_CPT)

# checking if the sum of all probabilities is different than 1:
# if equal to 1 : print the vector Severity
# if not  : give an error value
sumRiCS = vRiCS[0]+vRiCS[1]+vRiCS[2]+vRiCS[3]+vRiCS[4]
sumRiCS = sumRiCS.tolist() # otherwise only double precision float
print ('Sum RiCS',sumRiCS)
if sumLCI < 1.000000001 and sumRiCS > 0.999999999:
    print('RiCS vector', vRiCS)
   RiCS = 2*vRiCS[0]+4*vRiCS[1]+6*vRiCS[2]+8*vRiCS[3]+10*vRiCS[4]
    print('RiCS', RiCS)
```

```
else:
   print ("Error: sum of probabilities higher than 1 for RiCS") #@@@@@@@@@ this error should come out in LARA. In any case the calculation is
stopped
   exit()
```

Attachment D3. Visual representation for Child nodes.

```
#test of the truncated normal distribution

from scipy.stats import truncnorm
import math

def get_truncated_normal(mean=0, sd=1, low=0, upp=10):
   return truncnorm((low - mean) / sd, (upp - mean) / sd, loc=mean, scale=sd)


#X1 = get_truncated_normal(mean=2, sd=1, low=1, upp=10)
#X2 = get_truncated_normal(mean=5.5, sd=1, low=1, upp=10)
#X3 = get_truncated_normal(mean=8, sd=1, low=1, upp=10)
#sigma=math.sqrt(0.1)
X4 = get_truncated_normal(mean=0.3, sd=0.1, low=0, upp=1)

aux=X4.cdf(1)-X4.cdf(0)

y1=X4.cdf(1)
y2=X4.cdf(0)
y3=X4.cdf(0.2)

#Ymean=X4.cdf(0.2)

#print('Ymean',Ymean)

print('X4.cdf(1)',y1)
print('X4.cdf(0)',y2)
print('X4.cdf(0.2)',y3)


#result=X4.cdf(0.2)/Ymean
result_EC=(y3-y2)/aux

#print('result',result)
print('result1',result_EC)


import matplotlib.pyplot as plt
fig, ax = plt.subplots(2, sharex=True)
#ax[0].hist(X1.rvs(10000), normed=True)
#ax[1].hist(X2.rvs(10000), normed=True)
#ax[2].hist(X3.rvs(10000), normed=True)
ax[0].hist(X4.rvs(1000), normed=True)
plt.show()
```

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