Safety of industrial tools, machines and processes

Studies and Research Projects

REPORT **R-684**

Experimental Analysis of Tools Used for Estimating Risk Associated with Industrial Machines

Yuvin Chinniah
François Gauthier
Serge Lambert
Florence Moulet

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This study was financed by the IRSST. The conclusions and recommendations are those of the authors.

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ABSTRACT

In this study, 31 qualitative tools used for estimation risks associated with industrial machines and which follow the ISO 14121-1: 2007 guidelines were analysed by (i) comparing their risk estimation parameters and (ii) applying the different tools to estimate risks associated with 20 hazardous situations (scenarios). The objective of this study was to theoretically compare the performances of tools in estimating risks and to evaluate whether tools estimate risks uniformly. Ideally, the risk levels obtained by different users when applying the different tools to the same risk scenarios should be more or less similar. The risk levels obtained by the same users when applying the different tools to the same risk scenarios at different times should also show certain similarities. As such, any important variability in risk estimations can be attributed to flaws or biases in the tools and these can be based on parameters as well as the architectures of the tools. In order to compare tools which have different parameters, as well as different number of levels or thresholds for those parameters, it was required to set up equivalence scales for the different risk estimation parameters. By using common benchmarks, it is showed that this comparison of different risk estimation tools is possible. Therefore, in this report, the setting up of those equivalence scales is described and some analysis of the different parameters used in the tools is presented. Some guidelines on how to define parameters in risk estimation tools in order to make risk estimations easier as well as independent of tools and users (i.e. repeatability of risk estimation results), are also provided. Moreover, the differences obtained in the risk estimation results when applying different risk estimation tools to the same hazardous situations involving dangerous machines are studied by investigating (i) the influence of the types of risk estimation parameters and methods of construction of the tools, (ii) the influence of the number of levels for each parameter and (iii) the influence of the number of risk levels on the results. As such, the 31 risk estimation tools are compared by applying them to 20 hazardous situations. The results show significant differences among the tools in estimating risks associated with the same hazardous situations, i.e. risk is tool dependent. The scope of the tool and its construction or architecture seem to be one of the contributing factors in this variability of the results. Tools that follow the 2 configurations proposed in ISO 14121-1:2007 produce similar average risk levels but both configurations have tools that will underestimate or overestimate risk associated with hazardous situations. This leads to conclude that simple tools, which have 2 parameters, can be as effective as more detailed tools, which have 4 parameters. It was also observed that the 31 tools could be grouped as 9 low risk estimating tools, 8 intermediate risk estimating tools and 14 high risk estimating tools**.** Moreover, there are tools which are not appropriate for machinery risk assessment even if their scopes often state the opposite. Finally, the observations in the behaviours of the different tools have guided the authors in proposing a series of construction rules for the tools in order to alleviate most of the problems associated with the variability in the risk estimations. Those recommendations can potentially guide users of risk estimation tools when choosing, designing or using a risk estimation tool. Future works include the validation of the most promising tools with a large sample of different users from industries. It should be mentioned that this study was done in collaboration with the Health and Safety Laboratory (HSL) in United Kingdom and the authors would like to acknowledge the involvement of Nicola Stacey, Nicola Healey and Simon Rice.

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1. INTRODUCTION

Machine risk assessment is a series of steps used to examine the hazards associated with machines and it consists of two stages namely risk analysis and risk evaluation as explained in ISO 14121-1 (2007). Risk analysis usually consists of three stages, namely determining the limits of the machine, hazard identification and estimating the risk.

Knowing the limits of the machines implies considering all phases of the machine life cycle; design, construction, transport, installation, commissioning, operation, starting up, shutting down, setting or process changeover, cleaning and adjustment. Moreover, as described in ISO 14121-1 (2007), it is important not to restrict oneself to the intended use and operation of the machine but also to consider the consequences of reasonably foreseeable misuse or malfunction, as well as the anticipated level of training and experience of workers.

In the hazard identification stage in machines, it is required to consider different forms of hazards. In general, hazards in machines tend to fall into two main categories, namely mechanical and electrical hazards. Forms of mechanical hazards include crushing, shearing, cutting, entanglement, entrapment, impact, abrasion and high pressure fluid jets. These mechanical hazards can be generated by the different machine parts, depending on their shapes, relative motions, masses and stabilities, masses and velocities and strength. Workers can get injured by mechanical hazards as a result of:

- Being trapped between the machine and a fixed structure;
- Being struck by material ejected from the machine;
- Being struck by ejected part of the machine;
- Being struck by jet of fluid under pressure;
- Being in contact or entangled with any material in motion; and
- Being in contact or entangled with the machine.

Workers can also get injured by electrical hazards which include situations such as contact with live parts, contact with live parts becoming live under fault conditions, approach to live parts carrying high voltage and thermal radiation. Electrical hazards can lead to electrification (injuries), electrocution (death), heart attacks and burns. Hazards generated by heat, noise, vibration, radiation and dangerous chemical and biological substances are other examples of hazards that should be considered at this important stage of the assessment.

After having completed the hazard identification phase, risk estimation is carried out for each identified hazard and hazardous situation. Risk is defined as a combination of the severity of harm and the probability of occurrence of that harm. According to ISO 14121-1 (2007), the probability of occurrence of harm can be estimated taking into account the frequency and duration of exposure to the hazard, the probability of occurrence of a hazardous event and the technical and human possibilities to avoid or limit the harm. The combination of these four parameters will be used to estimate risk values which can then be used for comparison purposes. At the last stage of the assessment process, risk evaluation allows decisions on the safety of the machine to be made.

Risk estimation tools are proposed by organizations involved in the safety of industrial machines and some companies have established their own methods and tools of analysis. All these processes are based on the same principles illustrated in Figure 1, derived from ISO 12100-1 (2003) standard, which identifies two steps in the risk assessment phase: risk analysis and risk evaluation. Figure 1 shows the model derived and simplified from ISO 12100-1 (2003) and used to represent a machine risk assessment and reduction process.

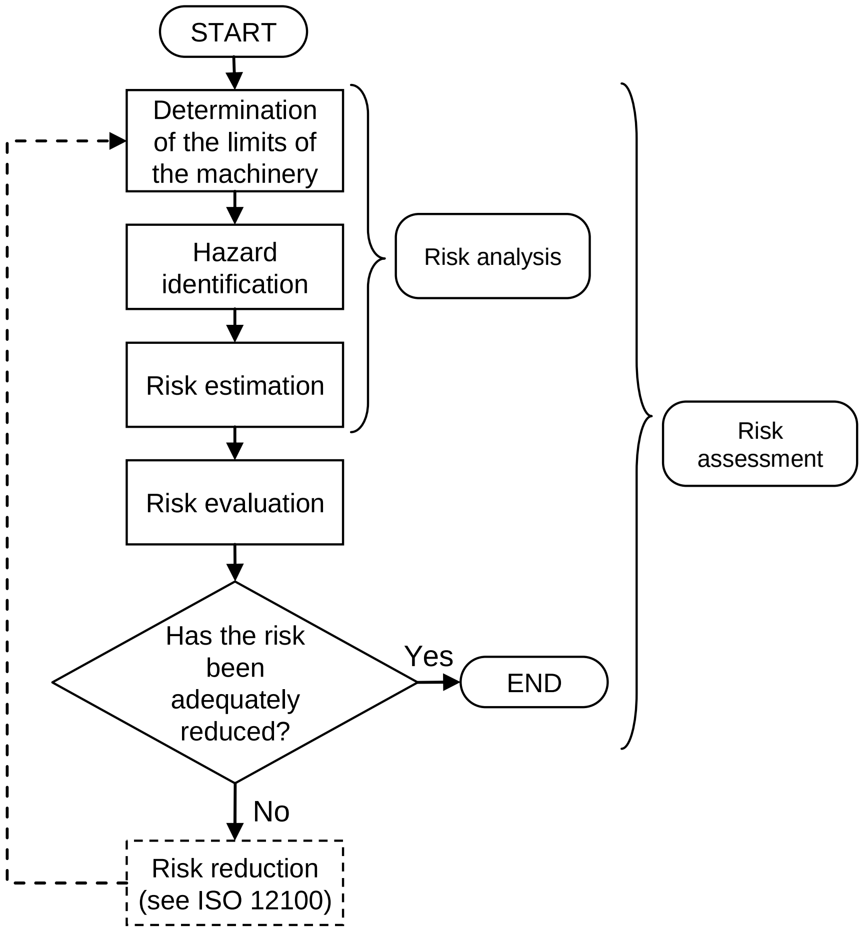


Figure 1: Simplified management of risk assessment based on ISO 12100-1 standard.

1.1 Training on risk assessment by the IRSST

In order to reduce risks which are responsible for machine related accidents, machines must be designed or modified by integrating means of risk reduction. Without carrying out risk assessment, it is very difficult to make optimal decisions regarding means of risk reduction for machines. Training sessions on machine risk assessment have been developed and given by the Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST) to occupational health and safety (OHS) professionals in the province of Quebec. A specific project (Paques et al., 2005) has made it possible to train OHS intermediaries and trainers who in turn explained machine risk assessment and risk reduction strategies linked to machinery to workers and managers in companies. More than 560 people were thus involved and sensitized during 16 awareness-raising sessions. Participants of the risk assessment training sessions applied various aspects of their training to their workplaces or to practical situations in industries (Lane et al., 2003). In addition, several questions were raised during these training sessions and one of the findings was that the needs for different companies, mainly small and medium enterprises (SME), could vary significantly and that one method or one tool used successfully in one plant did not necessarily meet the requirements of another plant. Besides, it is likely that the diversity of tools available to carry out the risk estimation stage, as revealed in a previous study (Paques et al., 2005a, Paques and Gauthier, 2007), could be partially attributed to the various needs of companies.

Moreover, few specific directives are available to companies when undertaking machine risk assessment. Only a few large corporations have invested the necessary resources to develop systematic methods for analyzing the risks associated with specific hazardous machines; however, it is difficult to have access to these tools which are often considered essential for the company's internal management strategy and are therefore confidential. Faced with a great diversity in risk assessment tools, OHS professionals who want to carry out risk assessment on dangerous machines are unequipped to choose one or more tools and to apply one or more tools that produce useful results but at the same time requiring little effort. SME are not well equipped to tackle this problem since fewer or no resources are allocated to this field.

1.2 Risk estimation –Various tools and methods

Due to the diversity of the methods and tools for risk estimation associated with industrial machinery and the divergence of results sometimes observed, a thematic program consisting of several research projects has been undertaken to analyze in depth the characteristics of the tools proposed in the literature or used in industry (Paques and Gauthier, 2006). A first study aiming at gathering data on existing risk estimation and evaluation tools for industrial machinery has been completed (Paques et al., 2005, Paques and Gauthier, 2006).

The objective of that study was to analyse the available documentation on risk assessment in order to classify tools. More precisely, the aim was to determine specificities of each method and tool in their risk estimation aspect and to classify them in groups or families. As such, 108 different tools used for risk estimation were identified. These tools have been classified according to many criteria including the means of estimating the risks. The families of risk estimation tools are illustrated in Figure 2 and are as follows:

- Two dimensional matrices (47.2%);
- More than 2 dimensional matrices (6.5%);
- Risk graphs (10.2%);
- Numerical operation methods (14.8%);
- Graphical (nomogram) methods (2.8%); and
- Hybrid methods using several approaches (18.5%).

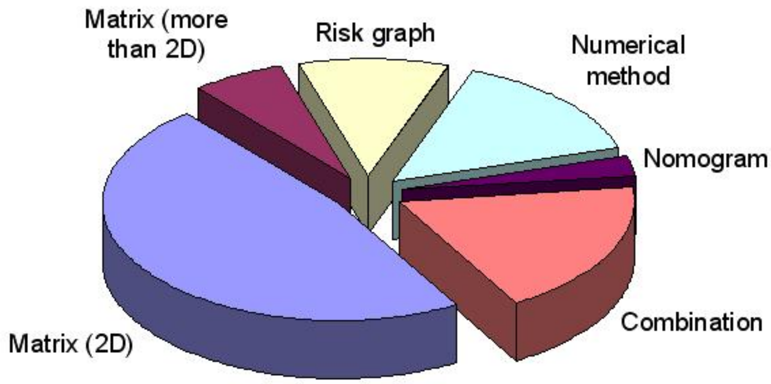


Figure 2: Distribution of risk estimation tools by families

The most notable aspect in the findings of this first study was the diversity at all levels: diversity in the nature of each risk estimation method and tool, on how to describe and define each parameter, in the number of parameters, on how to calculate, quantify and qualify the risk, on how to classify or evaluate the final result, etc. Differences in the number of parameters, types of parameters, number of thresholds (levels) and definitions of the parameters significantly contributed to the diversities in the identified risk estimation tools.

The primary objective of the users of a risk estimation tool is to rank the different hazardous situations (scenarios) as per the risk indexes they represent in order to identify intolerable (unacceptable) risks and to prioritize their interventions. This objective will not be achieved if the tool places all scenarios at the same risk level (e.g. medium or high risk). There is a lack of research dealing with the understanding and evaluation of risk estimation tools in the field of machine safety and the attempt to identify the variables that can influence the proper estimation of risk (Etherton 2007, Lamy et. al. 2009). For example, Abrahamsson (2002) attempted to analyze various quantitative risk estimation tools in different contexts and particularly in the occupational exposure to hazardous substances. His research was focused exclusively on the analysis of the various types of uncertainty associated with the tools. The three major groups of uncertainty were (i) parameter uncertainty, i.e. values of the parameters were not accurately known, (ii) model uncertainty, i.e. uncertainty arising from the fact that any model, conceptual or mathematical will be a simplification of the reality it is designed to represent and (iii) completeness uncertainty, i.e. uncertainty originating from the fact that not all contributions to risk are addressed in quantitative risk analysis models. Abrahamsson did not analyze other variables that can modulate a proper estimate of risks, for example, variable originating from prior training, or variables originating from individual characteristics of the person performing the risk analysis. Another study which is relevant to this problem was done by Wallstein et al. (1986) who noted that "*non-numerical probability expressions convey vague uncertainties*" and that the definition of probability in the verbal form is not reliable.

Training sessions on risk assessment also revealed that differences exist in the results of an exercise carried out on the same machine from one group of individuals to another in estimating the risk associated with some of the tasks or activities (Paques, 2005d). Some variability in the results can be considered "*natural*", and therefore tolerable, but too great a dispersion may eventually lead to erroneous means of risk reduction (Parry, 1999). In different European countries, experts interested in risk estimation observe that: “*The methods used in the different European countries for assessing a machine’s risks, when these methods exist, may lead to different, and even contradictory results. In some cases, they may potentially require, for a given machine, different levels of safety.*” (Charpentier, 2003). Abrahamsson also mentions that potential users perceive the risk estimation tools as not being very credible or unusable (Abrahamsson, 2002).

This second project of the thematic program deals mainly with the risk estimation phase associated with industrial machines. It addresses the sources of uncertainty related to the “*model uncertainty*”, as defined by Abrahamson (2000) or Parry (1998) and in opposition to the two other classes of uncertainty namely “*parameter uncertainty*” and “*completeness uncertainty*” which will be addressed in the subsequent projects of the thematic program.

The standard ISO 14121-1 defines risk as the combination of four parameters. Each parameter used for risk estimation purposes can be considered as a measurement parameter. The classification in the four levels of measurement proposed by Stevens (1946) can then be applied. The level of measurement of a variable describes the nature of information contained within numbers (or words) assigned to objects. The four recognized levels of measurement are: (i) nominal, (ii) ordinal, (iii) interval and (iv) ratio. This classification is very often referred to by others (Trochim, 2005a), despite the limitation of such scales used in social sciences (Marradi, 1990, Velleman and Wilkinson, 1993). As one of the objectives of the risk estimation process is to classify risk, parameters used to estimate risk have to be under the format of an ordinal measurement; this may explain that most of the existing tools for risk estimation make use of scales close to Likert scales (Trochim, 2005a). For example, tool 1 (see section 4) has 2 parameters; severity of harm and probability of harm. The severity of harm parameter has 3 levels ranging from 1 to 3 in increasing order of severity with the following descriptions:

1. Slight – less than 3 days lost time;
2. Serious – over 3 days lost time; and
3. Major – death or serious injury.

However, some parameters may be defined as intervals or even ratios.

1.3 Risk estimation parameters in ISO 14121-1

According to ISO 14121-1, “*the risk associated with a particular hazardous situation depends on the following elements: (a) the severity of harm; (b) the probability of occurrence of that harm, which is a function of (1) the exposure of person(s) to the hazard, (2) the occurrence of a hazardous event, (3) the technical and human possibilities of avoiding or limiting the harm.*” ISO 14121-1 also mentions that the severity of harm can be estimated by taking into account (a) the severity of injuries or damage to health (e.g., slight, serious, or death) and (b) the extent of harm (e.g., one or several persons).

Factors to be taken into account when estimating the exposure parameter are, among others: (a) need for access to the hazard zone (e.g., for normal operation, correction of malfunction, maintenance or repair); (b) nature of access (e.g., manual feeding of materials); (c) time spent in the hazard zone; (d) number of persons requiring access and (e) frequency of access.

The occurrence of a hazardous event parameter can be estimated by taking into consideration factors such as (a) reliability and other statistical data; (b) accident history; (c) history of damage to health; and (d) risk comparison.

When estimating the possibility of avoiding or limiting harm, factors which could be taken into consideration, as described in ISO 14121-1 include (a) the different persons who can be exposed to the hazard(s), (e.g., skilled, or unskilled); (b) how quickly the hazardous situation could lead to harm (e.g., suddenly, quickly, or slowly; (c) any awareness of risk (e.g., by general information, information for use, by direct observation, or through warning signs and indicating devices on the machinery; (d) the human ability of avoiding or limiting harm (e.g., reflex, agility, possibility of escape); (e) practical experience and knowledge, e.g., of the machinery, of similar machinery, or absence of experience.

2. OBJECTIVES

This report analyses and compares, using experimental methods, the performance of previously identified tools used for estimating risks associated with industrial machines. The comparison of the theoretical performances of a sample of tools will enable the researchers to identify influential factors on risk estimation. The following research questions will be addressed:

- What are the differences in the results when applying different tools to the same hazardous situation?
- What is the influence of the types of parameters used to define risk in each tool on resulting risk levels?
- What is the influence of the number of parameters used to define risk in each tool on resulting risk levels?
- What is the influence of the number of thresholds or levels for each parameter on resulting risk levels?
- What is the influence of the number of risk levels on the results obtained when applying each risk estimation tool?

Eventually, the results of this study will enable the researchers to define theoretically the characteristics of reliable and robust tools, as well as to identify tools which can potentially lead to errors when estimating risks.

The proposed research hypothesis was that this comparison of the theoretical performances of a sample of different risk estimation tools is possible despite the diversity in these tools, once equivalence scales have been defined for each parameter used in each risk estimation tool.

The objective was to analyze tools by comparing their risk estimation parameters and by applying them to test scenarios in order to verify whether the tools performed uniformly in estimating risks. Another objective of this study was to describe the limits of some tools, the desirable characteristics of risk estimation tools and to propose guidelines on the construction of tools, i.e. number and types of parameters, number of thresholds for the different parameters and number of risk levels for the tools. Those guidelines could ensure repeatability of results and avoid biases in the tools which could lead to under or over estimation of risks and consequently to the incorrect choice of risk reduction measures.

3. METHODOLOGY

Two teams, namely Polytechnique/IRSST/UQTR and the Health and Safety Laboratory (HSL) worked together on this project. The methodology consisted of five main stages:

- Selecting a sample of risk estimation tools out of the 108 tools identified and analyzed during the previous study;
- Setting up equivalent scales for each parameter in every selected risk estimation tool;
- Analyzing the equivalent scales for each parameter and identifying problems with the types of parameters, definitions of the different levels, and number of thresholds or levels for those parameters;
- Applying each tool to 20 hazardous situations associated with machines. Those situations were selected to represent different hazards, different phases of the machine lifecycle, as well as different types of industries. A predefined format for test scenarios was used to minimize parameter uncertainty and to focus on model uncertainty. Each tool was applied to the 20 hazardous situations by the teams; and
- Analyzing the results, identifying any variability in the risk levels for the same situations and interpreting them based on the architecture of the tools.

The tools were classified into an MS ACCESS database to facilitate the analysis part. At that stage, each tool was given a number and a name in order to avoid identification errors.

3.1 Selecting a sample of risk estimation tools

The tool selection was based on predefined criteria which were:

1. Tools which were matrices or which could be converted into matrices were selected (e.g., risk graphs or numerical tools can be converted into matrices). One nomogram was also selected.

2. Elimination of tools which were not in line with ISO 14121-1 (2007), i.e. tools which used parameters not found in ISO 14121-1 (2007) were not included in the study. Therefore, only tools using the six parameters described in ISO 14121-1 (2007) were kept. Those parameters were the severity of harm, the probability of occurrence of that harm, the frequency of exposure to the hazard, the duration of exposure to the hazard, the probability of occurrence of a hazardous event and the technical and human possibilities to avoid or limit the harm. All the tools which were included in the sample used the severity of harm parameter. This step resulted into the elimination of:

    a. Tools which used parameters which are not defined in ISO 14121-1 (2007) (e.g., other parameters);
    b. Tools which had an undefined probability parameter (e.g., it was unclear whether it was probability of harm or probability of occurrence of hazardous event);
    c. Tools which had 2 parameters but which did not use probability of harm (except for tool 55 which originates from a company and which was included in the sample);
    d. Tools which had more than 2 parameters but which used probability of harm;
    e. Tools which had more than 2 parameters but which used severity of harm in

conjunction with only exposure parameters (frequency and duration); and

f. Tools which used the probability of harm and frequency of exposure.

After setting up the criteria, the two teams met in order to finalise the list of tools to be included in this study. Other secondary factors which were taken into consideration were the sources of the tools (i.e. standards, guides, industry etc.), the popularity of the tools, their architectures (i.e. matrices, graphs, nomograms, hybrids) and the number and types (definitions) of parameters. This resulted in the selection of a sample of 31 risk estimation tools out of the 108 tools identified and analysed during the previous study.

3.2 Setting up and analysis of equivalence scales for the risk estimation parameters

The next step was to set up equivalent scales for the parameters in the tools in order to compare the selected risk estimation tools. This comparison was based on their different parameters, their definitions and their number of thresholds. The equivalent scales were set up one parameter and one tool at a time, without a referential or predefined equivalence. The objective was to compare tools among themselves and to obtain complete descriptions of equivalent scales at the end, based on the results. The approach was initially tested on five tools with different architectures, namely tools 49, 62, 67, 91 and 48. The equivalent scales for the risk estimation parameters were set up independently by each team and the results were compared. A consensus was reached and the teams felt comfortable with the approach and moved on to develop the equivalent scales for the remaining tools. At the end, equivalent scales for 6 parameters were set up, namely:

- Severity of harm (S);
- Probability of occurrence of harm (Ph);
- Frequency of exposure to the hazard (Exf);
- Duration of exposure to the hazard (Exd);
- Probability of occurrence of a hazardous event (Pe); and
- Technical and human possibilities to avoid or limit the harm (A).

The risk estimation parameters were positioned in a tabular form with the columns as the equivalence scales and the rows as the parameters for each tool. The descriptions of the parameters were kept in their original format and languages (English or French versions) in order to eliminate translation or interpretation errors at this stage. The columns were created to represent the different thresholds for the different parameters in the tools. In the beginning of the construction of the equivalent scales, the final number of “universal” levels (e.g., S1 to S8 for severity of harm) was not known.

Once the equivalent scales were defined, they were analysed in order to identify potential problems, e.g., construction or thresholds errors and definition issues.

3.3 Development of equivalent scales for risk levels

In order to compare the different tools, equivalent scales for risk levels were needed for each tool. The equivalent scales were constructed using the following three rules: 1) the risk grows linearly up to 100%, 2) each risk level is a range and not a punctual value, and 3) a zero risk is not possible. This method assumes that the highest risk level is the same for every tool and eliminates the need to rank them. Since some tools define the risk qualitatively and other quantitatively, the equivalent scales obtained are not biased by judgment or experience of an individual. The lowest risk level of a tool does not translate to a zero risk in the equivalent scales. This can be easily explained by the fact that a risk will always exist for hazardous situations producing the lowest risk level, but usually, this risk is tolerable. To illustrate this, a tool with three risk levels (Low, Medium and High) is analyzed. The equivalent risk range for this tool would be as follows: Low risk being 0 to 33.3 %, medium risk being 33.3% to 66.6% and high risk being 66.6 to 100%. For the comparison done later, the maximum risk value of the range is used in order to illustrate the worst case. As an example, Table 1 presents the equivalent risk scales for tools 48, 62 and 91.

Table 1 : Risk equivalence scales for tools 48, 62 and 91

<table>
<tr><th colspan="3">Tool risk levels</th><th rowspan="2">Equivalent risk level</th></tr>
<tr><th>48</th><th>62</th><th>91</th></tr>
<tr><td rowspan="2">Low</td><td rowspan="3">3</td><td>1</td><td>16.7%</td></tr>
<tr><td rowspan="2">2</td><td>25%</td></tr>
<tr><td rowspan="2">Medium</td><td>33.3%</td></tr>
<tr><td rowspan="2">2</td><td>3</td><td>50.0%</td></tr>
<tr><td rowspan="2">High</td><td>4</td><td>66.7%</td></tr>
<tr><td rowspan="3">1</td><td rowspan="2">5</td><td>75%</td></tr>
<tr><td rowspan="2">Extreme</td><td>83.3%</td></tr>
<tr><td>6</td><td>100%</td></tr>
</table>

3.4 Applying the 31 risk estimation tools to 20 hazardous situations (scenarios)

The researchers applied the 31 tools to hazardous situations in order to compare the resulting risk levels obtained when applying different tools to the same hazardous situations or scenarios, as explained in the following sections.

3.4.1 Selection and development of scenarios

The two teams proposed a number of real life hazardous situations from different industries and of different perceived risk levels. The hazardous situations represented different hazards occurring during different phases of the life cycle of machines. From those situations, 20 were kept for the development of machine related hazardous situations. In order to apply the tools consistently and in order to alleviate subjectivity issues, a predefined format for the scenarios was selected. As such, the description of the scenarios included a picture of the process or machine and the worker involved in the task, a brief description of the hazardous situation and some information to help estimating the parameters. It is to be noted that in real life analysis, the team doing risk estimation usually has access to more data if required. Nonetheless, the level of details was sufficient for the evaluation. Each scenario had a picture of the work station and machine, a description of the activity, hazard, hazardous situation, hazardous event, probability of occurrence of hazardous event, possible harm, exposure information and avoidance information. Figure 3 presents an example (scenario R) of one of the hazardous situations which were developed. This scenario depicts a worker cutting out thermo-formed panel still at an elevated temperature. The worker does not wear any protective equipment while doing the task on average 5 hours a day.

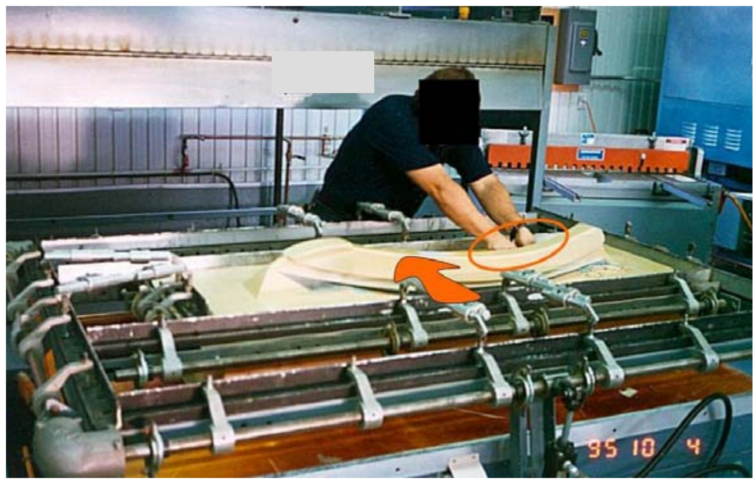
Scenario R **Thermal Hazard**	
Activity	Cutting out thermo-formed panel.
Hazard	Elevated temperature of cut panel (60 °C).
Hazardous situation	Worker in the proximity of the panel.
Hazardous event (choose and define one specific hazardous event)	Worker is in extended contact with the panel.
Probability of occurrence of hazardous event (considering training, experience, reliability of safety and non safety components, safeguards, supervision, defeating of safety devices, procedures…)	The worker is experienced in undertaking this task. The cuts and the tools necessary for this task need to be as close as possible to the panel and done while the panel is still hot.
Possible harm	Recurrent light burns.
Exposure information	On average 5 hours a day during an 8 hour shift.
Avoidance information (considering information on time and speed, warnings, escape route, training, experience, …)	The worker is experienced and aware of the danger. The nature of the work makes it difficult to avoid the contact with the hot panel. The worker is not wearing protective gloves.

Figure 3: Example of a hazardous situation

3.4.2 Estimating risk for the scenarios

Two different teams carried out the risk estimation associated with each scenario. Each of the Polytechnique/IRSST/UQTR and HSL team consisted of three researchers in machine safety. The results of both teams were then compared. Discrepancies in the risk levels were discussed until a consensus was reached. Interpretation problems were minimized since necessary information about the scenarios has been well defined before applying the risk estimation tools. Table 2 shows the selected thresholds for the different parameters for tools 48, 62 and 91 and the resulting risk levels associated with scenario R which is described in Figure 3. It is important to mention that very few discrepancies were found when deciding on the risk levels for the scenarios and those were due to the fact that a team had not paid attention to a detail in the scenario description. Hence, the argumentation was short and a consensus was reached very quickly.

Table 2: Evaluation of scenario R for tools 48, 62 and 91

<table>
<tr><th>Tool #</th><th>Parameter</th><th>Parameter level</th><th>Resulting risk level</th><th>Equivalent risk level</th></tr>
<tr><td rowspan="2">48</td><td>S</td><td>3</td><td rowspan="2">E</td><td rowspan="2">100%</td></tr>
<tr><td>Ph</td><td>A</td></tr>
<tr><td rowspan="4">62</td><td>S</td><td>IV</td><td rowspan="4">2</td><td rowspan="4">66.7%</td></tr>
<tr><td>A</td><td>5</td></tr>
<tr><td>Exd</td><td>4</td></tr>
<tr><td>Pe</td><td>2</td></tr>
<tr><td rowspan="4">91</td><td>S</td><td>2</td><td rowspan="4">6</td><td rowspan="4">100%</td></tr>
<tr><td>A</td><td>2</td></tr>
<tr><td>Exf</td><td>2</td></tr>
<tr><td>Pe</td><td>3</td></tr>
</table>

3.4.3 Analysis of the estimated risk levels

The average risk using the 31 tools and associated with each scenario was calculated. Tools that tend to underestimate or overestimate risk were further analysed based on their architectures and parameters.

4. RESULTS AND ANALYSIS

4.1 Sample of 31 risk estimation tools

The tools that were rejected from the initial sample of 108 tools had defects or were difficult to use and as such were intrinsically faulty when using ISO 14121-1 as the benchmark. Example of a potential bias will be to double count the probability of harm parameter (e.g., tool using both probability of harm and frequency of exposure). Also, tools which used probability parameters which were undefined or unclear and which could be interpreted in numerous ways were rejected since the results of risk estimation could be user dependent. It was interesting to note that the majority of tools were not in line with ISO 14121-1 (Paques et. al., 2005b). The reason for that is unclear but it can be argued that the standard is relatively new and some risk estimation tools have existed for several years. Another reason might be the appropriation of tools by organisations and industries such that tools might be modified or upgraded without proper assessment of their effectiveness in estimating risks adequately. Moreover, risk in industry is generally defined as the severity of harm or consequence and some sort of probability. The vagueness associated with the probability term accounts partly for the variations which were seen in this study.

Therefore, a sample of 31 tools which possessed the desirable characteristics in terms of their parameters and architectures was established. The list of tools is given in Table 3 and is presented in the reference list. The tools had different architectures and were from different sources. The tools used two to four parameters and had two to six thresholds for the parameters as described in Table 3. It is worth noting that 27 tools defined the parameters in English and 4 in French.

Table 3: Number of thresholds for each parameter for all the tools that were selected

Tool	S	Ph	Exf	A	Exd	Pe	R	Reference
1	3	3	-	-	-	-	6	Worsell and Wilday (1997) p. 7-10
3	3	4	-	-	-	-	5	BS8800 (2004) p. 46-50
6	4	5	-	-	-	-	4	Worsell and Wilday (1997) p. 24-26
7	4	5	-	-	-	-	3	Worsell and Wilday (1997) p. 32-34
10	5	5	-	-	-	-	6	Worsell and Wilday (1997) p. 38-40
17	6	-	-	-	3	6	4	Worsell and Wilday (1997) p. 85-90
19	3	-	2	2	2	3	4	Worsell and Wilday (1997) p. 98-101
24	4	4	-	-	-	-	4	ANSI B11.TR3 (2000)
33	3	3	-	-	-	-	3	Main (2004) p. 155-157
34	3	3	-	-	-	-	3	Main (2004) p. 164-165
35	5	5	-	-	-	-	4	Main (2004) p. 174-177
41	4	6	-	-	-	-	3	ISO/TS 14798 (2006)
44	4	5	-	-	-	-	4	MIL-STD-882D (2000)
45	4	5	-	-	-	-	5	Main (2004) p. 286-290
46	4	4	-	-	-	-	5	Main (2004) p. 290-293
48	5	5	-	-	-	-	4	AS/NZS 4360:2004
49	2	-	2	2	-	-	7	ANSI/RIA R15.06 (1999)
53	3	-	3	-	-	3	15	Company A (2002)
55	4	-	4	-	-	-	4	Company X (1997)
57	4	-	5	5	-	5	2	Company P (2003)
58	5	5	-	-	-	-	3	Company R (2004)
62	5	-	-	3	5	5	3	SUVA (2002)
66	4	6	-	-	-	-	4	IEC 62278 (2001)
67	4	-	5	3	-	5	3	ISO 14121-2 (2007)
69	3	-	2	2	2	3	11	Görnemann (2003)
85	4	5	-	-	-	-	7	Ruge (2004)
89	3	4	-	-	-	-	6	The Metal Manufacturing and Minerals Processing Industry Committee (2002)
91	2	-	2	2	2	3	6	ISO 14121-2 (2007)
94	4	5	-	-	-	-	4	CSA-Q634-91 (1991)
102	3	3	-	-	-	-	6	Gondar (2000)
114	4	-	4	4	-	-	3	HSL (2008)

S : Severity of harm; **Ph** : Probability of harm; **Exf** : Exposure frequency; **A** : Avoidance; **Exd** : Exposure duration; **Pe** : Probability of hazardous event and **R** : Risk

4.2 Equivalence scales for the severity of harm

As explained previously, equivalence scales were set up for each parameter. As such, Table 4 shows the equivalence scales for the severity of harm parameter (S) for the 31 risk estimation tools.

Table 4: Equivalence scale for the severity of harm

		Levels							
Tools	Severity of harm	S1 slight injuries (bruises) requiring no first aid	S2 slight injuries requiring first aid but without lost time	S3 injuries requiring more than first aid and with lost time	S4 irreversible harm, slight disability but able to return to same job	S5 serious disability, able to return to work but perhaps not to the same job	S6 permanent disability and can no longer work	S7 single death	S8 multiple deaths
49	Severity of injury	- S1 : Slight Injury (Normally reversible; or requires only first-aid as defined in OSHA 1904.12)		- S2 : Serious Injury (Normally irreversible; or fatality; or requires more than first-aid as defined in OSHA 1904.12)					
62	Gravité du dommage	- V : Très faible (Blessure sans arrêt de travail)		- IV : Faible (Blessure avec arrêt de travail)	- III : Moyen (Invalidité légère, capacité de travail pour la profession acquise ou pour une profession équivalente; influe peu sur la qualité de vie	- II : Grave (Invalidité grave – incapacité de travail pour la profession acquise ou pour une profession équivalente ; influe sur la qualité de vie)		- I : Très grave (Décès)	
67	Severity	1- Scratches, bruises that are cured by first aid or similar.		2- More severe scratches, bruises, stabbing, which require medical attention from professionals.	3- Normally irreversible injury. It will be slightly difficult to continue work after healing	4- Irreversible injury in a way that it will be very difficult to continue work after healing, if possible at all.			
91	Severity of harm (S)	- S1 : slight injury (usually reversible), for example, scratches, laceration, bruising, light wound requiring first aid		- S2 : serious injury (usually irreversible, including fatality), for example, broken or torn-out or crushed limbs, fractures, serious injuries requiring stitches, major musculoskeletal troubles (MST), fatalities					
48	Qualitative measures of impact	5 : Insignificant – No injuries, low financial loss, negligible environmental impact	4: Minor – First aid treatment, on-site release immediately contained, medium financial loss	3: Moderate – Medical treatment required, on-site release contained with outside assistance, high financial loss	2: Major – Extensive injuries, loss of production capability, off-site release contained with outside assistance and little detrimental impact, major financial loss			1: Catastrophic – Death, toxic release off-site with detrimental effect, huge financial loss	
1	Hazard in term of the potential to cause harm	1: Slight – less than 3 days lost time			2: Serious – over 3 days lost time	3: Major – death or serious injury			
3	Severity of	Superficial injuries – minor cuts and		Lacerations –	Fatal injuries – amputations, multiple injuries, major fractures				

		Levels							
Tools	Severity of harm	S1 slight injuries (bruises) requiring no first aid	S2 slight injuries requiring first aid but without lost time	S3 injuries requiring more than first aid and with lost time	S4 irreversible harm, slight disability but able to return to same job	S5 serious disability, able to return to work but perhaps not to the same job	S6 permanent disability and can no longer work	S7 single death	S8 multiple deaths
	harm	bruises, eye irritation from dust		burns, concussion, serious sprains, minor fractures					
6	Worst likely outcome	Environmental – plant damage i.e. no injury	Minor injury		Major injury – permanent disability including permanent ill health			Fatality	
7	Consequences (severity)	Minor		Major		Severe		Fatal	
10	Severity class	1: Minor: possible injury to plant personnel, near-miss incident		2: Appreciable: injury to plant personnel, reportable near miss incident under CIMAH Regulations	3: Major: injuries to less than five plant personnel with one in ten chance of fatality		4: Severe: more than five injuries or one fatality of plant personnel, a one in 10 chance of a public injury		5: Catastrophic: three or more fatalities of plant personnel, more than five injuries or fatality of member of public
17	Consequences or potential severity of injury	VI – Insignificant	V – Minor	IV – Major		III – Severe		II – Fatality	I – Multiple fatalities
19	Severity (of the possible harm)	1: Slight (normally reversible) injury or damage to health			2: Serious (normally irreversible) injury or damage to health			3: Death	
24	Severity of harm	Minor – no injury or slight injury requiring no more than first aid (little or no lost work time)		Moderate – significant injury or illness requiring more than first aid (able to return to same job)	Serious – severe debilitating injury or illness (able to return to work at some point)		Catastrophic – death or permanently disabling injury or illness (unable to return to work)		
33	Severity of injury or illness	Moderate injury or illness			Serious injury or illness		Death / grievous injury or illness		
34	Severity level	Low – other injury or illness	Medium – Injury or illness causing short-term disability			High – Fatality, major injuries or illness causing long-term disability			

		Levels							
Tools	Severity of harm	S1 slight injuries (bruises) requiring no first aid	S2 slight injuries requiring first aid but without lost time	S3 injuries requiring more than first aid and with lost time	S4 irreversible harm, slight disability but able to return to same job	S5 serious disability, able to return to work but perhaps not to the same job	S6 permanent disability and can no longer work	S7 single death	S8 multiple deaths
35	Consequences (qualitative impact measures)	5: Insignificant – no injuries, low financial loss, negligible environmental impact	4: Minor – First aid treatment, on-site release immediately contained, medium financial loss	3: Moderate – medical treatment required, on-site release contained with outside assistance, high financial loss	2: Major – extensive injuries, loss of production capability, off-site release contained with outside assistance and little detrimental impact, major financial loss			1: Catastrophic – death, toxic release off-site with detrimental effect, huge financial loss	
41	Levels of severity of harm	4: Negligible – does not result in injury, occupational illness, or system or environmental damage	3: Low – Minor injury, minor occupational illness, or minor system or damage		2: Medium – severe injury, severe occupational illness, or major system or environmental damage			1: High – death, system loss, or severe environmental damage	
44	Suggested mishap severity categories	IV Negligible – could result in injury or illness not resulting in a lost work day, loss exceeding $2K but less than $10K, or minimal environmental damage not violating law or regulation		III Marginal – could result in injury or occupational illness resulting in one or more lost work days(s)	II Critical – could result in permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel			I Catastrophic – could result in death, permanent total disability, loss exceeding $1M, or irreversible severe environmental damage that violates law or regulation	
45	Hazard severity	VI Negligible – little or no adverse impact on mission capability. First aid or minor medical treatment (accident risk). Slight equipment or system damage, but fully functional and serviceable. Little or no property or environmental damage		III Marginal – degraded mission capability or unit readiness	II Critical – significantly (severely) degraded mission capability or unit readiness. Permanent partial disability, temporary total disability exceeding 3 months time (accident risk)			I Catastrophic – loss ability to accomplish the mission or mission failure. Death or permanent total disability (accident risk)	
46	Hazard severity	Category IV – the hazard presents a minimal threat to personnel safety or health, property, national, service or command interests or efficient use of assets	Category III – the hazard may cause minor injury, illness, property damage, damage to national, service or command interest or degradation to efficient use of assets		Category II – the hazard may cause severe injury, illness, property damage, damage to national or service interests or degradation to efficient use of assets			Category I – the hazard may cause death, loss of facility/asset or result in grave damage to national interests	
53	Sévérité (S)	2 – blessure mineure requérant seulement les premiers soins (<1K$)		6 – Blessure majeure résultant en cas consignable (>1K$, <10K$) 12 – blessure majeure résultant en fatalité, maladie ou blessure avec perte de temps (>10K$)					
55	Severity of harm	4 – negligible : less than minor injury or occupational illness		3 – marginal : minor injury or occupational illness	2 – critical : severe injury or occupational illness			1 – catastrophic : death	

		Levels							
Tools	Severity of harm	S1 slight injuries (bruises) requiring no first aid	S2 slight injuries requiring first aid but without lost time	S3 injuries requiring more than first aid and with lost time	S4 irreversible harm, slight disability but able to return to same job	S5 serious disability, able to return to work but perhaps not to the same job	S6 permanent disability and can no longer work	S7 single death	S8 multiple deaths
57	Severity of harm	1 – reversible, first aid		2 – reversible, medical attention	3 – permanent, loosing fingers		4 – death, losing an eye or arm		
58	Conséquence	pas de blessure	premiers soins: premiers soins administrés sur place sans perte de temps	perte de temps: traitement médical hors site ou perte de temps de courte durée (jours)	blessure importante: traumatisme important, perte de temps de longue durée (semaines)			Décès	
66	Hazard severity level	Insignificant : possible minor injury		Marginal : minor injury and/or significant threat to the environment	Critical : single fatality and/or severe injury and/or significant damage to the environment				Catastrophic: fatalities and/or multiple severe injuries and/or major damage to the environment
69	Severity of harm	Low : trivial harm with no permanent results		Middle: serious harm with no permanent results	High: serious harm with permanent results, death				
85	Severity	S4 – on site: potential minor injuries, or irritation		S3 – on site: potential for one or more lost time injuries	S2 – on site: potential for one or more serious injuries (irreversible)			S1 – on site: potential for one or more fatalities	
89	How severe the injury could be (consequence)	Minor: first aid only, no lost time		Major: maiming, significant injury, not permanent	Catastrophic: kills, disables, permanent injury				
94	Severity	Negligible	Minor		Major			Catastrophic	
102	Severity (estimate how serious such an accident)	I Minor: means that the consequences are not very serious	II Significant: means that works has to stop, first aid is really needed		III Disastrous: means that there has been a very serious accident (someone has been scarred for life, blinded or even killed)				
114	Severity of harm	Slight: first aid needed but no time of work or change of duties required		Temporary: injury or ill-heath requiring time-off work from which	Permanent: disability or health impairment which is normally irreversible, having impact on quality of life			Death: injury or damage to health resulting, within a short period, in the death of operator and/or any other person in vicity	

		Levels							
Tools	Severity of harm	S1 slight injuries (bruises) requiring no first aid	S2 slight injuries requiring first aid but without lost time	S3 injuries requiring more than first aid and with lost time	S4 irreversible harm, slight disability but able to return to same job	S5 serious disability, able to return to work but perhaps not to the same job	S6 permanent disability and can no longer work	S7 single death	S8 multiple deaths
				essentially a full recovery normally expected (i.e. no loss of quality of life)					

4.2.1 Terminology

Severity of harm (as defined in ISO 14121) is expressed in numerous ways in the different tools, e.g. "*severity of injury*, *hazard in term of potential to cause harm*, *worst likely outcome* or *consequences*". It was observed that the severity of harm is linked to the type or source of the tool. For example, tools 48 and 35 were taken from risk management standards and they used "*qualitative measures of impact*" since the tools estimate injury but also financial loss, toxic release and its impact. Moreover, tool 6 uses "*worst likely outcome*" since environmental or plant damage is included. Tool 44 is from a military standard and uses "*suggested mishap severity categories"* since environmental and financial damage are also included. Lack of homogeneity in the terminology for this parameter was observed but could be explained. This could raise the question to whether these tools are appropriate to estimate risks associated with machinery.

4.2.2 Construction of the equivalence scales for severity of harm

The construction of this table was challenging since the tools defined this parameter differently and with different levels. Two additional columns were added namely S1: Scratches without first aid and S8: Multiple deaths. The addition of the first column was necessary since many tools possess this level. The addition of the last column was required to accommodate tools 10, 17 and 66 which included multiple deaths.

It was observed that the severity of harm was described in various ways in the tools. Various factors which were often mixed together were being used. Examples of those factors were:

- First aid;
- Loss of work time;
- Extent of harm or impact on the physical integrity;
- Reversibility of harm;
- Disability;
- Number of persons injured;
- System damage financial loss; and
- A single worded qualitative description (major, negligible, etc.).

4.2.3 General equivalence scales for severity of harm from the tools

The setting up of an equivalence scale for this parameter has led to the definition of eight approximate thresholds for this parameter based on the tools which were analyzed. These thresholds are:

- S1 which corresponds to slight injuries (bruises) requiring no first aid (e.g., superficial injuries, minor cuts and bruises, eye irritation from dust);
- S2 which corresponds to slight injuries requiring first aid but without lost time (e.g., superficial burns);
- S3 which corresponds to injuries requiring more than first aid (medical assistance) and with lost time (e.g., stabbing, deep cuts, minor fractures, burns);
- S4 which corresponds to irreversible harm, slight disability but able to return to same job (e.g., loss of part of the finger);
- S5 which corresponds to serious disability, able to return to work but perhaps not to the same job (e.g., major fractures, losing an eye);
- S6 which correspond to permanent disability and can no longer work (e.g., amputation of arm or leg);
- S7 which corresponds to single death; and
- S8 which corresponds to multiple deaths.

4.2.4 Granularity and number of levels

From the equivalence table for the severity of harm parameter, it can be observed that the granularity or dispersion for this parameter over its range of possible values varies substantially. There exists a relationship between the amount of detail in the definitions of the thresholds and the number of thresholds needed to define the whole range of severity associated with hazardous scenarios. Tools which incorporate broad generalization and/or lots of information in one level tend to have fewer levels. For example, in the sample, tools 49 and 91 have two levels which are used to define the severity of harm. Tool 49 defines these levels as "*Slight Injury (Normally reversible; or requires only first-aid as defined in OSHA 1904.12)* and *Serious Injury (Normally irreversible; or fatality; or requires more than first-aid as defined in OSHA 1904.12)*". Tool 91 defines these levels as "*Mild injury (usually reversible); e.g. scratches, lacerations, bruise, light cut requiring first aid, etc* and *Serious injury (usually irreversible, including fatal) Examples: broken/crushed or amputated arm/leg; other fractures; serious cuts requiring stitches; major musculoskeletal disorders (MSDs), death, etc.*"

It is observed that both tools use the reversibility of the injury and the need for first aid as selection criteria and they both place death at the same level as serious injury. There seem to be a contradiction with Tool 49 where a broken finger or limb is reversible but requires more than first aid and a cut is reversible and can require more than first aid. However, the tool also mentions that when multiple criteria can apply, the most restrictive criteria need to be used. But the use of "*or*" can make the selection criteria confusing.

Tool 91 overcomes this problem by giving some examples of injuries making the choice a bit clearer. However, the use of two levels seems insufficient since it forces permanent injury to be on the same level as death. Loss of a finger is placed at the same level as death and this can lead to potential biases in the risk indices. It was observed that in those tools, neither the concept of *loss time* nor of *return to work to the same or different job* was expressed. The majority of tools in that sample placed death in a separate category in line with ISO 14121-1 (2007) which uses three classes namely slight, serious and death to describe this parameter. Tools with three or more levels tend to place death on a separate level. For instance, tool 1 has the following levels and definitions for the severity of harm: "*1: Slight – less than 3 days lost time*; *2: Serious – over 3 days lost time* and *3: Major – death or serious injury*." It can be observed that the extent of injury and the number of days of lost time are used as the selection criteria. The assumption that the extent of injury is positively correlated to the number of days of lost time is seen in other tools as well but the number of days is not necessarily specified. Here there is a contradiction since an injury with 3 or more days lost time could be classified as serious or major. The tool is not clear about the kind of damage to health. Also, the use of the word "serious" as a level as well as in the description of a different level can be confusing.

Another tool with 3 levels for the severity parameter uses reversibility of harm as the selecting criterion. For example, tool 19 uses "*1: Slight (normally reversible) injury or damage to health*; *2: Serious (normally irreversible) injury or damage to health* and *3: Death.*" However, no examples are given and the choice is not straight forward. Injuries can be serious but reversible (e.g. a broken finger). The qualitative expressions provide few clues.

Another tool with three levels is tool 33 which uses "*Moderate injury or illness; Serious injury or illness* and *Death / grievous injury or illness*." The qualitative expressions which are used in the tool provide few clues to the user and the difference between moderate and serious is unclear. Decisions will tend to be very subjective and based on personal experience.

Tool 3 also uses 3 levels which are "*Superficial injuries – minor cuts and bruises, eye irritation from dust; Lacerations – burns, concussion, serious sprains, minor fractures;* and *Fatal injuries – amputations, multiple injuries, major fractures.*" This tool provides some examples of injuries or harm in order to guide the users. However, there is a substantial jump from lacerations to fatal injuries and permanent injury and fatality are placed on the same level.

It is also seen that tools 69 and 89 have 3 levels and the loss of part of a finger is at the same level as death and that permanent harm and death are at the same level.

Tools having four levels for severity, such as tool 57, use reversibility as well as severity or type of injury as criteria for selecting the different levels. These levels are: "*1 – reversible, first aid*; *2 – reversible, medical attention*; *3 – permanent, loosing fingers*; *4 – death, losing an eye or arm*." There seems to be a smooth transition between the levels. This tool uses the reversibility, type of treatment and extent of harm as criteria. This tool also provides additional information in the document but not in the matrix. This has been observed in some tools and inserting all information in the matrix was not easy at times (not enough space) but it needed to be done whenever possible or at least be easily identified because it facilitated the risk estimation process. For example, tool 67 uses "*1 means scratches, bruises which can be cured by a first aid* *or similar; 2 means more severe scratches, bruises, stabbing, which require medical attention from professionals; 3 means normally irreversible injury. It will be slightly difficult to continue work after healing; 4 means irreversible injury in a way that it will be difficult to continue work after healing, if possible at all.*" In this tool, additional information is found in the text and is not easily identified. Death is also not mentioned in the severity parameter of this tool.

Some tools use only the severity (extent of injury), the type of treatment needed, lost time and ability to return to work criteria and not the reversibility criteria. This approach might be better than reversibility since it takes into consideration fractures, or serious injuries which are reversible. One example is tool 24 where the levels are: "*Minor – no injury or slight injury requiring no more than first aid (little or no lost work time); Moderate – significant injury or illness requiring more than first aid (able to return to same job); Serious – severe debilitating injury or illness (able to return to work at some point)* and *Catastrophic – death or permanently disabling injury or illness (unable to return to work).*" Moreover, the use of reversibility criterion to define the severity of harm tends to limit the number of levels for this parameter to 2 and 3 levels (except for tool 57).

4.2.5 Single worded levels

The same word can be defined or used differently in different tools, although sometimes, no definitions are provided. The words can have different meanings or weights depending on the other terms used to estimate severity in that tool. An example of such a word is "*Major*" and it is found in several tools. For instance, tool 1 which has 3 levels uses "*Slight; Serious and Major*" to define its levels. Tool 10 which has 5 levels uses "*Minor; Appreciable; Major; Severe and Catastrophic*". The use of single or few and imprecise words to define the levels for the severity parameter is observed in many tools. Examples are tools 17 and 94 which use only qualitative terms without defining them or giving examples. Others, such as tools 66, 17 and 24, provide more detailed definitions for each level. The use of single words or imprecise terms can lead to different interpretations by different users and lead to inconsistencies in risk levels.

4.2.6 Inconsistent definitions

Moreover, there are tools using terms which are inappropriate when compared to the definitions provided. For example, tool 41 uses "*medium*" for "*severe injuries, severe occupational illness or major system or environmental damage*". Some tools have levels and definitions which are not consistent. For example, tool 89 uses "*major*" and defines it as "*maiming, significant injury, not permanent*". Firstly, the use of the word "*major*" is not consistent with "*not permanent*". Secondly, the use of terms such as "*maiming, significant injury and not permanent*" seems odd. The word "*medium*" instead of "*major*" might be more appropriate and the term "*not permanent*" can be removed from the definition.

4.2.7 Mixing different factors or concepts

Some tools tend to mix different concepts or factors when defining the different levels for the severity of harm. Tool 1 uses "*loss time*" for the first two levels i.e. "*Slight-less than 3 days lost time*" and "*Serious-over 3 days loss time*" and the impact on the physical integrity for the last level i.e. "*Major- death or serious injury*". Tool 58 uses extent of injury for S1 and S2 and for S5 to S8 but refers to loss time for S3 and S4.

4.3 Equivalence scale for the probability of harm

The probability of harm is used in 23 out of the 31 selected tools. The equivalence scales were set up for this parameter and the results are shown in Table 5. This resulted in seven approximate thresholds for this parameter.

- Ph1: Nearly impossible to occur (improbable, unlikely);
- Ph2: Unlikely to occur but possible;
- Ph3: Could occur but not expected;
- Ph4: Could occur, not unexpected (possible);
- Ph5: Near certain to occur;
- Ph6: Will occur at least once; and
- Ph7: Will occur frequently (very likely).

Table 5: Equivalence scales for the probability of harm

<table>
<tr><th></th><th></th><th colspan="7">Levels</th></tr>
<tr><th>Tools</th><th>Probability of harm</th><th>Ph1 Nearly impossible to occur</th><th>Ph2 Unlikely to occur but possible</th><th>Ph3 Could occur but not expected</th><th>Ph4 Could occur, not unexpected (possible)</th><th>Ph5 Near certain to occur</th><th>Ph6 Will occur at least once</th><th>Ph7 Will occur frequently</th></tr>
<tr><td>48</td><td>Qualitative measures of likelihood</td><td colspan="2">E – Rare – Occurs only in exceptional circumstances</td><td>D – Unlikely – Could occur but not expected</td><td>C – Possible – Could occur</td><td>B – Likely – Will probably occur in most circumstances</td><td colspan="2">A – Almost certain – Is expected to occur in most circumstances</td></tr>
<tr><td>1</td><td>Likelihood to cause harm</td><td colspan="3">1: Low – unlikely</td><td>2: Medium – possible</td><td colspan="3">3: High – probable</td></tr>
<tr><td>3</td><td>Likelihood of harm</td><td colspan="4">Very unlikely – Less than 1% chance of being experienced by an individual during their working lifetime</td><td>Unlikely – Typically experienced once during the working lifetime of an individual</td><td>Likely – Typically experienced once every five years by an individual</td><td>Very likely – Typically experienced at least once every six months by an individual</td></tr>
<tr><td>6</td><td>Probability or likelihood of harm occurring</td><td>Improbable – so unlikely that probability is close to zero</td><td colspan="2">Remote – unlikely, though conceivable</td><td>Possible – could occur sometime</td><td colspan="2">Probable – not surprised, will occur several times</td><td>Likely / frequent – occurs repeatedly / event only to be expected</td></tr>
</table>

		Levels						
Tools	Probability of harm	Ph1 Nearly impossible to occur	Ph2 Unlikely to occur but possible	Ph3 Could occur but not expected	Ph4 Could occur, not unexpected (possible)	Ph5 Near certain to occur	Ph6 Will occur at least once	Ph7 Will occur frequently
7	Likelihood (chances)	Remote	Improbable	Possible		Probable	Likely	
10	An acceptable annual frequency of each severity category	$1x10^{-5}$ per year $1x10^{-4}$ per year	$1x10^{-3}$ per year	$1x10^{-2}$ per year		$1x10^{-1}$ per year		
24	Probability of occurrence of harm	Remote – so unlikely as to be near zero	Unlikely – not likely to occur		Likely – may occur	Very likely – near certain to occur		
33	Likelihood of occurrence (of injury)	Not likely, but possible			Likely	Very likely		
34	Likelihood level	Low – very seldom or never occurs			Medium – reasonably likely to occur	High – certain or near certain to occur		
35	Likelihood (Qualitative likelihood measures)	E: Rare – occurs only in exceptional circumstances		D: Unlikely – could occur but not expected	C: Possible – could occur	B: Likely – will probably occur in most circumstances	A: Almost certain – is expected to occur in most circumstances	
41	Level of probability of the occurrence of harm	F- Highly improbable – probability cannot be distinguished from zero	E- Improbable – very unlikely to occur in the life cycle	D- Remote – unlikely but may possibly occur in the life cycle	C- Occasional – likely to occur at least once in the life cycle		B- Probable – likely to occur several times in the life cycle	A- Highly probable – likely to occur frequently in the life cycle
44	Suggested mishap probability levels (potential occurrences)	E: Improbable – so unlikely, it can be assumed occurrence may not be experienced, with a probability of occurrence less than 10^{-6} in that life	D: Remote – unlikely but possible to occur in the life of an item, with a probability of occurrence less than 10^{-3} but greater than 10^{-6} in that life		C: Occasional – likely to occur some time in the life of an item, with a probability of occurrence less than 10^{-2} but greater than 10^{-3} in that life		B: Probable – will occur several times in the life of an item, with a probability of occurrence less than 10^{-1} but greater than 10^{-2} in that life	A: Frequent – likely to occur often in the life of an item, with a probability of occurrence greater than 10^{-1} in that life

		Levels						
Tools	Probability of harm	Ph1 Nearly impossible to occur	Ph2 Unlikely to occur but possible	Ph3 Could occur but not expected	Ph4 Could occur, not unexpected (possible)	Ph5 Near certain to occur	Ph6 Will occur at least once	Ph7 Will occur frequently
45	Accident probability Individual soldier, and all soldiers exposed-definitions vary	E: Unlikely – can assume will not occur, but not impossible		D: Seldom – remotely possible, could occur at some time		C: Occasional – occurs sporadically	B: Likely – occurs several times	A: Frequent – occurs very often, continuously experienced
46	Mishap probability	Sub-category D – unlikely to occur			Sub-category C – may occur in time. Can reasonably be expected to occur some time to an individual item or person or several times to a fleet, inventory or group.		Sub-category B – probably will occur in time. Expected to occur several times to an individual item or person or frequently to a fleet, inventory or group	Sub-category A – likely to occur immediately or within a short period of time. Expected to occur frequently to an individual item or person or continuously to a fleet, inventory or group.

<table>
<tr><th></th><th></th><th colspan="7">Levels</th></tr>
<tr><th>Tools</th><th>Probability of harm</th><th>Ph1
Nearly impossible to occur</th><th>Ph2
Unlikely to occur but possible</th><th>Ph3
Could occur but not expected</th><th>Ph4
Could occur, not unexpected (possible)</th><th>Ph5
Near certain to occur</th><th>Ph6
Will occur at least once</th><th>Ph7
Will occur frequently</th></tr>
<tr><td>58</td><td>Probabilité de chaque évènement dangereux (en supposant que l'évènement dangereux ici veut dire dommage)</td><td colspan="2">Peu plausible: très peu probable : aucun membre de l'équipe n'a jamais entendu parler d'un tel évènement dans l'industrie</td><td>Improbable : peu probable mais peut exceptionnellement se produire : un membre de l'équipe connait quelqu'un à qui cet évènement est arrivé</td><td colspan="3">Occasionnel : peut parfois se produire : l'évènement est arrivé à un membre de l'équipe au cours des deux dernières années</td><td>Probable : peut se produire souvent : l'évènement arrive à tous les membres de l'équipe au moins une fois par année

Fréquent : occurrence régulière ou continue : l'évènement arrive souvent à tous les membres de l'équipe lorsqu'ils exécutent cette activité</td></tr>
<tr><td>66</td><td>Frequency of occurrence of hazardous events</td><td>Incredible: extremely unlikely to occur. It can be assumed that the hazard may not occur</td><td colspan="2">Improbable: unlikely to occur but possible. It can be assumed that the hazard may exceptionally occur</td><td colspan="2">Remote: likely to occur sometime in the system life cycle. The hazard can reasonably expected to occur</td><td>Occasional: likely to occur several times. The hazard can be expected to occur several times</td><td>Probable: will occur several times. The hazard can be expected to occur often

Frequent: likely to occur frequently. The hazard will be continually experienced.</td></tr>
</table>

		Levels						
Tools	Probability of harm	Ph1 Nearly impossible to occur	Ph2 Unlikely to occur but possible	Ph3 Could occur but not expected	Ph4 Could occur, not unexpected (possible)	Ph5 Near certain to occur	Ph6 Will occur at least once	Ph7 Will occur frequently
85	Probability of harm (frequency classes)	P4 - not plausible (less than once per 10 000 years)	P3 – Never happened, but is thinkable (approx. Once in 1000 years)		P2 – Almost happened, near miss (approx. Once in 100 years)	P1 – happened once (approx. once in 10 years)		P0 – happened a couple of times (once per year or more often)
89	Likelihood of the hazard causing an injury (Probability)	Very unlikely: could happen but probably never will		Unlikely: could happen but rare		Likely: could happen occasionally		Very likely: could happen frequently
94	Frequency of occurrence	Improbable	Remote		Occasional	Probable		Frequent
102	Likelihood of an accident happening	1: Unlikely: means that there is a very small chance of the hazard causing an accident			2: Probable: means that there is a good chance that there is an accident	3: Certain: means that an accident is almost certain		
114	Probability of occurrence of harm	Remote: incidents not foreseen	Unlikely: incidents not known but feasible		Likely: incidents have occurred	Very likely: incidents almost inevitable		

4.3.1 Terminology

The probability of harm is sometimes referred to as "*probability of occurrence of a hazardous event*" in tool 58, as "*the frequency of occurrence*" in tool 94, as "*likelihood*" in tools 35 and 7, as "*likelihood level*" in tool 34, as "*qualitative measures of likelihood*" in tool 48, as "*an acceptable annual frequency of each severity category*" in tool 10, as "*likelihood of occurrence (of injury)"* in tool 33 and as *frequency of occurrence of hazardous events* in tool 66. There is the need to have a uniform terminology for this parameter.

4.3.2 Graduation discrepancies

The majority of tools use qualitative description for this parameter. However, there are graduation problems and examples are as follows: tool 7 uses "*<u>Remote</u>, Improbable, Possible, Probable and <u>Likely</u>*"; tool 6 uses "*Improbable, <u>Remote</u>, Possible, Probable, <u>Likely</u>/frequent"*;

tool 24 uses "*Remote, Unlikely, Likely, Very likely*"; tool 3 uses "*Very unlikely, Unlikely, Likely, Very likely;* tool 48 uses "*Rare, Unlikely, Possible, Likely, Almost certain*" and tool 41 uses "*Highly improbable, Improbable, Remote, Occasional, Probable, Highly probable*".

4.3.3 Number of levels

All the tools use 3 or more levels to describe this parameter. The three equivalent levels or thresholds which are most commonly found in the tools are:

- Ph1: Nearly impossible to occur (improbable, unlikely);
- Ph4: Could occur, not unexpected (possible); and
- Ph7: Will occur frequently (very likely).

4.3.4 Single worded definitions

Two tools (tools 7 and 94) provide little guidance on the choice of the different levels for this parameter by having one word per level to describe them. However their first two levels have interchanged the definitions (i.e. "*remote*", "*improbable*" in tool 7 and "*improbable*", "*remote*" in tool 94).

4.3.5 Qualitative and quantitative definitions

Tools provide definitions with some descriptions which guide their users. There are also some tools which provide quantitative definitions with probabilities which can be of three types:

- Probability over the lifetime of the item (e.g. tool 44);
- Probability over the lifetime of the individual (e.g. tool 3); and
- Probability expressed annually (e.g. tool 10).

The probability over the life cycle of the item can be challenging since the lifetime of the item is not known and have to be assumed. The use of the probability over the life time of the individual can also be difficult since it is unclear if the tools are referring to the working life time or not.

4.3.6 Tools combining two levels

Tools 58 and 66 have a construction problem since they combine Ph6 and Ph7. For example, tool 66 has the following two levels which are equivalent:

- *Probable: will occur several times. The hazard can be expected to occur often* and
- *Frequent: likely to occur frequently. The hazard will be continually experienced.*

In general, it was observed that the amount of uncertainty associated with this parameter, as compared to severity, tend to make the setting up of the equivalence scales and therefore selection of the levels by users more difficult.

4.4 Equivalence scale for the frequency of exposure

The frequency of exposure parameter is found in 9 of the 31 tools. The equivalence scales for this parameter is presented in Table 6. The positioning of the tools has required the addition of columns to the table. Tools 67 and 114 needed Exf8 to be defined for the continuous exposure level.

Table 6: Equivalence scale for the frequency of exposure parameter

<table>
<tr><th></th><th></th><th colspan="8">Levels</th></tr>
<tr><th>Tools</th><th>Frequency of exposure</th><th>Exf1 Frequency less than once per year</th><th>Exf2 Annual frequency</th><th>Exf3 Monthly frequency</th><th>Exf4 Weekly frequency</th><th>Exf5 Daily frequency, once to twice per day</th><th>Exf6 Betw. twice per day to once per 2 hours</th><th>Exf7 Betw. once per 2 hours and once per hour</th><th>Exf8 Several times per hour</th></tr>
<tr><td>49</td><td>Exposure</td><td colspan="4">E1 : Infrequent exposure (Typically exposure to the hazard less than once per day or shift)</td><td colspan="4">E2 : Frequent exposure (Typically exposure to the hazard more than once per hour)</td></tr>
<tr><td>67</td><td>Average interval between frequency of exposure its duration (Fr)</td><td>1- Interval between exposure is more than a year</td><td colspan="2">2- Interval between exposure is more than two weeks but less than or equal to a year</td><td>3- Interval between exposure is more than a day but less than or equal to two weeks</td><td colspan="3">4- Interval between exposure is more than an hour but less than or equal to a day. Where the duration is shorter than 10 min, the value may be decreased to the next level</td><td>5- Interval less than or equal to an hour. This value is not to be decreased at any time</td></tr>
<tr><td>91</td><td>Frequency and/or duration of exposure to hazard</td><td colspan="5">F1: Twice or less per work shift or less than 15 min cumulated exposure per work shift</td><td colspan="3">F2: More than twice per work shift or more than 15 min cumulated exposure per work shift</td></tr>
<tr><td>19</td><td>Frequency of exposure of persons to the hazard</td><td colspan="5">1 : seldom to quite often</td><td colspan="3">2 : frequent to continuous</td></tr>
<tr><td>53</td><td>Potentiel relié à la fréquence d’activité (PFA)</td><td colspan="4">1 – hebdomadaire</td><td colspan="2">2 – deux fois par jour au maximum</td><td colspan="2">3 – toutes les deux heures ou plus</td></tr>
</table>

		Levels							
Tools	Frequency of exposure	Exf1 Frequency less than once per year	Exf2 Annual frequency	Exf3 Monthly frequency	Exf4 Weekly frequency	Exf5 Daily frequency, once to twice per day	Exf6 Betw. twice per day to once per 2 hours	Exf7 Betw. once per 2 hours and once per hour	Exf8 Several times per hour
55	Frequency of exposure	4 – improbable : so unlikely, it can be assumed occurrence may not be experienced	3 – remote : yearly or at least once during the life of the machine or system	2 – occasionnal : monthly		1 – frequent : daily			
57	Frequency	1 – Less	2 – Yearly	3 – Monthly	4 – Weekly	5 – Daily			
69	Exposure to harm	Low : seldom or very short exposure to harm				Middle: often or short to longer exposure to harm			
114	Frequency of exposure	Rare: exposure not anticipated during normal use	Occasional : exposure possible during normal use			Frequent: exposure at least once a day			Continuous: exposure every use or all the time during use

The equivalence scale has defined 8 approximate thresholds or levels namely:

- Exf1: Frequency less than once per year;
- Exf2: Annual frequency;
- Exf3: Monthly frequency;
- Exf4: Weekly frequency;
- Exf5: Daily frequency, once to twice per day;
- Exf6: Between twice per day to once per 2 hours;
- Exf7: Between once per 2 hours and once per hour; and
- Exf8: Several times per hour (continuous)

4.4.1 Terminology

Different tools define this parameter in different ways. Tools 55 and 114 for example will refer to this parameter as the "*frequency of exposure*". Others such as tool 49 will use "*exposure*" or "*exposure to harm*" in tool 69, although in this definition, the frequency is not mentioned. An employee may be exposed to one hour as well as throughout his shift. It therefore lacks precision on the frequency or the number of times that the worker is at risk. Tool 53 proposes a definition related to potential activity, which is unrelated to the frequency of exposure. This tool gives no indication on the number of times the worker is at risk. Some tools do not provide enough information to enable the user to estimate this parameter correctly, which can lead to misinterpretation when selecting the levels.

4.4.2 Number of levels

The frequency of exposure is defined in different tools by either two, three, four or five levels. Most tools which have this parameter will use two levels, as in tools 49, 91, 19 and 69. The first level in tool 19 uses "*Seldom to quite often*" tool 49 uses "*infrequent*", and tool 69 uses "*low*". For the second level, tool 19 uses "*frequent to continuous*", tool 49 uses "*frequent exposure*" and tool 69 uses "*middle*". Tool 91 defines different levels using the work shift and uses, as the first level "*twice or less by work shift*" and as the second level "*more than twice by work shift*". Tool 53 defines three levels namely "*weekly*", "*twice a day maximum*, and "*every two hours*". Tools 55 and 114 define four levels, whereas tools 57 and 67 have five levels for this parameter.

4.4.3 Single worded and vague definitions

Tool 57 uses only words to define the frequency parameter. The number of times the worker is exposed to the hazardous situation in the given time frame is not defined and this is open to interpretations by the user.

Tool 19 uses "*seldom to quite often*" and "*frequent to continuous*" but does not specify the time scale. The number of time per year, per month, per week, day or hours is not mentioned, making the estimation of this parameter difficult and paving the way to inconsistencies in risk estimation.

Tool 53 uses the term "*weekly*" at its first level, but does not specify the number of times. This is unclear since a worker can be exposed to hazardous situations once or more per week. So the user will have to define it and each person may interpret it differently.

4.5 Equivalence scale for the duration of exposure

This parameter is found in 5 of the 31 tools. The equivalence scale for this parameter is shown in Table 7. The positioning of the tools has required the addition of columns to this table. Tools 17, 19 and 62 needed Exd5 to be defined for the continuous exposure level.

Table 7: Equivalence scale for the duration of exposure parameter

		Levels				
Tools	Duration of exposure	Exd1 < 1/20 of the worktime (shift)	Exd2 1/10 of the worktime (45 mins/8h)	Exd3 1/5 of the work time (90 mins/8h)	Exd4 Half of the worktime 4h/8h	Exd5 Continuous during worktime
62	Indice de fréquence et durée de l'exposition aux phénomènes dangereux (e)	- e = 1 : 2 heures/ semaine (1 jour/mois)	- e = 2 : 4 heures/ semaine (1/2 jour/semaine)	e = 3 : 8 heures/ semaine (1 jour/semaine)	- e = 4 : 20 heures/ semaine (Mi-temps)	- e = 5 : 40 heures/ semaine (Temps complet)
69	Duration to harm	Low : seldom or very short exposure to harm	Middle: often or short to longer exposure to harm			
91	Duration of exposure to hazard (F)	F1: Twice or less per work shift or less than 15 min cumulated exposure per work shift	F2: More than twice per work shift or more than 15 min cumulated exposure per work shift			
17	Exposure to hazard (% of time based on 24hr day)	Less than or equal to 1%	More than 1% to 25%			More than 25% to 100% Note: 25% is an 8 hour shift of continuous exposure to hazard
19	Duration of exposure of persons to the hazard	Seldom to quite often				Frequent to continuous

The equivalence scale for the duration of exposure parameter has resulted in the definition of 5 approximate thresholds namely:

- Exd1: < 1/20 of work time;
- Exd2: 1/10 of work time (45 min per 8 hour shift);
- Exd3: 1/5 of work time (90 min per 8 hour shift);
- Exd4: half of work time (1/2) (4 hours per 8 hour shift); and
- Exd5: continuous during work time.

4.5.1 Terminology

The parameter is defined uniformly and correctly. For instance, tool 69 uses “*duration to harm*”, tool 91 uses “*duration of exposure to hazard*”, and tool 19 uses “*duration of exposure of persons to the hazard*”. Thus the definitions for this parameter are clear.

4.5.2 Number of levels

Three tools use two levels to define the duration of exposure parameter. Tools 69 and 91 use “*short exposure*” and “*long exposure*” for their two levels. Tool 19 defines the two levels differently and uses “*Seldom to quite often*” and “*Frequent to continuous*”, which are in fact unrelated to the duration of exposure. Tool 62 defines 5 levels which are actual exposure times.

4.5.3 Vague definitions for the levels of the duration of exposure parameter

Five tools in the sample use the duration of exposure. The absence of a time scale is a problem for users. Tool 69 uses the terms “*very short exposure*” and “*short to long exposure*” to define the two levels of the duration of exposure parameter. Tool 17 defines this parameter as a percentage but mentions that “*25% is an 8 hour shift of continuous exposure to hazard*” which is incorrect.

4.6 Equivalence scale for the possibility of avoidance

The possibility of avoidance of harm parameter is found in 8 of the 31 tools. The equivalence scale for this parameter is shown in Table 8. The positioning of the tools has required the addition of columns to the table. Tools 57, 67, 91 and 114 needed A6 to be defined for the impossible level.

Table 8: Equivalence scale for the avoidance parameter

		Levels					
Tools	Possibility of avoidance	A1 Easy	A2 Probable	A3 Possible	A4 Possible under certain conditions	A5 Improbable	A6 Impossible
49	Avoidance	A1: Likely (Can move out of way; or sufficient warning/reaction time; or robot speed less than 250 mm/sec)				A2: Not likely (Cannot move out of way; or inadequate reaction time; or robot speed greater than 250 mm/sec)	
62	Indice de possibilité d’évitement ou de limitation du dommage (L)	L = 1 : si – danger perceptible et instruction périodique et bonne qualification du personnel		L = 3 : si 1 à 2 critères du niveau 1 ne sont pas satisfaits		L = 5 : si – danger non perceptible et pas d’instruction et qualification insuffisante du personnel	

		Levels					
Tools	Possibility of avoidance	A1 Easy	A2 Probable	A3 Possible	A4 Possible under certain conditions	A5 Improbable	A6 Impossible
67	Possibility to avoid or limit harm (Av)	1 Likely. E.g. it is likely to avoid contact with moving parts behind an interlocked guard, in most cases, should the interlocking fail where the movements continue		3 Possible. E.g. it is possible to avoid an entanglement hazard where the speed is slow			5 Impossible. E.g. it is impossible to avoid an inhalation of harmful gas hazard where there are no warning signs
91	Possibility of avoidance or reduction of the harm (A)	A1: Possible under some conditions: If parts move at a speed less than 0,25 m/s and the exposed worker is familiar with the risks and with the indications of a hazardous situation or impending hazardous event ; depending of particular conditions (temperature, noise, ergonomic, etc)					A2 : Impossible
19	Avoidance – the technical or human possibilities to avoid or limit the harm	1 : Possible under specific conditions				2: Scarcely possible	
57	Avoidance (Av)	1 – obvious	2 – likely	3 – possible		4 – rarely	5 – impossible
69	Harm avoidance	Avoidable : harm can be normally avoided				Not avoidable: harm avoidance is seldom or not possible	
114	Possibility to avoid or limit harm	Possible: for all exposed people		Possible if trained: possible for people trained to recognise warning and how best to react and warning allows sufficient time	Difficult: possible but warning may not be obvious or time is limited		Impossible: no warning and/or not enough time to react

The setting of the equivalence scale for this parameter has resulted in the definition of 6 approximate thresholds namely:

- A1: Easy;
- A2: Probable;
- A3: Possible;

- A4: Possible with certain conditions;
- A5: Improbable; and
- A6: Impossible.

4.6.1 Terminology

The definitions given in the tools to describe this parameter are clear. Examples are tool 69 which refers to this parameter as "*harm avoidance*", tool 91 which uses "*possibility of avoidance or reduction of the harm*", tool 19 which uses "*avoidance - the technical or human possibilities to avoid or limit the harm*" and tool 67 which makes use of "*possibility to avoid or limit harm*".

4.6.2 Number of levels

Tools 49, 69 and 91 define two levels for the possibility of avoidance parameter. For the first level, tool 49 uses "*likely*", tool 69 "*avoidable*" and tool 91 "*possible*". For the second level, tool 49 uses "*not likely*", tool 69 "*scarcely possible*" and tool 91 "*impossible*". Three levels are defined by tools 62 and 67. Tool 114 defines four levels and tool 57 uses five levels.

4.6.3 Vague definitions for the levels of the avoidance parameter

Tool 19 uses the notions of "*possible under specific conditions*" and "*scarcely possible*" to define the two levels for this parameter. These two terms are imprecise since no information is provided to guide the user when selecting the levels. Similar vague definitions are given in tool 69 which uses "*harm can be normally avoided*" and "*harm avoidance is seldom or not possible*" to describe the two levels.

4.6.4 Single worded definitions

Tool 57 uses only single words to define the levels for the possibility of avoidance parameter. As was mentioned previously, the use of single words makes the parameter estimation process challenging and paves the way to different interpretations by users.

4.7 Equivalence scale for the probability of hazardous event

The probability of hazardous event parameter is found in 8 of the 31 tools. The equivalence scale for this parameter is shown in Table 9.

Table 9: Equivalence scale for the probability of occurrence of hazardous event

		Levels				
Tools	Probability of occurrence of hazardous event	Pe1 Negligible	Pe2 Rare	Pe3 Possible	Pe4 Probable	Pe5 Frequent
62	Indice de probabilité d’occurrence d’un événement dangereux (po)	- po = 1 : événement difficilement imaginable (mesures conformes à l’état de la technique	- po = 2 : événement imaginable, mais inhabituel (mesures prises)	- po = 3 : l’évènement est possible (mesures partiellement prises, des insuffisances évidentes)	- po = 4 : on peut s’attendre à ce que l’événement se produise (il y a un début de mesures)	- po = 5 : il faut s’attendre à ce que l’événement se produise (pas de mesures existantes)
67	Probability of occurrence of a hazard event (Pr)	1: Negligible. E.g. this kind of component never fails so a hazardous event occurs. No possibility of human mistakes	2: Rarely. E.g. it is unlikely this kind of component fails so a hazardous event occurs. Human mistakes are unlikely to occur	3: Possible. E.g. this kind of component may fail so a hazardous event occurs. Human mistakes are possible to occur	4: Likely. E.g. this kind of component will probably fail so a hazardous event occurs. Human mistakes are likely to occur	5: Very high. E.g. this kind of component is not made for this application. It will fail so a hazardous event occurs. Human behaviour is such that the likelihood of mistakes is very high
91	Probability of occurrence of the hazardous event (O)	O1: Mature technology, proven and recognised in safety application; robustness		O2 : Technical failure observed in last two years; inappropriate human action by a well trained person, aware of the risks, with more than six months experience on the work station	O3: Technical failure regularly observed (every six months or less); inappropriate human action by an untrained person, with less than six months experience on the workstation; similar accident observed in the plant since ten years	
17	The chance a hazard is likely to occur (probability level)	Extremely remote – 1 in million Improbable – 1 in 100 000	Remote – 1 in 10 000	Occasional – 1 in 1 000	Probable – 1 in 100	Frequent – 1 in 10
19	Probability of occurrence of an event which can cause harm	1: Low – so unlikely that it can be assumed occurrence may not be experienced		2: Medium – likely to occur sometime in the life of an item		3: High – likely to occur frequently
53	Potentiel relié à l’activité	1 – faible		2 – moyen		3 – haut

		Levels				
Tools	Probability of occurrence of hazardous event	Pe1 Negligible	Pe2 Rare	Pe3 Possible	Pe4 Probable	Pe5 Frequent
57	Probability of occurrence of hazardous event	1 – negligible	2 – rarely	3 – possible	4 – likely	5 – Common
69	Probability/likelihood of occurrence	Low: harm will occur very seldom		Middle: harm is possible but not necessary	High: harm is mostly consequence of exposure	

The setting of the equivalence scales for this parameter has resulted in the definition of 5 approximate thresholds namely:

- Pe1: Negligible;
- Pe2: Rare;
- Pe3: Possible;
- Pe4: Probable; and
- Pe5: Frequent.

The positioning of the tools has required the addition of columns to the table. Tools 17, 57, 62 and 67 needed Pe5 to be defined for the "*frequent*" level.

4.7.1 Terminology

Tools 91 and 57 refer to this parameter as "*probability of occurrence of hazardous event*", tool 19 uses "*probability of occurrence of an event which can cause harm*" and tool 67 defines it as "*probability of occurrence of a hazard event*". Thus the definitions for this parameter are clear, except for tool 53 which defines the parameter as "*potential related to the activity*".

4.7.2 Number of levels

The probability of occurrence of hazardous event parameter is defined by three or five levels. Four tools, namely 19, 53, 69 and 91 define this parameter using three levels. Regarding the first level, the first three tools use "*low*". Tool 91 refers to "*mature technology*". For the second level, tools 19 and 53 use "*medium*", and tool 69 uses "*middle*". Tool 91 uses "*technical failure observed in last two years*". The first three tools use "*high*" as their third level. Tool 91 describes this third level as "*technical failure or inappropriate human action by an untrained person, with less than six months experience*"

Tools 17, 57, 62 and 67 define this parameter with five consistent levels. Tool 17 uses "*extremely remote*", tools 57 and 67 use "*negligible*" and tool 62 uses "*unimaginable event*" as level one. For the second level, the definitions for the four tools are "*remote*", "*rarely*", "*event imaginable*" and "*rarely*" respectively. For the third level, tool 17 uses "*occasional*", tool 57 "*possible*", tool 62 "*event is possible*", and tool 67 "*possible*". For the fourth level, tool 17 uses "*probable*", tool 57 "*likely*" tool 62 "*can be expected that the event occurs*" and tool 67 "*likely*". For level five, tool 17 uses "*frequent*", tool 57 refers to "*common*", tool 62 refers to "*can be expected that the event occurs*" and tool 67 uses "*very high*".

4.7.2.1 Single worded and vague definitions

Tools 53 and 57 use single words to define the probability of occurrence of hazardous event parameter. The use of single words makes the estimation of the parameter less precise. Tool 17 uses vague probabilities to define this parameter. The use of probability can be subjective because each user can make a different interpretation.

4.8 Results of risk estimation for the different hazardous situations

The results of risk estimation for the different hazardous situations are presented and analyzed in this section. The result of estimating the risk associated with the 20 scenarios by using each of the 31 risk estimation tool is shown in Table 10. The overall risk average is 69.4% with a standard deviation of 24.8.

4.8.1 Scenarios analysis

This first analysis consisted in finding discrepancies in the distribution of the resulting risk levels among the scenarios and the tools. The average risk for the 20 scenarios was computed first. Then, the 20 scenarios were classified in terms of risk levels from low-risk scenarios to high risk scenarios according to the average of the resulting risk level obtained by the 31 tools as given in Table 10. Scenario T has the lowest standard deviation (8.2) among the scenarios and is statistically different from the other scenarios at a significance level of 5%.

Table 10 : Scenario risk levels

Tool #	# Scenario																				Average by tool
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	
17	25,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	50,0	25,0	50,0	100,0	25,0	50,0	75,0	25,0	75,0	37,5
45	20,0	20,0	20,0	40,0	20,0	20,0	40,0	40,0	20,0	40,0	60,0	60,0	40,0	40,0	60,0	40,0	40,0	80,0	60,0	100,0	43,0
6	50,0	25,0	25,0	50,0	25,0	25,0	50,0	50,0	25,0	25,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	75,0	75,0	45,0
85	28,6	14,3	14,3	28,6	42,9	42,9	28,6	28,6	42,9	42,9	57,1	57,1	57,1	57,1	57,1	57,1	57,1	42,9	71,4	85,7	45,7
19	25,0	25,0	50,0	25,0	25,0	50,0	25,0	25,0	50,0	50,0	50,0	75,0	50,0	50,0	75,0	50,0	75,0	50,0	75,0	100,0	50,0
91	33,3	66,7	50,0	33,3	33,3	50,0	66,7	33,3	66,7	50,0	33,3	33,3	33,3	50,0	33,3	50,0	66,7	100,0	33,3	100,0	50,8
46	40,0	20,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	80,0	80,0	100,0	53,0
66	25,0	25,0	25,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	75,0	75,0	50,0	75,0	75,0	100,0	75,0	75,0	56,3
1	50,0	16,7	50,0	50,0	50,0	33,3	50,0	50,0	50,0	50,0	50,0	50,0	83,3	83,3	50,0	83,3	83,3	50,0	83,3	100,0	58,3
89	50,0	50,0	50,0	66,7	50,0	50,0	66,7	66,7	50,0	66,7	66,7	66,7	66,7	66,7	66,7	66,7	66,7	83,3	66,7	83,3	63,1
62	33,3	66,7	66,7	33,3	66,7	33,3	33,3	33,3	66,7	66,7	66,7	66,7	66,7	66,7	100,0	66,7	100,0	66,7	66,7	100,0	63,3
44	25,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	100,0	100,0	63,8
69	27,3	54,5	72,7	18,2	54,5	72,7	45,5	45,5	81,8	72,7	54,5	63,6	63,6	72,7	72,7	72,7	90,9	63,6	81,8	100,0	64,1
102	83,3	33,3	50,0	83,3	50,0	50,0	83,3	83,3	50,0	50,0	50,0	50,0	33,3	83,3	50,0	83,3	83,3	83,3	83,3	100,0	65,8
33	66,7	33,3	66,7	66,7	66,7	33,3	66,7	66,7	66,7	66,7	66,7	66,7	100,0	66,7	66,7	66,7	66,7	66,7	100,0	100,0	68,4
58	66,7	66,7	33,3	66,7	33,3	33,3	66,7	66,7	33,3	66,7	66,7	66,7	100,0	100,0	66,7	100,0	100,0	100,0	100,0	100,0	71,7
3	20,0	20,0	80,0	60,0	80,0	80,0	60,0	60,0	80,0	80,0	80,0	80,0	80,0	80,0	80,0	80,0	80,0	100,0	80,0	100,0	73,0
114	66,7	100,0	33,7	66,7	33,3	100,0	66,7	100,0	100,0	66,7	100,0	66,7	33,3	33,3	100,0	100,0	100,0	100,0	100,0	100,0	78,4
10	16,7	33,3	66,7	66,7	100,0	66,7	66,7	66,7	100,0	100,0	100,0	100,0	100,0	83,3	100,0	83,3	83,3	66,7	100,0	100,0	80,0
94	75,0	50,0	50,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	100,0	100,0	75,0	75,0	100,0	75,0	75,0	100,0	100,0	100,0	80,0
34	66,7	33,3	66,7	100,0	66,7	33,3	100,0	100,0	66,7	66,7	66,7	66,7	100,0	100,0	66,7	100,0	100,0	100,0	100,0	100,0	80,0
53	26,7	93,3	86,7	73,3	73,3	86,7	93,3	80,0	86,7	86,7	73,3	80,0	80,0	80,0	80,0	86,7	93,3	100,0	80,0	93,3	81,7
41	66,7	66,7	33,3	66,7	66,7	66,7	66,7	66,7	66,7	66,7	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	81,7
55	25,0	50,0	100,0	50,0	100,0	100,0	50,0	50,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	50,0	100,0	100,0	83,8
49	57,1	100,0	85,7	66,7	71,4	85,7	85,7	100,0	100,0	85,7	71,4	71,4	71,4	71,4	71,4	85,7	100,0	100,0	100,0	100,0	84,0
24	75,0	50,0	50,0	100,0	75,0	75,0	100,0	100,0	75,0	75,0	75,0	75,0	100,0	100,0	75,0	100,0	100,0	100,0	100,0	100,0	85,0
35	75,0	50,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	86,3
48	75,0	50,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	86,3
57	50,0	100,0	100,0	50,0	100,0	100,0	50,0	50,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	90,0
7	66,7	66,7	66,7	100,0	66,7	66,7	100,0	100,0	66,7	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	90,0
67	66,7	100,0	100,0	33,3	100,0	100,0	66,7	66,7	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	91,7
Average	47,7	50,2	56,7	57,6	59,4	59,5	61,9	61,9	65,6	66,6	72,5	73,6	74,8	76,4	77,4	78,5	82,9	83,3	85,0	96,4	69,4
Std dev	21,3	27,1	24,3	22,4	23,7	24,7	21,4	23,3	24,1	21,6	22,4	19,8	24,9	20,6	20,7	21,1	18,5	19,9	19,8	8,2	24,8

The 20 scenarios can be categorized in terms of risk levels as low, mid-low, mid-high and high based on the number of times that a scenario was evaluated to the lowest or highest risk level by the 31 tools. Table 11 shows the number of times a scenario was evaluated to the lowest or highest risk level, their average and standard deviation and a normalized value. Table 12 presents the resulting criteria for grouping scenarios per categories. An analysis of variance (ANOVA) of the groups showed that risk scenario categories have significantly different means (F=61.283 and p=0.000). Also, a Duncan's Multiple Range Test indicated that all the means are different. The results of the 4 categories of scenarios are analyzed below.

Table 11: Frequency of lowest and highest risk level per scenario

Category	Scenario	Count of risk levels		Average risk	Standard deviation	Normalized value
		Lowest	Highest			
Low	A	11	0	47,7	21,3	-0,88
	B	11	4	50,2	27,1	-0,78
	C	8	3	56,7	24,3	-0,51
Mid-Low	D	4	3	57,6	22,4	-0,48
	E	6	4	59,4	23,7	-0,40
	F	7	4	59,5	24,7	-0,40
	G	3	3	61,9	21,4	-0,30
	H	4	6	61,9	23,3	-0,30
	I	3	5	65,6	24,1	-0,15
	J	2	5	66,6	21,6	-0,11
Mid-High	K	1	10	72,5	22,4	0,13
	L	0	9	73,6	19,8	0,17
	M	2	12	74,8	24,9	0,22
	N	1	10	76,4	20,6	0,28
	O	1	12	77,6	20,5	0,33
	P	1	11	78,5	21,1	0,37
High	Q	0	13	82,9	18,5	0,55
	R	1	16	83,3	19,9	0,56
	S	1	16	85,0	19,8	0,63
	T	0	25	96,4	8,2	1,09

Table 12 : Scenarios per category

Risk category	Count of risk levels		Scenarios	Normalized value range
	Lowest	Highest		
Low	≥ 8	≤ 4	A to C	Below -0.5
Mid-Low	≤ 7	≤ 6	D to J	Between -0.5 and 0
Mid-High	≤ 2	> 6 and ≤ 12	K to P	Between 0 and +0.5
High	≤ 1	≥ 13	Q to T	Above +0.5

4.8.1.1 Low risk scenarios

Out of the 20 scenarios, 3 (A, B and C) are considered low-risk scenarios with an average risk level of 51.5% and a standard deviation of 24.4%. These scenarios represent situations of mechanical or radiation hazards where non life threatening harm could occur. The average and standard deviation varies from 47.7 to 56.7% and 21.3 to 27.1% respectively for the scenarios in this category. Firstly, it was observed that not too many scenarios were evaluated without both extreme risk levels (lowest and highest). When estimating the risk associated with scenario A with the 31 tools, it was found that none of the tools estimated the risk level to its highest value and only one third of the tools gave it its lowest value. Scenarios B and C were estimated at the highest risk level by 4 and 3 tools respectively, including tools 57 and 67 for both.

4.8.1.2 Mid-low risk scenarios

The second category represents mid-low risk level, with an average risk level of 61.8% and a standard deviation of 22.9%, and includes scenarios D to J. Ergonomic, material substance, mechanical, noise and pressure are the type of hazards that an individual is subjected to in these scenarios. Again, these were not life threatening situations but some might cause some irreversible damage (loss of hearing or sight). For this category the average and the standard deviation varied from 57.6 to 66.6% and 21.4 to 24.7% respectively for the different scenarios. Tools 6, 17, 19 and 45 were the one yielding risk levels to the lowest values. Highest risk levels were achieved with tools 55, 57 and 67.

4.8.1.3 Mid-high risk scenarios

The mid-high category had 6 scenarios (K to P) covering fall, mechanical, thermal and vibration hazards. However some of the scenarios resulted in the possible harm being death or amputation. The average risk level of this category is 75.5% with a standard deviation of 21.4%. The average and standard deviation for the scenarios varies from 72.5 to 78.5% and 19.8 to 24.9% respectively for the tools in this category. For the scenarios in this category, tools 17, 91 and 114 each gave the lowest risk values, respectively 3, 4 and 2 times as shown in Table 10. Seven tools (7, 35, 41, 48, 55, 57 and 67) gave the highest risk level or the one just below the highest risk level for those scenarios.

4.8.1.4 High risk scenarios

The last category corresponds to 4 high risk level scenarios (Q to T) with an average risk level of 86.9% and a standard deviation of 17.9%. The scenarios involved possible death or amputation due to material substance, mechanical or thermal hazards. The average and standard deviation of the scenarios in this category varies from 82.9 to 96.4% and 8.2 to 19.9% respectively. The standard deviation is the lowest of the 4 categories. Interestingly, tool 17 gave its lowest risk level to scenario S, while 16 tools gave their highest risk level to this scenario. Scenario T has the lowest standard deviation (8.2) of the category since most of the tools score the highest risk level.

4.8.2 Tools analysis

A similar analysis was repeated for the tools. A box plot of the result is presented in Figure 4. It provides a visual representation of the data set by showing the median (shown as diamond), Q1 or 25th quartile and Q3 or 75th quartile (yellow bar) and the minimum and maximum values (single line). A median of 100% is possible when more than half of the data points have the same maximum value. In such cases, like for tools 7, 55, 57, 67, 114, the median, Q3 and max are all equal. Table 13 shows the number of times a tool estimated the lowest or highest risk level for the 20 scenarios. Here it is less obvious to find criteria to group the tools based on the frequency of lowest or highest risk level or by looking at the tools average risk compared to the overall average risk of 69.4%. However, they can be grouped into three categories such as low, intermediate and high estimating tools based on the normalized value. The tools in the low estimating group have a normalized value under -0.3, the tools in the intermediate estimating group have a normalized value between -0.3 and 0.3, and the tools in the high estimating group have a normalized value above 0.3. An ANOVA confirmed that there are significant differences between the means of the groups (F=176.6 and p=0.000). Moreover, a Duncan's Multiple Range Test corroborated that averages of the groups are significantly different from each other. The results of the 3 categories of tools are examined next.

4.8.2.1 Low estimating tools

Low estimating tools are tools with an average risk for the scenarios that is lower than the overall average. The 9 tools (1, 6, 17, 19, 45, 46, 66, 85 and 91) in this category have an average of 48.8% with a standard deviation of 20.6%. The average and standard deviation of the tools varies from 37.5 to 58.3% and 15.5 to 21.8% respectively. Moreover, they reach the highest level of risk not more than once for the scenarios (except for tool 91) even though, previously, 4 scenarios had been defined as high risk.

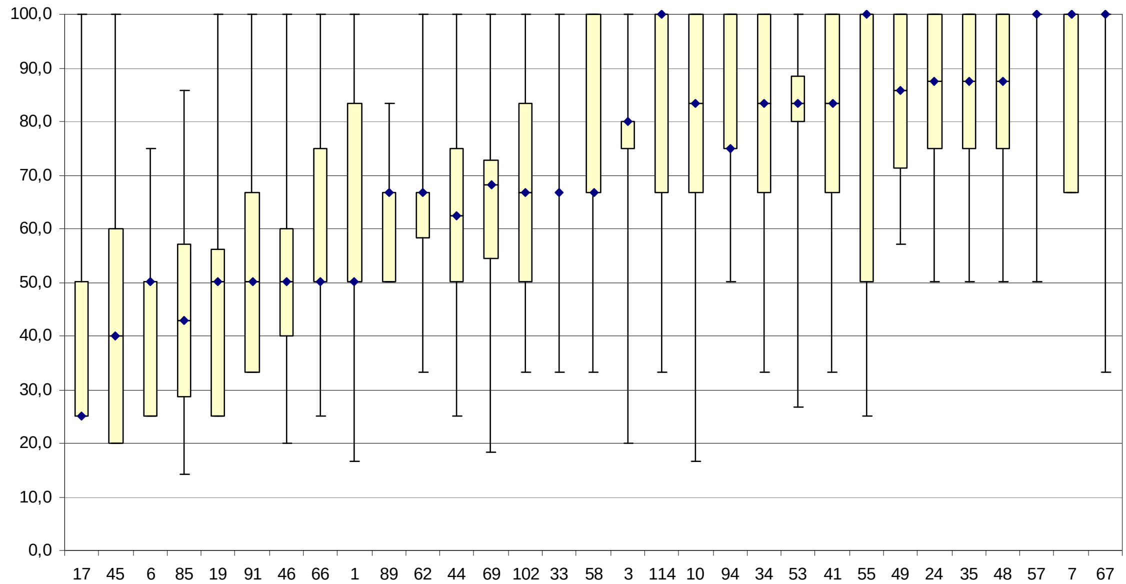


Figure 4 : Box plot of risk per tool

LEGEND: Diamond (Median); Yellow bar (Q1 or 25th quartile and Q3 or 75th quartile); and Single line (minimum and maximum values)

Table 13: Frequency of lowest and highest risk level per tools

Group	Tool #	Count of risk level		Average risk	Standard deviation	Normalized value
		Lowest	Highest			
Low estimating tools	17	14	1	37,5	22,2	-1,29
	45	6	1	43,0	21,8	-1,06
	6	6	0	45,0	15,4	-0,98
	85	2	0	45,7	18,3	-0,96
	19	6	1	50,0	21,5	-0,78
	91	9	2	50,8	21,3	-0,75
	46	1	1	53,0	18,7	-0,66
	66	3	1	56,3	19,7	-0,53
	1	1	1	58,3	20,6	-0,45
Intermediate estimating tools	89	0	0	63,1	10,2	-0,26
	62	5	3	63,3	21,4	-0,24
	44	1	2	63,8	19,0	-0,23
	69	0	1	64,1	19,9	-0,21
	102	0	1	65,8	20,6	-0,14
	33	2	3	68,4	17,0	-0,04
	58	4	7	71,7	24,8	0,09
	3	2	2	73,0	20,8	0,15
High estimating tools	114	4	11	78,4	27,1	0,36
	10	1	9	80,0	23,9	0,43
	94	0	6	80,0	15,4	0,43
	34	2	10	80,0	22,7	0,43
	53	0	1	81,7	15,0	0,49
	41	1	10	81,7	20,2	0,50
	55	1	14	83,8	26,0	0,58
	49	0	7	84,0	14,1	0,59
	24	0	10	85,0	17,0	0,63
	35	0	10	86,3	15,1	0,68
	48	0	10	86,3	15,1	0,68
	57	4	16	90,0	20,5	0,83
	7	0	14	90,0	15,7	0,83
	67	1	16	91,7	18,3	0,90

4.8.2.2 Intermediate estimating tools

This category of tools (3, 33, 44, 58, 62, 69, 89 and 102) is estimating the scenarios with an average of 66.6%, with a standard deviation of 19.5%. The average and standard deviation of the tools in this group varies from 63.4 to 73% and 10.2 to 24.8% respectively. Interestingly, 6 of the 8 tools in this category are 2 parameter matrix tools with the exception of tools 62 and 69 that are 4 parameter matrix tools. Tool 89 does not give its lowest or its highest risk level to any scenarios and has the lowest standard deviation (10.2%) of all the tools. This tool produces risk levels from 50% to a maximum of 83.3% for the different scenarios.

4.8.2.3 High estimating tools

The 14 high estimating tools (7, 10, 24, 34, 35, 41, 48, 49, 53, 55, 57, 67, 94 and 114) tend to produce a higher average risk level of 84.2% with a standard deviation of 19.5%. The average and standard deviation for the tools varies from 78.3 to 91.7% and 14.1 to 27.1% respectively for the 20 scenarios. It should be pointed out that tool 114 behaves differently for scenarios M and N by producing a low risk level when the other tools tend to produce a high risk. Moreover, tools 7, 57 and 67 are those producing the highest risk levels of the tools in this category with an average from 90% to 91.7%. The tools in this category include all the different tool configurations that will be reviewed in the next section.

4.8.3 Impacts of tools configurations

This section will look at how the risk level is impacted depending on the parameters used by the different tools. The results by tool configuration are presented in Table 14. Statistically, there is no significant difference between the different configurations using a one-way ANOVA on the samples' means (F=1.314 and p=0.269). Hence there is no major difference between tools using the two basic parameters compared to the other configuration.

4.8.3.1 Tools using the two basic parameters (S and Ph)

In this study, this configuration was considered the first "standard configuration" as described in ISO 14121-1 (see section 1.3). It was observed that 20 of the 31 tools analyzed used the two basic parameters (S & Ph). The average of the 20 tools applied to the scenarios is around 68.8% with a standard deviation of 23.5%. The average risk levels for the 20 scenarios are quite different among the tools in this group and vary from 38.3 to 96%. At the lower end, tools 6 and 45 have an average risk level of around 44% while at the other end, tools 7 and 48 have an average risk level of 88%.

Table 14: Scenario average risk levels for each tool configuration

	Configuration		
Scenario	**S & Ph**	**S, Pe, A & Ex**	**Other**
A	52.1	39.3	40.1
B	38.7	68.8	73.7
C	49.4	73.2	66.2
D	65.5	32.2	56.3
E	57.9	63.3	60.4
F	52.1	67.7	79.5
G	65.5	47.9	64.1
H	65.5	42.3	71.0
I	57.9	77.5	82.3
J	63.1	73.2	72.8
K	73.7	67.4	73.9
L	73.7	73.1	73.6
M	79.8	68.9	61.9
N	79.8	73.2	66.9
O	73.4	80.2	90.3
P	79.8	73.2	79.5
Q	79.8	88.8	88.7
R	83.9	80.1	85.0
S	88.7	76.1	81.0
T	96.0	100.0	93.7
Average	68.8	68.3	73.1
Standard deviation	23.5	26.2	27.7

4.8.3.2 Tools using severity of harm in conjunction with all the three auxiliary parameters (S, Pe, A and Ex)

This configuration is the second "standard configuration" proposed in ISO 14121-1 where the S parameter is used in conjunction with all three auxiliary parameters. There were 6 tools using four parameters (S, Pe, A and Ex) out of the 31 tools with an average risk level of 68.3% and a standard deviation of 26.2%. The results of the scenarios could be divided into three distinct groups. Group 1 includes two low estimating tools (19 and 91) that produced an average risk of 50%. The second group composed of tools 62 and 69 from the intermediate estimating tools, yielded an average risk around 64%. Finally, the last group (tools 57 and 67 from the high estimating tools) gave a significantly higher average risk of around 91% compared to the other two groups as confirmed by an ANOVA (F=16.169 and p=0.000) and a Duncan's Multiple Range Test.

4.8.3.3 Tools using a different configuration

The remaining 5 tools (17, 49, 53, 55 and 114) use a different configuration than the "standard configurations" proposed in ISO 14121-1. All of them used the severity of harm parameter in conjunction with only one or two of the auxiliary parameters (Pe, A or Ex). For the 20 scenarios, those tools had an average risk level of 73.1% slightly higher than the other configurations with a standard deviation of 27.7%. Looking at Table 13, one might notice that except for tool 17, these tools tend to behave as high estimating tools for the low and mid-low risk scenarios.

4.8.3.4 Impacts of the number of levels of each risk estimation parameters

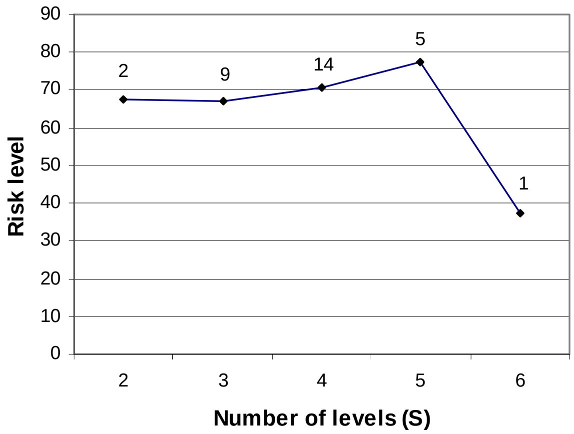
This section analyses the different parameters of the tools based on the results of the 20 scenarios. Due to the small number of tools using each of the auxiliary parameters, the analysis could only be done on the two basic parameters, S and Ph. Figure 5 a) and b) presents the results in terms of the number of levels for these two parameters. Note that the digit on the curves indicates the number of corresponding tools.

4.8.3.4.1 Severity of harm (S)

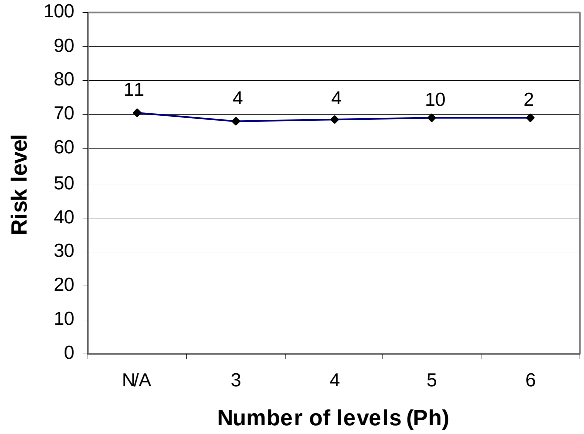
The severity of harm parameter is used by all tools. The number of levels of S varies from 2 to 6 among the 31 tools selected in this study as shown in Figure 5a. One might notice that there is a small increase in the average risk level for the 20 scenarios as the number of levels of S increases from 2 to 5. Tool 17 with 6 levels of S has a significantly lower average risk than the other tools as confirmed by an ANOVA (F=12.363 and p=0.000) and a Duncan's Multiple Range Test.

4.8.3.4.2 Probability of harm (Ph)

This parameter is used by 20 tools and the number of levels of Ph varies from 3 to 6. Figure 5 b) presents an interesting result; the number of levels of Ph does not seem to influence the average risk level obtained. Moreover, one might observe that not using Ph does not produce a very significant difference on the average risk level.



a) Parameter S



b) Parameter Ph

Figure 5: Number of risk levels and average risks (with the number of tools)

4.8.3.5 Impacts of the number of levels of risk

The different tools analyzed have different number of risk levels. The number of risk levels varies from 2 to 15 among the tools selected in this study. Figure 6 plots the average risk based on the number of risk levels of the tools for the 20 scenarios. An ANOVA (F=10.115 and p=0.000) demonstrated that the number of levels of risk will have an influence on the average risk. The figure clearly shows a decrease in the average risk from 2 to 5 risk levels. Tools with 2, 3 or 15 levels of risk appear to produce an average risk level greater than tools with 5 or more risk levels. The Duncan’s Multiple Range Test showed that tools with 4, 5, 6, 7 and 11 levels of risk will produce a similar average risk.

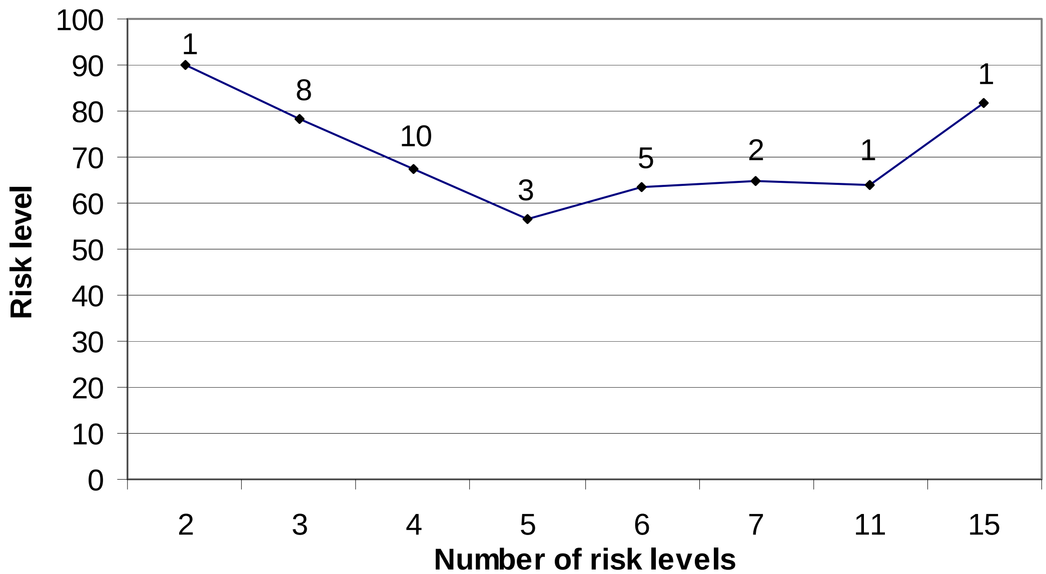


Figure 6: Number of risk levels and average risks (with the number of tools)

5. DISCUSSION

5.1 Discussion on the equivalence scales

The equivalent scales enabled the different definitions for parameters and the different levels for parameters to be compared to common bases and be further analyzed. The characteristics of tools that can potentially lead to errors when estimating risks were identified, and are presented below.

5.1.1 Definition of the risk estimation parameters used by the different tools

The first observation resulting from the comparative analysis of the various tools concerns the large variety in the terminology or names given to the parameters used for risk estimation. The most marked differences are found in the definition of the severity of harm (S) and the probability of harm (Ph) parameters. For example, for the S parameter one finds definitions such as "*hazard in terms of the potential to cause harm*, *consequences or potential severity of injury*, *severity of injury or illness*, *consequences*, *severity*, and *severity of harm*". For the Ph parameter, definitions such as "*probability of harm*, *probability of occurrence of harm*, *probability or likelihood of harm occurring*, *frequency of occurrence*, *likelihood*, *likelihood level*, and *qualitative measures of likelihood*" were found.

For each of these parameters, even if many of the given names or definitions may be considered as equivalent, some are vague, imprecise and may mislead the users of these tools. For example, using "*Consequence*" as the definition for the S parameter might bring the users to question themselves on the nature and the extent of the damages that they should consider in their risk estimation for a given situation: injuries, material damage, impact on the environment, production loss, etc. The definition "*severity of injury or illness*" is more precise and leaves less room for interpretation.

This problem with the ambiguity of names and definitions is also very unsettling for the Ph parameter. Definitions such as "*frequency of occurrence*" or "*likelihood*" will unavoidably bring the user to question (or make assumptions) about whether this refers to the probability of harm (Ph) or the probability of the hazardous event (Pe). It is therefore very easy for the user to get confused over these two parameters. However, Ph is usually much lower than Pe, since Ph is made up of other parameters such as exposure or possibility of avoidance. A more precise definition of the Ph parameter (e.g., "*probability of occurrence of specified harm*") could help improve the understanding of the required input by users of those tools.

5.1.2 Number of thresholds for each parameter

The number of thresholds for a given parameter can differ from one tool to another. The analysis of the equivalent scales suggests that there are a minimum number of thresholds required to allow proper risk estimation in a given situation. For example, some tools use only two thresholds for the S parameter, separating the two by the reversibility of the injury (e.g., tool 49). Thus, with such tools, an injury that is irreversible (e.g., a cut off finger tip) will be considered at the same level as the death of a worker for this parameter. In such a situation, the user might feel uncomfortable in selecting the required level. When the number of thresholds of any given parameter is inadequate, some thresholds tend to include too many different and sometimes extreme situations. The tools selected in this study use three to five thresholds for each parameter and these tend to provide the desired granularity when estimating the parameter.

5.1.3 Definition of each thresholds for each parameter

The analysis of the equivalent scales shows that there are major differences in the definitions that the tools give to the various thresholds for their different parameters. These differences could lead to problems with the use of certain tools. In fact, some tools use only a figurative word or expression (e.g., "*Possible*" or "*Probable*" for Ph parameter or "*seldom to quite often*" for the Exf parameter) to define the different thresholds of their risk estimation parameters. The use of figurative words by themselves leaves much room for interpretation by the user: does "*Possible*" have the same meaning for all users? What exactly is meant by "*quite often*"? Each person using these tools can interpret every threshold differently from another person, considering the lack of details in the terms used. This interpretation problem is of course lessened when a detailed definition is added to the figurative word. For example, when the term "*Probable*" is accompanied by a definition such as "*Likely to occur several times in the life cycle*", the user is in a better position to understand the conditions which should lead to the selection of this level of probability. When used in conjunction with figurative words or terms, detailed definitions can give the user an improved structure to work in, providing a better inter/intra user's reproducibility (repeatability) of the final risk estimation results.

5.1.4 Consistency of terms used to define the thresholds

Despite the use of detailed definitions for each of the thresholds of some of the risk estimation parameters, some tools use inappropriate words considering the specific threshold and its definition. For example, one of the tools defines a specific level of its S parameter by "*Medium – severe injury, severe occupational illness, or major system or environmental damage*". Another tool uses the term "*major*" in conjunction with "*maiming, significant injury, not permanent*". In these cases, there is an inconsistency between the terms used in the definition: a "*severe injury*" that is qualified as "*Medium*" and "*Not permanent*" qualified as "*Major*". This kind of situation might mislead some users when selecting the severity of harm. It is thus desirable to give precise and comprehensible definitions, which correspond to the figurative words given for the specific threshold, so that there is no ambiguity. For example, in order to produce equivalent scales for the probability of a hazardous event parameter it was, on occasion, necessary to make thresholds with very different labels equivalent to one another. This would appear to be due to the different definitions given to the same labels, number of thresholds or need to find equivalences for other thresholds. A possible reason may be that certain labels have different meanings depending on their industrial context.

In addition, one tool used the terms "*remote*" and "*improbable*" in a different order than another tool that used these labels. The coherence in the use of terms with respect to the graduation of thresholds within a tool is also important. Some tools might for example use the same word in two subsequent levels: "*serious – over 3 days lost time*" (2^{nd} level) and "*major – death or serious injury*" (3^{rd} level). In this example, the figurative term "*Serious*" appears in the label of one threshold and the definition of the other, which may confuse the users. As such, for any given parameter, its thresholds should show a progression from lowest to highest, and the terms used should reflect this progression in order to help the user see clearly the difference between each threshold and select the level that corresponds to the situation at hand.

5.1.5 Gaps between thresholds

The detailed analysis of the different tools showed that for many of them, there were gaps in the progression of the thresholds of some of their parameters. This problem is especially present with exposure parameters (Exf and Exd). For example, one tool defines its Exf parameter with two levels, the first by "*infrequent exposure (typically exposure to the hazard less than once per day)*" and the second by "*frequent exposure (typically exposure to the hazard more than once per hour)*". In this case, the definitions go from less than once per day to many times per hour. Consequently, there is a gap in the time scale where an exposure of twice a day could not be easily fitted in the defined levels, thus confusing the user.

5.1.6 Definition of the exposure interval

Another problem that mainly affects probability parameters (Ph and Pe) is the definition of the exposure interval. When deciding on a Ph level for example, the users must know the exposure interval of time on which to base his judgement. An event that is "*Improbable*" over a very short exposure interval becomes "*Remote*" or "*Occasional*" over a longer interval. Thus, changing exposure interval influences Ph and Pe. However, few tools give sufficient information on the exposure interval that should be considered, as shown by this example: "*Technical failure regularly observed (every six months or less); inappropriate human action by an untrained person, with less than six months experience on the workstation; similar accident observed in the plant since ten years.*" This example shows partial exposure interval information (incomplete for the "*inappropriate human action...*") for one level of the Pe parameter. This results in users of the tools making different assumptions such as that the exposure interval is per shift, per year, over a person's working life or the lifetime of the machine.

5.2 Discussion on the risk estimations

From the 31 tools analyzed, this study brings some insight in how they perform, their differences in construction and their defined scope. The following sections discuss the important results and findings and look at their impact on the estimated risk level.

5.2.1 Distribution of resulting risk levels

The distribution of the resulting risk levels was analyzed with respect to the scenarios and on a tool by tool basis. The analysis of the risk estimations with the different scenarios leads to the following three observations:

- The tools produce risk levels that are sometimes very different one from the other i.e. from maximum risk to minimum risk for the same scenario (see Table 10 for scenario B and tools 49, 57, 67 and 114 or scenario S and tools 17 and 91).
- Some tools tend to systematically underestimate high risk scenarios (see for example tools 6, 17, 19, 45, 46, 85 and 91).

- Some tools tend to systematically overestimate low to mid-low risk scenarios (see for example tools 7, 10, 24, 34, 35, 41, 48, 49, 53, 55, 57, 67, 94 and 114).

Looking at Table 11 it can be seen that very few scenarios have been estimated without both extreme values (lowest and highest risk) and this would indicate that many tools oddly estimate the risk in some circumstances. Moreover, for most of the scenarios, tools 17 (14 out of 20) and tool 91 (9 out of 20) will produce the lowest risk level while tools 67 (16 out of 20) and 114 (11 out of 20) produce the highest risk level.

Tools 17 and 114 use a different configuration than the two “standard configuration”. Their characteristics will be discussed later. Tools 67 and 91 are 4 parameters tools based on ISO 14121-1. Their characteristics are discussed in the next paragraph.

Tool 67 is the highest estimating tool of the 31 tools in this study. It is a hybrid tool (computation of class, see ISO 14121-2 (2007)), not a pure matrix. It adds given values for three parameters namely Ex, Pe and A in order to define a “class” (corresponding to Ph as per ISO 14121-1, see section 1.3) in a risk matrix. One possible explanation for this tool’s high estimating tendency lies with the relative weight of the auxiliary risk estimation parameters. In fact, with this tool, a continuous exposure to a hazard is mathematically equivalent to the highest probability of occurrence of a hazardous event (Pe). One might argue that the Pe parameter should have more importance in the determination of the probability of harm than the exposure parameter.

As for tool 91, it uses 4 parameters with only 2 levels for the severity, while the other tools have at least 3 levels for this parameter. It can be argued that having only 2 levels for severity tend to make it more difficult to discriminate properly some intermediate situations. Moreover, its risks levels are not uniformly distributed in the risk matrix. This characteristic is discussed further in section 5.2.3.

5.2.2 Impacts of tool configurations

5.2.2.1 Tools using one of the two “standard configurations” proposed in ISO 14121-1

As stated before, this study considered two “standard configurations” according to the risk estimation parameters used: 2 parameters (S and Ph) and 4 parameters (S, Ex, Pe and A). The analysis of the 2 architectures has not permitted to conclude which of the 2 is to be favored or better. The average risk of the 2 parameter tools is 68.8% which is very similar to the 4 parameter tools (68.3%) and the standard deviation is large in both cases. Although based on the results and analysis, it can be stipulated that simple tools (2 parameters) can be as effective as more complex 4 parameter tools in estimating risks associated with industrial machines. This may also explain why in this study 20 tools use the first method of construction compared to 6 for the second.

5.2.2.2 Tools using a different configuration

Tools that use a different configuration from the two "standard configurations" (tools 17, 49, 53, 55 and 114) tend to produce sometimes awkward results since they omit at least one important parameter. As mentioned before, most of these tools tend to behave as high estimating tools for the low and mid-low risk scenarios, thus producing an average risk level of 73.1%, slightly higher than the two other configurations.

In this group of tools, tools 49 and 114 do not use the probability of hazardous event (Pe) since they use only 3 parameters (S, Exf and A). This could explain why they tend to produce higher risk levels since they cannot take into account factors which could result in risk reduction, such as reliable safety control systems.

Tool 53 is a hybrid tool that computes the sum of 3 parameters (S+Pe+Exf). This tool is missing the avoidance (A) parameter in order to conform to ISO 14121. While this tool can take into account some risk reduction measures, it cannot consider the avoidance in estimating the risk, resulting in a higher risk in many circumstances where harm could be avoided or limited by proper human reaction or by technical means.

Tool 55 has only 2 parameters (S and Exf). Thus, it estimates the risk solely on the basis of the exposure to a hazardous situation, without considering other probability related parameters (Pe and A). With such construction, the simple fact of being continuously exposed to a hazard is enough to produce a high risk estimation.

Finally, tool 17 has an average risk of 37.5% while the others give an average risk of around 80%. This tool uses 3 parameters (S, Pe and Exd). It does not consider the avoidance parameter and, unlike other tools, defines multiple fatalities as its maximum severity level. Moreover, it is the only graphical tool (nomogram) evaluated in this study. The theoretical experimentation carried out in this study showed that this method offers more flexibility in selecting the level of a parameter due to its continuous scales. At the same time, it is more demanding because intermediate values are possible for the parameters and the resulting risk level. The conversion of a graphical tool to a matrix is possible but it needs to have well defined threshold for the different parameters. For those reasons, matrix tools are easier to use and preferred. Moreover, graphical tools tend to hide the dispersion of results. This is in part due to the nature of their continuous scales.

5.2.3 Impacts of the number of levels of each risk estimation parameters

As shown in Figure 5a, there is a small increase in the average risk level for the 20 scenarios as the number of levels of S increases from 2 to 5. The reasons for this behavior are not clear. As mentioned before, one can argue that having only 2 levels for severity tend to make it more difficult to discriminate properly some intermediate situations. The majority of tools use between 3 and 5 levels for this parameter.

In contrast, it seems that the number of levels of Ph has no effect on the resulting average risk as Figure 5b shows an almost flat line. More interestingly, it was observed that not using Ph only slightly increases the average risk. This seems to confirm that 2 parameter (S and Ph) tools are equivalent to the other "standard configuration" in terms of performance in risk estimation. The majority of tools also use between 3 and 5 levels for this parameter.

5.2.4 Impacts of the number and the distribution of levels of risks

The results of this analysis suggest that the number of risk levels of a tool must be greater than 3 or the tool will tend to produce high risk estimation in some cases as shown in Figure 6. Also, if the objective of a risk estimation tool is to "rank" the different hazardous situation scenarios according to their risk level, one might consider that this is more easily done when there are more that 3 levels in the "ranking system". Hence, it is believed that 4 risk levels is a minimum but the optimal number of levels is open to discussion.

Moreover, a detailed analysis of the tools revealed two types of problems with the distribution of the risk levels of some tools. The first problem lies with the uniformity or evenness of the distribution of the levels themselves. For example, tool 91 which is derived from ISO 14121-2, has 15 out of the 24 possible combinations or outcomes defined as low risk levels (1 or 2). Following this tool's construction, if the severity of harm parameter is set to its lowest level (S1), the resulting risk level will always be a low risk level independently of the level of the other parameters. Hence, this tool tends to behave as a low estimating tool. Similarly, tool 48 is built such that 16 out of the 25 combinations or outcomes fall into the extreme and high risk, thus producing a higher risk level on average. For this tool, if one selects a severity of harm of 1 or 2, this will lead to an extreme or high risk whatever the probability of harm selected. This accounts for 10 of the 16 occurrences of extreme and high risk in the matrix. Interestingly, tools 35 and 48 have the same construction (S x Ph) and risk matrix, thus the same risk level in this study. In order to have a uniform progression in risk, it can be argued that tools should have a reasonably uniform or even distribution of their risk levels, i.e. risk zones about the same size in the matrix. Furthermore each level of each parameter used in a tool should be able to yield a reasonable number of different risk levels.

The second problem is related to the continuity of the distribution of the risk levels. In fact, some tools (1, 3, 45, 46, 55, 85 and 94) have discontinuities in their risk matrix, i.e. absence of uniform graduation represented by adjacent cells of the matrix leaping to more than one level as one moves from one cell to another. For example, for the tool presented in Figure 7, one might notice a leap between risk levels in the matrix, risk going from "Moderate" to "Intolerable" in the second row, and in the third column, leaping over "Substantial" risk in one step. Such discontinuities in the risk matrix will not ensure that the risk levels are evenly distributed and also this leads to a parameter that contributes unevenly in the determination of the risk.

Probability of occurrence of harm	Severity of Harm		
	Slightly harmful	**Harmful**	**Extremely harmful**
Highly unlikely	Trivial	Tolerable	Moderate
Unlikely	Tolerable	Moderate	Intolerable
Likely	Moderate	Substantial	Intolerable

Figure 7 : Example of a 2 dimension matrix risk estimation tool.

5.2.5 Calibration of the tools

Some tools have a broader scope than safety of machinery and should not be used in these situations as they will systematically produce lower risk level. During the study of the tools, it became obvious that certain tools were designed for a different purpose than safety of machinery. Tools derived from major risk industries (railways, petrochemical, ...) usually have a severity of harm parameter were multiple deaths are considered as the worst case, while safety of machinery tools will consider a single and probable death as the maximum level of severity of harm. To achieve a maximum risk level, those tools require a "multiple deaths" level (e.g., tools 10, 17 and 66). Because in safety of machinery multiple deaths will seldom occur, the tool will never yield a maximum risk, potentially delaying or even avoiding risk reduction measures in many common hazardous situations. It is clear that such tool is not calibrated for machinery safety evaluation where a single and probable death should score maximum. Such tools are not appropriate to machinery risk assessment even if their scope often states the opposite.

5.2.6 Construction rules proposition

Table 15 summarizes the findings of this study linking the identified deviations or construction flaws in relation with the low estimating tools and the high estimating tools. As shown in this table, some of these deviations are mostly attributed to either the low or high estimating tools, while others might affect the risk estimation process in both ways. Nevertheless, all the deviations or construction flaws of the tools have the potential to oddly estimate the risk in some circumstances. From the previous discussion a certain number of construction rules for risk estimation tools can be proposed. These construction rules, which can also be applied in the selection of a risk estimation tool, are the following:

1. Follow one of the "standard configuration" defined in this study and proposed in ISO 14121-1 (2 or 4 parameters) to ensure that no risk estimation parameter is neglected, since most tools using a different configuration tend to overestimate low to mid-low risk scenarios.
2. The relative weight or contribution of each parameter should be carefully defined in order to avoid that one parameter overly influences the risk level.
3. Define and document each parameter carefully. For example, differentiate between probability of harm and probability of hazardous event.
4. Use between 3 and 5 levels for the severity of harm parameter to be consistent with the majority of risk estimation tools. Tools with 2 levels for this parameter discriminates poorly some intermediate situations, producing odd risk estimation in some circumstances.
5. Use between 3 and 5 levels for the probability of harm parameter to be consistent with the majority of risk estimation tools.
6. Use at least 4 levels of risk. Tools with less risk levels tend to overestimate risk in many circumstances.
7. Prefer a matrix type tool over a graphical (nomogram) tool. The graphical tool used in this study underestimated most scenarios. Its use was complicated by its continuous scales.
8. Avoid discontinuities or gaps in thresholds or levels of parameters.
9. Avoid the use of one word or vague terms to define the thresholds of parameters.
10. The frequency of exposure parameter should be defined with respect to a reference in terms of time (X per shift, X per hour etc.).

11. Avoid using the same word or phrase to describe two different thresholds for the same parameter.
12. Provide a good even distribution of risk levels in the matrix. This implies that each level of each parameter should give a reasonable access to a good number of risk levels and that no risk level predominates or takes up the most of the risk matrix.
13. Avoid tools with outputs that are overly sensitive to a single incremental change of an input. Such discontinuities affect the distribution of the results and also lead to a parameter that contributes unevenly in the determination of the risk (e.g. leaps between risk levels in the matrix should be no more than one risk level change between adjacent cells).
14. Design or choose a tool appropriate to the scope of the machine risk assessment. This could imply calibrating the levels of parameters for the analysis of safety of machinery. For example, a tool derived from the major risk industries in which multiple deaths are required in order to reach maximum risk is not appropriate for risk estimation of machines.

Table 15 : Summary of findings

Deviation	**Low estimating tools** (Tend to underestimate high risk scenarios)									**High estimating tools** (Tend to overestimate low to mid-low risk scenarios)													
	1	6	17	19	45	46	66	85	91	7	10	24	34	35	41	48	49	53	55	57	67	94	114
Different configuration from the two proposed in ISO 14121-1 (e.g. one or more parameter absent)			X														X	X	X				X
Relative weight of one parameter is too important in the resulting risk level (e.g. parameter has more weight based on tool architecture)									X					X		X					X		
Less than 3 levels for the S parameter									X								X						
Less than 4 levels of risk										X			X		X					X	X		X
Distribution of risk levels not uniform (e.g. construction of the tool often leads to the same risk level)		X			X	X		X	X	X	X	X		X		X			X				
Discontinuities in risk matrix (e.g. leaps in risk levels)	X				X	X		X											X			X	
Not calibrated for safety of machinery (requires multiple deaths to achieve maximum risk)			X				X				X												

6. CONCLUSION

This study analyzed a selected sample of thirty one risk estimation tools associated with industrial machines. The tools were chosen and analyzed systematically in order to characterize their similarities and differences based on equivalence scales for their parameters. This approach was used to analyze different tools using common benchmarks. The results show that the structure of the tools and terminology used in the tools can potentially lead to biased or incorrect risk estimations. The factors that designers and users of risk estimation tools should consider include:

- The definition of the risk estimation parameters;
- The number of levels or thresholds for each parameter;
- The definition of each level or threshold for each parameter;
- The gaps between levels or thresholds;
- The definition of the exposure interval; and
- The number of risk levels.

Moreover, in this report, the differences in results when using different machine safety risk estimation tools applied to the same hazardous situations were studied and investigated. As such, the influence of the types of risk estimation parameters used in the tools, the construction or architecture of the tools, the influence of the number of levels for each parameter and the influence of the number of risk levels on the results when applying each tool to hazardous situations were studied. Consequently, 31 risk estimation tools have been selected based on predefined criteria and compared in estimating the risk level associated with 20 hazardous situations. The results show a large difference between the tools in evaluating the same situation. The scope of the tool and its construction seem to be one of the contributing factors in the variability of the results. Tools that follow the 2 "standard configurations" as defined in this study and proposed in ISO 14121-1 produce similar average risk levels even though both configurations have tools that will underestimate or overestimate risks associated with hazardous situations. This leads to conclude that a simple 2 parameter tool can be as effective as a more detailed 4 parameter tool. The observations following the behaviours of the different tools have guided the authors in proposing a series of construction rules or recommendations in order to have balanced tools which will not contain biases tending to over or under estimate risks. These recommendations could potentially help users when choosing or designing a risk estimation tool. Future works include the validation of the most promising tools with a large sample of different users from industries. The ultimate purpose for the risk estimate is the selection and implementation of protective measures and risk estimates which are unbiased will lead to the appropriate risk reduction measures.

REFERENCES

Abrahamsson, M. (2000). Treatment of uncertainty in risk based regulations and standards for risk analysis, Report 3116, Lund University, Sweden, 82 pages.

Abrahamsson, M. (2002). Uncertainty in quantitative risk analysis- characterisation and methods of treatment. Department of Fire Safety Engineering, Lund University, Lund, Sweden.

ANSI B11.TR3 (2000). ANSI Technical Report - Risk assessment and risk reduction - A guide to estimate, evaluate and reduce risk associated with machine tools, American national Standard.

ANSI/RIA R15.06 (1999). American National Standard for Industrial Robots and Robots Systems - Safety Requirements.

AS/NZS 4360:2004 (2004). Risk management, Australian and New-Zealand Standard, 28 p.

Charpentier, P. (2003). Projet européen RAMSEM- Développement et validation d'une méthode d'appréciation du risque machine basée sur les principes de la norme EN 1050. Projet A.5/1,058 de l'INRS.

Company A (2002). Identification des dangers et risques en Santé/Sécurité, Internal company document.

Company P (2003). Risk assessment and risk reduction, Internal company document.

Company R (2004). Évaluation des risque - Partie 2: Évaluation des mesures de réduction des risques, Internal company document.

Company X (1997). Tableau d'analyse de risque (sans titre) , Internal company document.

CSA-Q634-91 (1991). Risk Analysis Requirements and Guidelines, Canadian Standard Association.

CSST (2002). Sécurité des machines, Phénomènes dangereux, situations dangereuses, événements dangereux, dommages, Commission de la santé et de la sécurité du travail du Québec, DC 900-337 (07-02), 15 p.

Etherton, J. (2007) Industrial Machine Risk Assessment: A Critical Review of Concepts and Methods. Risk Analysis Journal, 27(1) 71-82.

Gondar Design (2000) Risk assessments, http://www.purchon.co.uk/safety/risk.html, 5 p.

Görnemann, O (2003). SICK AG Scalable Risk Analysis & Estimation Method (SCRAM), ISO/TC199 WG 5 N 0049, 12 p.

IEC 62278 (2001). Railway applications - The specification and demostration of Reliability, availability, Maintainability and safety (RAMS), International Electrotechnical Committee.

ISO 12100-1 (2003). Safety of machinery- Basic concepts, general principles for design - Part 1: Basic terminology, methodology, International Standard.

ISO 14121-1 (2007). Safety of machinery - Principles of risk assessment, Part 1: General Principles, International Standard.

ISO 14121-2 (2007). Risk Assessment - Part 2: Practical guidance and examples of methods, International Standard.

ISO/TS 14798 (2006). Lifts (elevators), escalators and moving walks -- Risk assessment and reduction methodology (annex C), International Standard.

Lamy et al. (2009). Estimation des risqué, recensement des méthodes et subjectivité des paramètres de l'estimation : INRS ND 2305-214-09.

Lane, J., Tardif, J., and Bourbonnière, R. (2003) Educational approaches to promote in order to favor the transfer of competencies in risk assessment and protective devices training. In J. Ciccotelli (dir.), *3rd International Conference: Safety of Industrial Automated Systems*, October 2003, Nancy, France.

Main, Bruce W. (2004). Risk Assessment: Basics and benchmarks, Design Safety Engineering Inc., 485 p.

Marradi, A. (1990). Classification, Typology, Taxonomy, *Quality and Quantity XXIV* (May 1990): 129-157.

MIL-STD-882D (2000). Standard Practice for System Safety (Appendix A), US Department of Defense.

Paques, J.-J., Bourbonnière, R., Daigle, R., Doucet, P., Masson, P., Micheau, P., Lane, J. and Tardif, J. (2005). Transfert de compétences en formation sur la gestion de la sécurité des machines et les moyens de protection. Institut de recherche en santé et en sécurité du travail du Québec, Rapport du projet 099-216, R394, 105 p.

Paques, J-J., Gauthier, F., Perez, A., Charpentier, P., Lamy, P. and David, R. (2005b). Bilan raisonné des outils d'appréciation des risques associés aux machines industrielles, Rapport R-459, IRSST #099-343, 64 p.

Paques, J-J., Perez, A., Lamy, P., Gauthier, F., Charpentier, P. and David, R. (2005c). Reasoned review of the tools for assessing the risks associated with industrial machines: Preliminary results, *4th International Conference Safety of Industrial Automated Systems*, September 26-28, 2005, Chicago, Illinois, USA

Paques, J.-J. (2005d) Results of exploratory tests on tools for assessing the risks associated with industrial machines, 4th *International Conference Safety of Industrial Automated Systems*, September 26-28, 2005, Chicago, Illinois, USA

Paques, J.-J. and Gauthier, F. (2006). Thematic program: Integrated projects on risk assessment tools for industrial machinery, *HST-CDN (Hygiène et sécurite du travail)*, ND 2259-205-06, p. 33-40.

Paques, J.-J. and Gauthier, F. (2007) Analysis and Classification of the Tools for Assessing the Risks Associated with Industrial Machines, *Journal of Occupational Safety and Ergonomics*, 13(2), p. 173-187.

Parry, G.W. (1999). Uncertainty in PRA and its implications for use in Risk-informed decision making. *Proceedings of the 4th International conference on probabilistic safety assessment and management, PSAM 4*, Edited by Mosleh, A. & Bari, R.A., New York.

Ruge, B. (2004). BASF Risk Matrix as Tool for Risk Assessment in the Chemical Process Industries, BASF.

Stevens, S.S. (1946). On the theory of scales of measurement. *Science*, 103, 677-680.

SUVA (2002). Méthode SUVA d'appréciation des risques liés aux installations et appareils techniques, Caisse nationale Suisse d'assurance en cas d'accidents.

The Metal Manufacturing and Minerals Processing Industry Committee (2002) A Guide to Practical Machine Guarding, Queensland Government - Workplace Healt and Safety.

Trochim, W. M. (2005a). Level of measurement, Research Methods Knowledge Base, Cornell University, Atomic Dog Publishing.

Trochim, W. M. (2005b). Likert scaling, Research Methods Knowledge Base, Cornell University, Atomic Dog Publishing.

Velleman, P. F. and Wilkinson, L. (1993). Nominal, ordinal, interval, and ratio typologies are misleading. *The American Statistician*, 47(1), 65-72.

Wikipedia (2006). Level of measurement, Wikipedia, the free encyclopedia, downloaded January 2006.

Worsell, N and Wilday, J. (1997). The application of risk assessment to machinery safety - Review or risk ranking and risk estimation techniques, Health and Safety Laboratory, 130 p.

HSL (2008) How to complete a methodical risk estimation, Health and Safety Laboratory.