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Experimental Analysis of 31 Risk Estimation Tools Applied to Safety of Machinery

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This article studies differences in the results of using different risk estimation tools in the same hazardous situations involving dangerous machinery. We investigated how (a) types of risk estimation parameters and methods of constructing tools, (b) the number of levels of each parameter, and (c) the number of risk levels influence the results. Consequently, 31 risk estimation tools were compared by using them to estimate risk levels associated with 20 hazardous situations. Risk estimation appears to be tool-dependent, as different tools give different results with identical hazardous situations. The scope of the tool, its use, and construction could explain these differences. This article also proposes a series of rules for constructing tools to alleviate many problems associated with the variability of risk estimations.

risk assessment risk estimation tools safety of machinery

1. INTRODUCTION

1.1. Risk Estimation in Risk Assessment

Risk assessment is a series of steps used in examining hazards associated with machinery. It has two phases—risk analysis and risk evaluation—as explained in Standard No. ISO 14121-1:2007 [1][1]. Risk analysis usually consists of three stages: (a) determining the limits of the machine, (b) identifying hazards, and (c) estimating the risk. Figure 1 shows a simplified model, derived from Standard No. ISO 12100-1:2003, representing the process of machinery risk assessment and reduction [2].

Determining the limits of the machine implies considering all phases of its life cycle: design, construction, transport, installation, commissioning, operation, starting up, shutting down, process setting or changeover, cleaning, and adjustment. Moreover, as described in Standard No. 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 workers' training and experience [1].

Standard No. ISO 12100-1:2003 defines a hazard as a "potential source of harm" (p. 2) [2]. When identifying hazards, their different forms have to be considered. In general, hazards in machinery fall into two main categories: mechanical and electrical. Mechanical hazards include crushing, shearing, cutting, entanglement, entrap-

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[1] The updated version of Standard No. ISO 14121-1:2007, i.e., Standard No. ISO 12100:2010, became available after preparing this article.

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ment, impact, abrasion, and high-pressure fluid jets. Different machine parts can generate those hazards, depending on their shape, relative motion, mass and stability, mass and velocity, and strength. Workers can also be exposed to electrical hazards, which include contact with live parts or parts becoming live under inappropriate conditions, contact with live parts carrying high voltage, and thermal radiation. Electrical hazards can lead to electric shocks (injuries), electrocution (death), heart attacks, and burns. Thermal hazards and hazards generated by noise, vibration, radiation, and dangerous substances are others examples to consider at this important stage of the assessment. According to Standard No. ISO 14121-1:2007, at the hazard identification stage, "all reasonably foreseeable hazards, hazardous situations, or hazardous events associated with the various tasks shall then be identified" (p. 9) [1].

After the hazard identification stage, risk is estimated for each identified hazard and hazardous situation. Risk is defined in the machinery safety standard as "the combination of the probability of occurrence of harm and the severity of that harm" (p. 3) [1]. According to Standard No. ISO 14121-1:2007, the probability of occurrence of harm can be estimated by taking into account the frequency and duration of exposure to a hazard, the probability of occurrence of a hazardous event, and the technical and human possibilities to avoid or limit the harm [1]. The combination of those parameters is used to estimate risk values, which can then be used to compare risk. Various organizations concerned with the safety of industrial machinery propose risk estimation tools, and some companies have developed their own methods and tools to estimate risks. At the last stage of the risk assessment process, risk evalua-

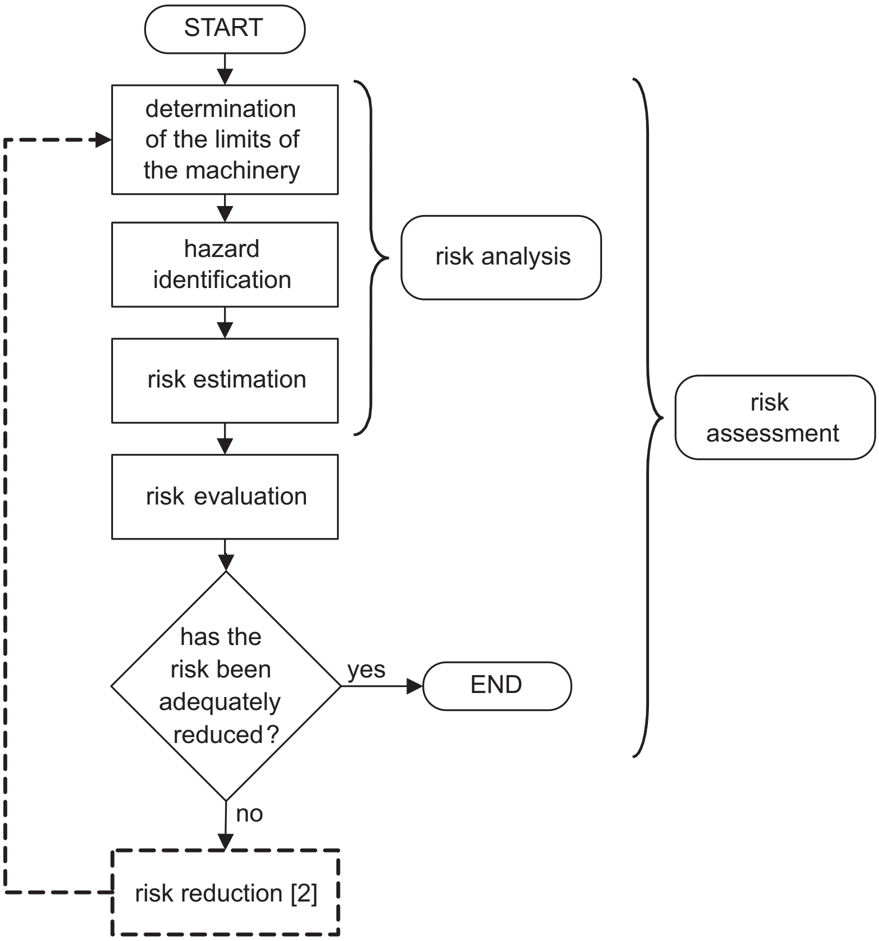

Figure 1. Simplified management of risk assessment based on Standard No. 12100-1:2003 [2].

tion allows to make decisions about the safety of machinery (Figure 1).

1.2. Risk Estimation Parameters According to Standard No. ISO 14121-1:2007 [1]

The risk associated with a hazardous situation depends on two basic parameters: the severity of harm (S) and the probability of occurrence of harm (Ph). As mentioned in section 1.1., the latter may be determined with three auxiliary parameters: the frequency or duration (or both) of exposure to the hazard (Ex), the probability of occurrence of a hazardous event (Pe), and the technical and human possibilities of avoiding or reducing the harm (A).

The factors to consider when estimating Ex include (a) the need for access to the hazard zone (e.g., for normal operation, correction of malfunction, maintenance, or repair); (b) the nature of access (e.g., feeding materials manually); (c) the time spent in the hazard zone; (d) the number of persons requiring access; and (e) the frequency of access. Pe can be estimated by considering (a) reliability and statistical data, (b) accident history, (c) history of damage to health, and (d) risk comparison.

As described in Standard No. ISO 14121-1:2007, when estimating A, one should consider (a) different individuals who can be exposed to the hazard (e.g., skilled or unskilled); (b) how quickly the hazardous situation could lead to harm; (c) awareness of risk (e.g., through general information, information for use, direct observation, or warning signs and indications on the machinery; (d) human ability (e.g., reflexes, agility, or ability to escape); and (e) practical experience and knowledge (e.g., of that or similar machinery or no experience) [1].

1.3. Previous Studies on Risk Estimation

To reduce the risk of machinery-related accidents, machinery must be designed or modified using integrated means of risk reduction. Without a proper risk assessment, it is very difficult to make optimal decisions about the means of risk reduction for machinery. Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST) developed training sessions on machinery risk assessment for the occupational health and safety (OHS) professionals in the province of Quebec, Canada. A specific project made it possible to train OHS intermediaries and trainers, who in turn explained machinery risk assessment and risk reduction strategies to workers and managers in companies [3]. Over 560 people participated in 16 training sessions. The participants applied their knowledge to their workplaces or to practical situations in industries [4]. These training sessions on risk assessment showed that the results of an exercise in estimating the risk associated with tasks carried out on the same machinery differed from one group to another [5]. Certain variability in the results can be considered natural [6], and therefore tolerable, but too big dispersion may eventually lead to erroneous means of risk reduction. “The methods used in different European countries for assessing a machine’s risks, may lead to different and even contradictory results. In some cases they may require, for a given machine, different levels of safety…” (p. 3) [7]. Abrahamsson also mentioned that potential users perceived risk estimation tools as not very credible or as useless [8].

There is no research on the understanding of the process of estimating risk of machinery safety and on identifying the variables that can influence proper estimation of risk. Abrahamsson attempted to validate various risk estimation tools in different contexts, particularly in relation to occupational exposure to chemicals [9]. His research focused exclusively on analysing the variables related to the tool (model, parameters, etc.) without analysing other variables that could affect proper risk estimation (i.e., prior training, characteristics of individuals performing the risk analysis, etc.). He concluded that some uncertainty was inherent in risk estimation, but industry-specific guidelines could help improve this process. Etherton, Main, Cloutier, et al. conducted a field evaluation of the risk assessment process [10] proposed in the technical report ANSI B11.TR3:2000 [11]. However, their study focused on the benefits of the entire risk assessment process and not on risk estimation itself.

Due to the diversity of tools for risk estimation associated with industrial machinery and the divergence of results sometimes observed, IRSST set up a thematic program consisting of several research projects to analyse in depth the characteristics of the tools proposed in literature or used in industry [12]. Paques, Gauthier, Perez, et al. completed the first study aimed at gathering data on the existing risk estimation and evaluation tools for industrial machinery [13]. The objective of that study was to analyse available documentation on risk assessment to classify the tools. More precisely, the aim was to determine specific characteristics of each tool and to classify them in groups or families. The study identified 108 different tools used for risk estimation [5, 14]. They were classified according to the means of estimating risks. The families of risk estimation tools were (a) two-dimensional matrices (47.2%), (b) matrices with more than two dimensions (6.5%), (c) risk graphs (10.2%), (d) numerical operation methods (14.8%), (e) graphic (abacus) methods (2.8%), and (f) methods combining several approaches (18.5%). Table 1 shows an example of a two-dimensional matrix tool. More examples of risk estimation tools can also be found in Standard No. ISO 14121-2:2007 [15]. The most notable aspect of the findings of the first study was diversity at all levels: nature of each risk estimation tool, description and definition of each parameter, number of parameters, calculation and quantification of the risk, classification and evaluation of the final result, etc. Differences in the numbers, types, thresholds, and definitions of the parameters contributed significantly to the diversity in the identified risk estimation tools.

Standard No. ISO 14121-1:2007 defines risk as a combination of different parameters [1]. Each parameter used for risk estimation can be considered a measurement parameter. Stevens' classification into four levels of measurement can then be used [16]. These four recognized levels of measurement are (a) nominal, (b) ordinal, (c) interval, and (d) ratio. Other authors often refer to this classification, despite the limitation of such scales used in social sciences or psychometrics [17, 18]. The primary objective of the users of a risk estimation tool is to rank different hazardous situation scenarios according to the risk indexes they represent to identify intolerable risks and to prioritize interventions. Therefore risk parameters have to be in the format of ordinal measurement [13]. This may explain why most existing tools for risk estimation use scales similar to Likert scales [19]. For example, in Table 1, S has three levels of 1–3 in increasing order of severity (ordinal measurement): *slightly harmful*, *harmful*, and *extremely harmful*.

2. OBJECTIVES

This study, the second in the thematic program mentioned in section 1.3., dealt mainly with the risk estimation tools and parameters, and addressed sources of uncertainty related to model uncertainty, as defined by Abrahamsson [8] and Parry [5] and in contrast to the two other classes of uncertainty, namely, "parameter uncertainty" and "completeness uncertainty" (p. 9) [8], which will be addressed in subsequent projects in the thematic program. The objectives of this study were to answer the following research questions:

- What are the differences in the results when using different tools applied in the same hazardous situation?
- What is the influence of the types of parameters used to define risk with each method or tool on the risk levels?

TABLE 1. Example of a 2-Dimension Matrix Tool Estimating Risk According to Harm

	Severity		
Probability	**Slightly Harmful**	**Harmful**	**Extremely Harmful**
Highly unlikely	trivial	tolerable	moderate
Unlikely	tolerable	moderate	intolerable
Likely	moderate	substantial	intolerable

- What is the influence of the number of parameters used in each method or tool on the risk levels?
- What is the influence of the number of thresholds for each parameter on the resulting risk levels?
- What is the influence of the number of risk levels on the results when using each method or tool?

The overall aim was to define the characteristics of reliable and robust methods, and to identify the risk estimation methods that can potentially lead to errors and the underlying reasons.

3. METHODOLOGY

3.1. Selection of a Sample of Risk Estimation Tools

Paques, Perez, Lamy, et al. gathered and analysed 108 risk estimation tools, many of which had only the two basic parameters to estimate risk

TABLE 2. Number of Levels of Parameters per Tool

Tool	S	Ph	Exf	A	Exd	Pe	R	C	Source Type	Reference
1	3	3	—	—	—	—	6	M	Company tool (machinery)	[21] p. 7–10
3	3	4	—	—	—	—	5	M	British Standards Institution	[21] p. 46–50
6	4	5	—	—	—	—	4	M	Machinery safety guide (UK)	[21] p. 24–6
7	4	5	—	—	—	—	3	M	Machinery safety book	[20] p. 32–4
10	5	5	—	—	—	—	6	N	Chemical safety book	[20] p. 38–40
17	6	—	—	—	3	6	4	N	Machinery safety book	[20] p. 85–90
19	3	—	2	2	—	3	4	G	Machinery directive guide	[20] p. 98–101
24	4	4	—	—	—	—	4	M	U.S. standard	[11]
33	3	3	—	—	—	—	3	M	Consumer products safety guide (USA)	[22] p. 155–7
34	3	3	—	—	—	—	3	M	Machinery safety guide (UK)	[22] p. 164–5
35	5	5	—	—	—	—	4	M	Australia/New Zealand Standard	[22] p. 174–7
41	4	6	—	—	—	—	3	M	International standard (machinery)	[23]
44	4	5	—	—	—	—	4	M	U.S. military standard	[24]
45	4	5	—	—	—	—	5	M	U.S. military guide	[22] p. 286–90
46	4	4	—	—	—	—	5	M	U.S. military guide	[22] p. 290–3
48	5	5	—	—	—	—	4	M	Australia/New Zealand Standard	[25]
49	2	—	2	2	—	—	7	M	U.S. Standard	[26]
53	3	—	3	—	—	3	15	N	Company tool (machinery)	[27]
55	4	—	4	—	—	—	4	M	Company tool (machinery)	[28]
57	4	—	5	5	—	5	2	M	Company tool (machinery)	[29]
58	5	5	—	—	—	—	3	M	Company tool (machinery)	[30]
62	5	—	—	3	5	5	3	M	Machinery safety guide (Switzerland)	[31]
66	4	6	—	—	—	—	4	M	International Electrotechnical Commission (railway)	[32]
67	4	—	5	3	—	5	3	H	International Organization for Standardization (machinery)	[15]
69	3	—	2	2	—	3	11	M	Company tool (machinery)	[33]
85	4	5	—	—	—	—	7	M	Company tool (chemical)	[34]
89	3	4	—	—	—	—	6	M	Machinery safety guide (Australia)	[35]
91	2	—	2	2	—	3	6	G	Machinery safety guide (Canada)	[15]
94	4	5	—	—	—	—	4	M	Canadian standard	[36]
102	3	3	—	—	—	—	6	M	Chemical safety guide (UK)	[37]
114	4	—	4	4	—	—	3	M	Machinery safety guide (UK)	[38]

Notes. S—severity of harm; Ph—probability of harm; Exf—exposure frequency; A—avoidance; Exd—exposure duration; Pe—probability of hazardous event; R—risk; C—tool construction method (M—matrix, G—graph, H—hybrid, N—numerical operation).

(S and Ph), while others used S in combination with one, two, or three auxiliary parameters (Ex, Pe, and A; see section 1.2.) [5]. This study focused on the tools with those different configurations, in conformity with Standard No. ISO 14121-1:2007 [1]. We did not include tools that were not in line with one of those configurations (e.g., having an unspecified probability parameter or a different type of parameter). We thus reduced the sample to 31 tools. Table 2 presents the main characteristics of those tools, including the number of levels of each parameter they use, the type of construction, and the reference document. Note that each tool retained its original number from the previous study for ease of cross-referencing.

3.2. Development of Equivalent Scales for Risk Levels

To compare the tools, we needed to develop equivalent scales of risk for each tool. The equivalent scales were constructed using three assumptions: (a) the risk grows linearly up to 100%, (b) each risk level is a range and not a point value, and (c) zero risk is not possible. This approach assumed that the highest risk level (100%) was the same for every tool. An advantage of this approach was that the equivalent scales obtained were not biased by an individual's judgment or experience. The lowest risk level of a tool did not translate into zero risk in the equivalent scales, since a risk would always exist for hazardous situations, even if it were tolerable. To illustrate how risk outputs were assigned a percentage range, a tool with three risk levels (*low*, *medium*, and *high*) would have low risk of 1–33.3%, medium risk of 33.4–66.6%, and high risk of 66.7–100%. Table 3 presents the equivalent risk scales for tools No. 48, 62, and 91.

TABLE 3. Risk Equivalence Scales for Tools No. 48, 62, and 91

Tool Risk Level			Equivalent Risk Level (%)
48	62	91	
Low	3	1	16.7
		2	25.0
Medium			33.3
	2	3	50.0
High		4	66.7
	1	5	75.0
Extreme			83.3
		6	100

Notes. Grey is used for clarity only, it does not convey any meaning.

3.3. Application to Different Scenarios of Hazardous Situations

3.3.1. Selection and development

To compare the different risk estimation tools, we used them for hazardous situations. The research team proposed a number of real-life hazardous situations from different industries and with different perceived risk levels. We selected 20 situations (scenarios A–T) representing different types of hazards occurring during different phases of the life cycle of machinery. To apply the tools consistently and to reduce subjectivity, we established a predefined format for the scenarios. The description of a scenario included a picture of the process or machinery and the worker involved in the task, a brief description of the hazardous situation, and some information to help choose the appropriate threshold for each parameter. In a real-life analysis, the team estimating risk usually has access to more data if required. Nonetheless, the level of detail proved sufficient for this evaluation. Figure 2 presents an example (scenario R) of a hazardous situation: a worker is cutting out a thermo-formed panel still at a high temperature, he is not wearing any protective equipment, he does the task on average 5 h a day.

3.3.2. Estimating risk for scenarios

Two different teams of researchers estimated risks independently for the developed scenarios. The results of both teams were then compared. Representatives of each team then discussed discrepancies in the risk levels to reach a consensus. Interpretation problems were minimized since the scenarios had been well defined before using the risk estimation tools. For scenario R (Figure 2), Table 4 gives the parameter levels and the resulting risk levels for tools No. 48, 62, and 91. There were only a few discrepancies, as a team had missed some details in a scenario description, and a consensus was reached.

Scenario R	
Thermal hazard	
Activity	Cutting out a thermo-formed panel.
Hazard	High temperature of the panel (60 °C).
Hazardous situation	Worker is near 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, etc.)	The worker is experienced in performing this task. The tools necessary for this task need to be as close as possible to the panel and cuts done while the panel is still hot.
Possible harm	Recurrent light burns.
Exposure information	On average 5 h a day during an 8-h shift.
Avoidance information (considering information on time and speed, warnings, escape route, training, experience, etc.)	The worker is experienced and aware of the danger. The nature of the work makes it difficult to avoid contact with the hot panel. The worker is not wearing protective gloves.

Figure 2. Example of a hazardous situation scenario.

TABLE 4. Evaluation of Scenario R for Tools No. 48, 62 and 91

Tool	Parameter	Parameter Level	Resulting Risk Level	Equivalent Risk Level (%)
48	S	3	E	100
	Ph	A		
62	S	IV	2	66.7
	A	5		
	Exd	4		
	Pe	II		
91	S	2	6	100
	A	2		
	Exf	2		
	Pe	3		

Notes. S—severity of harm, Ph—probability of harm, Exf—exposure frequency, A—avoidance, Exd—exposure duration, Pe—probability of hazardous event.

4. ANALYSIS OF RESULTS

This section presents and analyses the results of applying the 31 tools to 20 different hazardous situation scenarios. Table 5 shows the results of estimating the risk associated with the scenarios by using each tool.

4.1. Distribution of Resulting Risk Levels

The first analysis consisted of finding discrepancies in the distribution of risk levels among the scenarios and tools. Then, we categorized the scenarios and tools in terms of risk levels.

TABLE 5. 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	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	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	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	33.3	100	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	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	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	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	66.7	100	66.7	66.7	100	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	100	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	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	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	66.7	66.7	66.7	66.7	66.7	100	100	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	100	66.7	100	100	100	100	100	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	80.0	100	73.0
114	66.7	100	33.7	66.7	33.3	100	66.7	100	100	66.7	100	66.7	33.3	33.3	100	100	100	100	100	100	78.4
10	16.7	33.3	66.7	66.7	100	66.7	66.7	66.7	100	100	100	100	100	83.3	100	83.3	83.3	66.7	100	100	80.0
94	75.0	50.0	50.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	100	100	75.0	75.0	100	75.0	75.0	100	100	100	80.0
34	66.7	33.3	66.7	100	66.7	33.3	100	100	66.7	66.7	66.7	66.7	100	100	66.7	100	100	100	100	100	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	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	100	100	100	100	100	100	100	100	100	81.7
55	25.0	50.0	100	50.0	100	100	50.0	50.0	100	100	100	100	100	100	100	100	100	50.0	100	100	83.8
49	57.1	100	85.7	66.7	71.4	85.7	85.7	100	100	85.7	71.4	71.4	71.4	71.4	71.4	85.7	100	100	100	100	84.0
24	75.0	50.0	50.0	100	75.0	75.0	100	100	75.0	75.0	75.0	75.0	100	100	75.0	100	100	100	100	100	85.0
35	75.0	50.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	100	100	100	100	100	100	100	100	100	100	86.3
48	75.0	50.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	100	100	100	100	100	100	100	100	100	100	86.3
57	50.0	100	100	50.0	100	100	50.0	50.0	100	100	100	100	100	100	100	100	100	100	100	100	90.0
7	66.7	66.7	66.7	100	66.7	66.7	100	100	66.7	100	100	100	100	100	100	100	100	100	100	100	90.0
67	66.7	100	100	33.3	100	100	66.7	66.7	100	100	100	100	100	100	100	100	100	100	100	100	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
SD	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

4.1.1. Scenario classification

The average risk for all 20 scenarios was 69.4% (*SD* 24.8). The scenarios were then sorted in terms of risk levels, from low- to high-risk ones, according to the average resulting risk levels obtained with the 31 tools (Table 5). Scenario T, with an average risk of 96.4%, has the lowest standard deviation (8.2) and is statistically different from the other scenarios at a significance level of 5%. This is easily explained, since scenario T is obviously high-risk, and leads to the highest risk estimation (100%) by most of the tools.

We grouped the 20 scenarios into four risk categories (low, mid-low, mid-high, and high), based on their normalized value according to the criteria in Table 6. The normalized value of the results (the average risk level for each scenario) provided a logical way to group the scenarios without any bias, assuming they were normally distributed. The normalization process allowed a comparison of the results on a common scale, using a unitless value based on a normal distribution with an average of 0 (*SD* 1). The normalized value was calculated as follows:

$$z = \frac{x - \mu}{\sigma},$$

where x—average risk level of scenario x, μ—average risk level for all 20 scenarios (69.4%), σ—standard deviation for all 20 scenarios (24.8).

TABLE 6. Categories of Scenarios

Risk Category	Normalized Value
Low	<–0.5
Mid-low	–0.5–0
Mid-high	0–0.5
High	>0.5

Table 7 shows the four categories of scenarios, the number of times they were evaluated at the lowest or highest risk level with the 31 tools, their average risk level, standard deviation, and normalized value. Interestingly, most scenarios were evaluated with both extreme risk levels (lowest and highest) with the 31 tools, even

TABLE 7. Frequency of Lowest and Highest Risk Level per Scenario

		Count of Risk Level				
Category	Scenario	Lowest	Highest	Average Risk	*SD*	Normalized Value
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

those in the low- and high-risk categories. The following sections analyse each of the four categories of scenarios.

4.1.1.1. Low-risk scenarios. Three of the 20 scenarios (A, B, and C) were low-risk with an overall average risk level of 51.5% (*SD* 24.4). Those scenarios represented situations with mechanical or radiation hazards where non-life-threatening harm could occur. The average risk levels were 47.7–56.7% (*SD* 21.3–27.1) for the scenarios in this category. When estimating the risk associated with scenario A with the 31 tools, we found that no tool estimated the risk level at its highest value, and only one third of the tools gave it its lowest value. Surprisingly, scenarios B and C were evaluated at the highest risk level by four and three tools, respectively, including tools No. 57 and 67 for both scenarios.

4.1.1.2. Mid-low-risk scenarios. The second category represented the mid-low risk level, with an average risk level of 61.8% (*SD* 22.9), and included scenarios D–J. These scenarios carried ergonomic, material substance, mechanical, noise, and pressure hazards. Again, those were non-life-threatening situations but some could cause irreversible damage (loss of hearing or sight). For this category, the average risk was 57.6–66.6% (*SD* 21.4–24.7) for different scenarios. Tools No. 6, 17, 19, and 45 were the ones yielding the lowest risk levels. The highest ones were obtained with tools No. 55, 57, and 67.

4.1.1.3. Mid-high-risk scenarios. The mid-high category had six scenarios (K–P) covering fall, mechanical, thermal, and vibration hazards. Some scenarios resulted in possible death or amputation. The average risk level of this category was 75.5% (*SD* 21.4). The average risk and standard deviation for the scenarios were 72.5–78.5% and 19.8–24.9, respectively, for the tools in this category. For those scenarios, tools No. 17, 91, and 114 gave the lowest risk values 3, 4, and 2 times, respectively. Seven tools (7, 35, 41, 48, 55, 57, and 67) gave those scenarios the highest or one below the highest risk level.

4.1.1.4. High-risk scenarios. The last category corresponded to four high-risk scenarios (Q–T) with an average risk level of 86.9% (*SD* 17.9). The scenarios involved possible death or amputation due to material substances, mechanical, or thermal hazards. The average risk of the scenarios in this category varied 82.9–96.4% (*SD* 8.2–19.9). The standard deviation was the

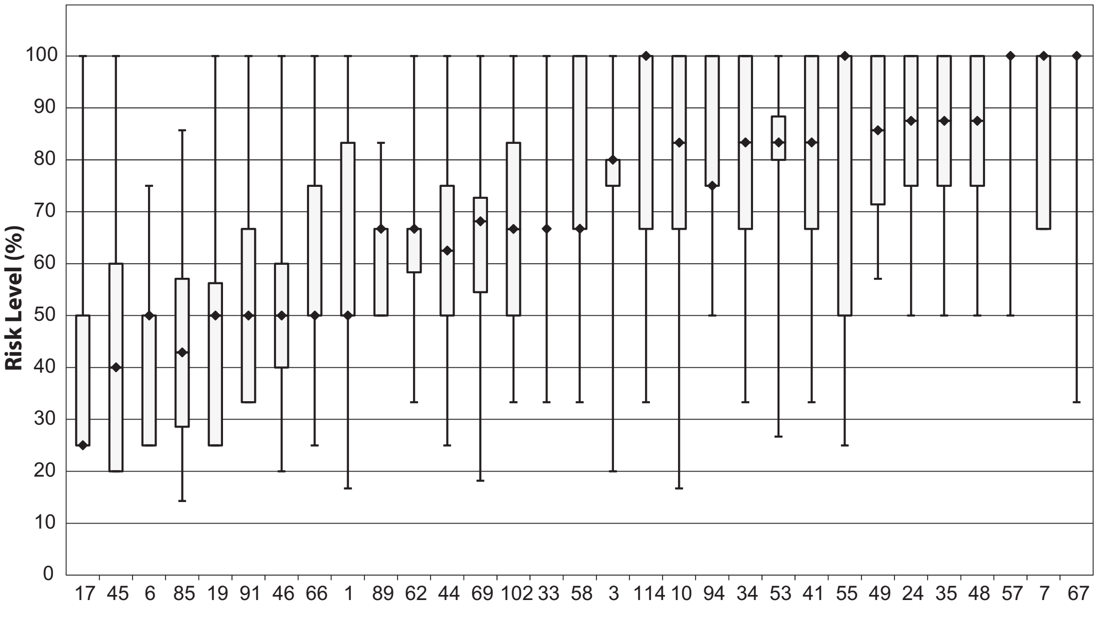

Figure 3. Box plot of risk per tool. *Notes.* The tools are listed in Table 2. The median is shown as a diamond; Q1 or 25th quartile, Q3 or 75th quartile are shown as bars; and the minimum and maximum values are shown as single lines.

lowest of the four categories. Interestingly, tool No. 17 gave its lowest risk level to scenario S, while 16 tools gave it their highest. Scenario T had the lowest standard deviation (8.2) of the category since most tools scored the highest risk level.

4.1.2. Tool analysis

We repeated a similar analysis for the tools. Figure 3 shows the dispersion of the results. It shows the median (a diamond), Q1 or 25th quartile, Q3 or 75th quartile (a bar), and the minimum and maximum values (a single line). A median of 100% is possible when over half of the data points have the same maximum value. In the case of tools No. 7, 55, 57, 67, and 114, the median, Q3, and the maximum were equal. Table 8 shows the frequency of the lowest and highest risk levels per tool for the 20 scenarios. The 31 tools were grouped into three categories in terms of risk levels, as low, intermediate, and high estimating tools, based on their normalized value. The tools in the low estimating category had a normalized value under –0.3, the tools in the intermediate estimating category had a normalized value of

TABLE 8. Frequency of Lowest and Highest Risk Level per Tool

		Count of Risk Level				
Group	**Tool**	**Lowest**	**Highest**	**Average Risk (%)**	***SD***	**Normalized Value**
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

–0.3–0.3, and the tools in the high estimating category over 0.3. An *F* test indicated that there were no significant differences between the variances of the groups at a significance level of 5%. However, the averages of the groups were significantly different. The following sections examine the results for the three categories of tools.

4.1.2.1. Low estimating tools. Low estimating tools were tools yielding a lower average risk for the scenarios than the overall average. The nine tools (1, 6, 17, 19, 45, 46, 66, 85, and 91) in this category had an average of 48.8% (*SD* 20.6). The average risk of the tools was 37.5–58.3% (*SD* 5.5–21.8). Moreover, the highest level of risk occurred only once for the 20 scenarios, while four scenarios had previously been defined as high-risk.

4.1.2.2. Intermediate estimating tools. This category of tools (3, 33, 44, 58, 62, 69, 89, and 102) estimated the risk of the scenarios with an average of 66.6% (*SD* 19.5). The average of the tools in this group was 63.4–73% (*SD* 10.2–24.8). Six of the eight tools in this category were two-parameter matrix tools, with the exception of tools No. 62 and 69, which were four-parameter matrix tools. Tool No. 89 did not give its lowest or its highest risk level to any scenarios and had the lowest standard deviation (10.2) of the tools. This tool produced risk levels of 50–83.3% for different scenarios.

4.1.2.3. High estimating tools. The 14 high estimating tools (7, 10, 24, 34, 35, 41, 48, 49, 53, 55, 57, 67, 94, and 114) tended to produce a higher average risk level of 84.2% (*SD* 19.5). The average risk of the tools was 78.3–91.7% (*SD* 14.1–27.1) for the 20 scenarios. Tool No. 114

TABLE 9. Average Risk Levels (%) of Scenarios by Tool Configuration

	Configuration of Risk Parameters		
Scenario	**S and Ph**	**S, Pe, A, and 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	93.7
average	68.8	68.3	73.1

Notes. S—severity of harm, Ph—probability of occurrence of harm, Pe—occurrence of a hazardous event, Ex—exposure to the hazard, A—technical and human possibilities of avoiding or limiting the harm.

behaved differently for mid-high-risk scenarios M and N, producing a low level of risk when the other tools produced a high risk. Moreover, tools No. 7, 57, and 67 produced the highest risk levels of the tools in this category, with an average of 90–91.7%. The tools in this category included all the different tool configurations reviewed in section 4.2.3.

4.2. Impact of Tool Configurations

This section describes how risk level depends on the parameters of different tools. Table 9 presents the results of tool configurations.

4.2.1. Tools with two basic parameters (S and Ph)

In this study, this configuration was considered the first standard configuration, in accordance with Standard No. ISO 14121-1:2007 (see section 1.2.) [1]. Twenty of the 31 analysed tools used the two basic parameters (S and Ph). The average risk yielded by the 20 tools was 68.8% (*SD* 23.5). The average risk levels were quite different in this group of scenarios (38.3–96%). Of these 20 tools, six were in the low estimating tool category (1, 6, 45, 46, 66, 85), six in the intermediate estimating tool category (3, 33, 44, 58, 89, 102), and eight in the high estimating tool category (7, 10, 24, 34, 35, 41, 48, 94). At the low end, tools No. 6 and 45 had an average risk level of ~44% while at the high end, tools No. 7 and 48 had an average risk level of 88%.

4.2.2. Tools with S and three auxiliary parameters (Pe, A, and Ex)

This configuration is the second standard configuration, in accordance with Standard No. ISO 14121-1:2007, where S is used with all three auxiliary parameters [1]. There were six tools using four parameters (S, Pe, A, and Ex) out of the 31 tools, with an average risk level of 68.3% (*SD* 26.2). Of these six tools, two were in the low estimating tool category (19 and 91) and produced an average risk of 50%. Tools No. 62 and 69 were intermediate estimating tools and yielded an average risk around 64%. Finally, tools No. 57 and 67 were high estimating tools and gave a significantly higher average risk of ~91% compared to the other two categories.

4.2.3. Tools with a different configuration

The remaining five tools (17, 49, 53, 55, and 114) used a configuration different from the two standard configurations described in sections 4.2.1. and 4.2.2. All of them used S in conjunction with one or two 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 (*SD* 27.7). Table 8 shows that except for tool No. 17, those tools were all in the high estimating tool category.

4.3. Impact of the Number of Levels of Risk Estimation Parameters

This section analyses different parameters of the tools based on the results of the 20 scenarios. Due to the small number of tools using each auxiliary parameter, we analysed only the two basic ones, S and Ph. Figures 4a and 4b present the results in terms of the number of levels for these two parameters. Note that the number on the curves indicates the number of corresponding tools.

4.3.1. S

All tools used S. Its number of levels varied from two to six among the 31 tools selected in this study. Figure 4a shows that there was a small increase in the average risk level for the 20 scenarios as the number of levels of S increased from two to five. Tool No. 17, with six levels of S, had a significantly lower average risk than the other tools. However, no other low estimating tool had more than four levels for S.

4.3.2. Ph

This parameter was used in 20 tools; the number of levels of Ph varied from three to six. Figure 4b presents an interesting result: the number of levels of Ph did not seem to influence the average risk level. Moreover, it shows that using the auxiliary parameters (Pe, Ex, and A) instead of

Ph (11 tools, N/A in Figure 4b) did not produce a significant difference in the average risk level.

4.4. Impact of the Number of Levels of Risk

Different tools had different numbers of risk levels. The number of risk levels varied 2–15 among the tools in this study (Table 1). Figure 5 plots the average risk based on the number of risk levels of the tools for the 20 scenarios. The figure clearly shows a decrease in the average risk as the number of risk level increased from two to five. Tools with 2–4 levels of risk produced a higher average risk level than tools with five or more risk levels.

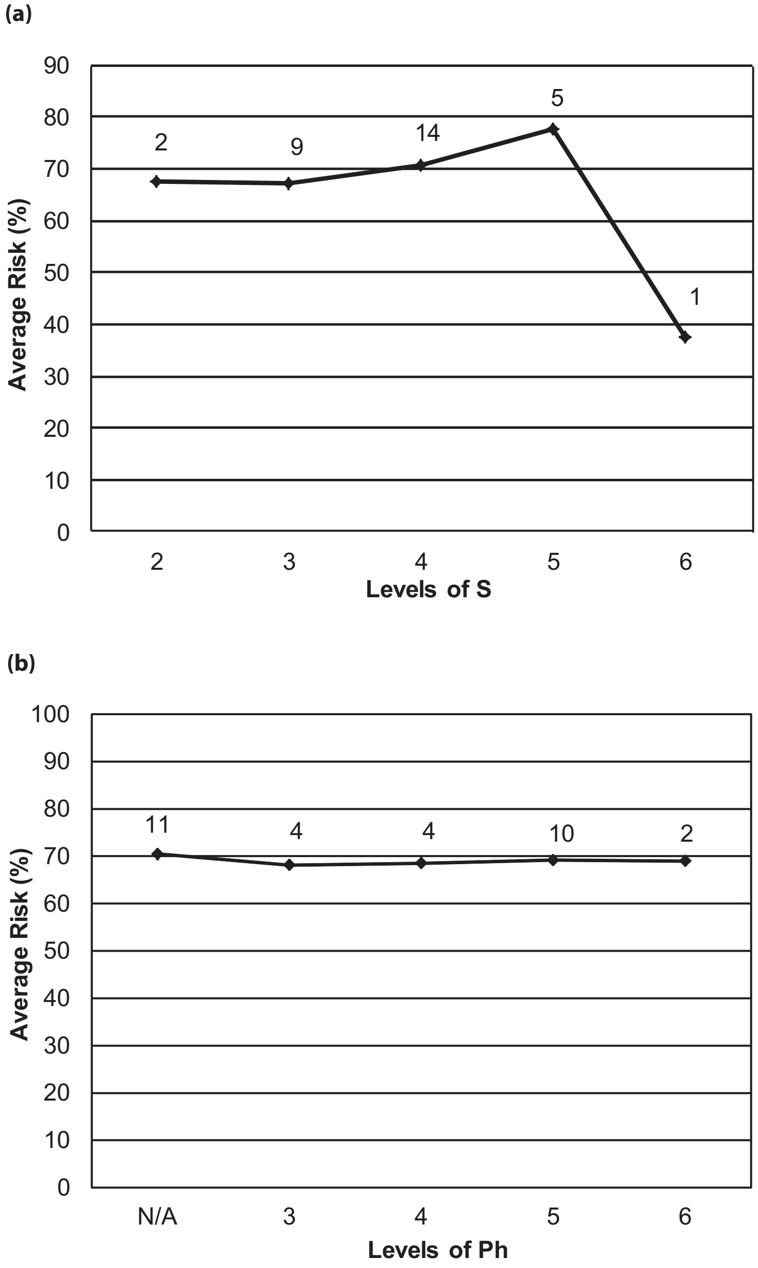

Figure 4. Number of parameter levels and average risks: (a) parameter S, (b) parameter Ph. *Notes.* S—severity of harm, Ph—probability of harm, N/A—not applicable. The number on the curve indicates the number of corresponding tools.

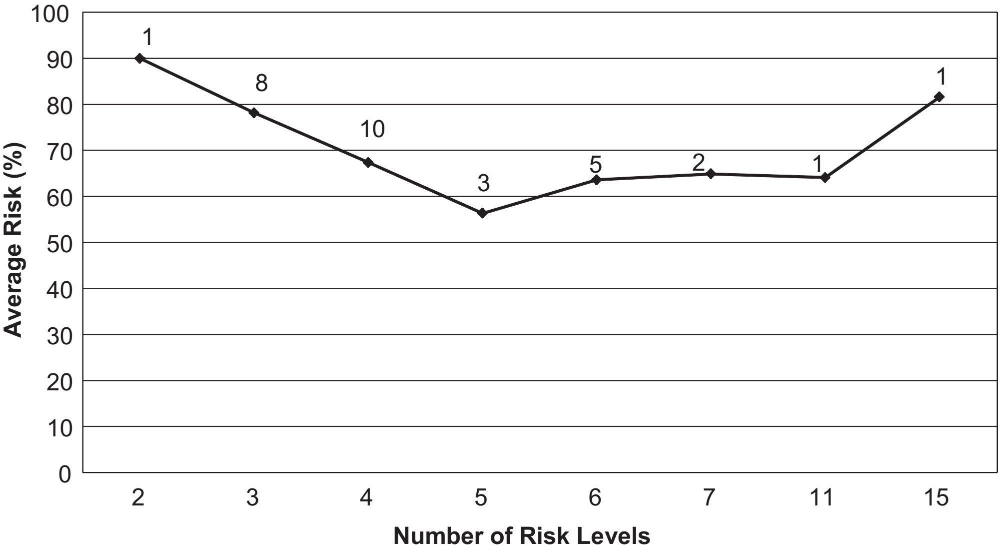

Figure 5. Number of risk levels and average risks. *Notes*. The number on the curve indicates the number of corresponding tools.

5. DISCUSSION

The results in section 4.4. show that the existing risk estimation tools may lead to different or contradictory results, thus confirming Charpentier's findings [7]. This study brings insight into the use of 31 tools, their different construction, and their defined scope. Sections 5.1.–5.6. discuss the results and findings and look at their impact on the estimated risk level.

5.1. Distribution of Resulting Risk Levels

We analysed the distribution of risk levels with respect to the scenarios and tool by tool. The analysis of risk estimations with different scenarios leads to the following observations:

- The tools produce varying risk levels, i.e., from maximum to minimum risk for the same scenario (see Table 5 for scenario B and tools No. 49, 57, 67, and 114, or scenario S and tools No. 17 and 91).
- Some tools tend to underestimate many high-risk scenarios (tools No. 6, 17, 19, 45, 46, 85, and 91).
- Some tools tend to overestimate many low- to mid-low-risk scenarios (tools No. 7, 10, 24, 34, 35, 41, 48, 49, 53, 55, 57, 67, 94, and 114). As stated before, the objective of a risk estimation tool is to rank the different hazardous situation scenarios according to their risk level. This objective will not be achieved if the tool places all scenarios at the same risk level (e.g., medium- or high-risk).

Table 7 indicates that very few scenarios were estimated without both extreme values (lowest and highest risk), which means that many tools awkwardly estimated the risk in certain circumstances. Moreover, for most scenarios, tools No. 17 (for 14 out of 20 scenarios) and 91 (for 9 out of 20) produced the lowest risk level, while tools No. 67 (for 16 out of 20) and 114 (for 11 out of 20) produced the highest risk level. Tools No. 17 and 144 used a configuration different from the two standard ones discussed in section 4.2.3. Their characteristics are discussed in section 5.2.2.

Tools No. 67 and 91 were four-parameter tools based on Standard No. ISO 14121-1:2007 [1]. Tool No. 67 was the highest estimating tool of the 31 tools in this study. It was a hybrid tool (computation of class [1]), not a pure matrix. It added given values for Ex, Pe, and A to define a class (corresponding to Ph as per Standard No. ISO 14121-1:2007, see section 1.2.) in a risk matrix. One possible explanation for the high estimating tendency of this tool is the relative weight of the auxiliary risk estimation parameters. In fact, with this tool, a continuous exposure to a hazard was mathematically equivalent to the highest Pe. It seems that Pe should have more importance than Ex in determining the probability of harm.

Tool No. 91 was a low estimating tool with four parameters with only two levels for S (based on the reversibility of the harm), while other tools had at least three levels for this parameter. With this tool, the amputation of the tip of a finger was equivalent to a worker's death since both harms are irreversible. Having only two levels for severity made it more difficult to discriminate some intermediate situations properly. Moreover, the risk levels were not uniformly distributed in the risk matrix. Section 5.4. discusses this characteristic further.

5.2. Impact of Tool Configurations

5.2.1. Tools using one of the two standard configurations

This study considered two standard configurations according to the risk estimation parameters: two parameters (S and Ph) and four parameters (S, Ex, Pe, and A) in accordance with Standard No. ISO 14121-1:2007 [1]. The analysis of the two configurations did not allow favoring either of the two. The average risk of the two-parameter tools was 68.8%, which was very similar to the four-parameter tools (68.3%), and standard deviation was high in all cases (Table 9). Based on the results and analysis, it can be stipulated that simple two-parameter tools can be as effective as more complex four-parameter ones in estimating risks associated with industrial machines. This may also explain why 20 out of 31 tools used the first method of construction compared to six for the second one.

5.2.2. Tools using a different configuration

Tools that use a different configuration from the two standard ones (tools No. 17, 49, 53, 55, and 114) tend to produce awkward results since they omit at least one important parameter. As mentioned before, most of those tools 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 methods.

In this group of tools, tools No. 49 and 114 do not use Pe, only three other parameters (S, A, and Exf [exposure frequency]). This could explain why they produce higher risk levels. Those tools cannot consider factors reducing risk, such as reliable safety control systems, which could significantly reduce Pe.

Tool No. 53 is a hybrid tool that computes the sum of three parameters (S, Pe, and Exf). This tool lacks the A parameter for conformity with Standard No. ISO 14121-1:2007 [1]. While this tool can include some risk reduction measures, it cannot include avoidance in estimating the risk, resulting in a high risk in many circumstances where harm could be avoided or limited by a proper reaction or by technical means.

Tool No. 55 has two parameters only (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 a construction, being continuously exposed to a hazard is enough to produce a high risk estimation.

Finally, tool No. 17 produces an average risk of 37.5% while the others ~80%. This tool uses three parameters (S, Pe, and Exd [exposure duration]). It does not consider A and, unlike other tools, defines multiple fatalities as its maximum severity level. Moreover, it is the only graphic tool (abacus) evaluated in this study. The theoretical experimentation in this study showed that this method offered more flexibility in selecting the level of a parameter owing to its continuous scales. At the same time, it is more demanding because the parameters and the resulting risk level can take intermediate values. The conversion of a graphic tool to a matrix is possible but requires well-defined thresholds for different parameters. For these reasons, matrix tools are easier to use and are preferable. Moreover, graphic tools tend to hide the dispersion of results, partly due to the nature of their continuous scales.

5.3. Impact of the Number of Levels on Each Risk Estimation Parameter

Figure 4a shows there is a small increase in the average risk level for the 20 scenarios as the number of levels of S increases from two to five. The reasons for that are not clear. As mentioned in section 5.2., having only two levels for severity probably makes it more difficult to discriminate some intermediate situations properly. Most tools use three to five levels for this parameter.

In contrast, it seems that the number of levels of Ph has no effect on the resulting average risk, with Figure 4b showing an almost flat line. More interestingly, it was observed that not using Ph increased the average risk only slightly. This seems to confirm that tools with two parameters (S and Ph) are equivalent to the other standard configurations in terms of risk estimation. Most tools also use 3–5 levels for this parameter.

5.4. Impact of the Number and Distribution of Levels of Risk

The results of this analysis suggested that the number of risk levels in a tool must be over three, or the tool produced high risk estimation or awkward results in some cases (Figure 5). Also, if the objective of a risk estimation tool is to rank different hazardous situations scenarios according to their risk level, it may be easier when there are more than two or three levels in the ranking system. Hence, we believe that four risk levels are 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 risk levels in some tools. The first problem is the uniformity of the distribution of the levels themselves. For example, the risk graph for tool No. 91 (taken from Standard No. ISO 14121-2:2007 [1]) has 24 possible combinations or outcomes, 15 of which are defined as low-risk (1 or 2). In the case of this tool, if S is set at its lowest level (S1), the resulting risk level will always be low, independently of the level of the other parameters. Hence, this tool tends to behave as low estimating. Similarly, tool No. 48 is built so that 16 out of the 25 outcomes fall into the extreme and high risk, thus, on average, producing a higher risk level. For this high estimating tool, selecting S of 1–2 will lead to extreme or high risk, whatever the probability of harm. This accounts for 10 of the 16 occurrences of extreme and high risk in the matrix. Interestingly, tools No. 35 and 48 have the same construction (S and Ph) and risk matrix, thus, the same risk level in this study. To have a uniform progression in risk, tools should have a reasonably uniform distribution of their risk levels, i.e., risk zones of 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 risk levels. A detailed analysis revealed that seven tools (1, 3, 45, 46, 55, 85, and 94) have discontinuities in their risk matrix, i.e., no uniform graduation when moving from one cell of the matrix to another. For example, in the tool in Table 1, the risk level leaps from *moderate* to *intolerable* in row 2, column 3, and omitting *substantial*. Such discontinuities in the risk matrix will not ensure that the risk levels are evenly distributed, and it also means that a parameter contributes unevenly to the determination of the risk.

5.5. Calibration of the Tools

During the study of the tools, it became obvious that certain tools were designed with a broader scope of application in view than safety of machinery. In the tools derived from major risk industries (railways, petrochemical, etc.) usually the worst case of severity of harm parameter are multiple deaths, while tools for safety of machinery consider a single and probable death as the maximum severity of harm. To achieve the maximum risk level, the former require multiple deaths (tools No. 10, 17, and 66). Since in the case of safety of machinery multiple deaths of its users are seldom, such a tool will never yield the maximum risk, potentially delaying or even preventing risk reduction measures in many common hazardous situations. It is clear that such a tool is not calibrated for evaluating safety of machinery where a single and probable death should score a maximum. Such tools are not appropriate for machinery risk assessment even if their scope states the opposite.

5.6. Construction Rule Proposal

Table 10 summarizes the findings of this study, linking the identified deviations or construction flaws to the low and high estimating tools, as described in section 4.1.2. Some of those deviations are attributed to the low or high estimating tools, while others might affect the risk estimation process in either way. Nevertheless, all those deviations or construction flaws can cause inaccurate estimation of risk in some circumstances. On the basis of this discussion, we propose some construction rules for risk estimation tools, which can also be applied in selecting a risk estimation tool.

1. Follow one of the standard configurations defined in this study in accordance with Standard No. ISO 14121-1:2007 (two or four parameters) [1] to ensure that no risk estimation parameter is neglected, since most tools with a different configuration overestimate low- to mid-low-risk scenarios (section 5.2.2.).
2. Carefully define the relative weight of each parameter to avoid having one parameter overly influencing the risk level (sections 5.1. and 5.4.).
3. Use 3–5 levels for S (sections 5.1. and 5.3.). Tools with two levels for S make it more difficult to discriminate some intermediate situations properly, producing awkward risk estimation in some circumstances. Moreover, most risk estimation tools use 3–5 levels.
4. Use 3–5 levels for Ph to be consistent with most risk estimation tools (section 5.3.).
5. Use at least four levels of risk (section 5.4.). Tools with fewer risk levels may overestimate risk.
6. Choose matrix-type tools rather than graphic (abacus) ones (section 5.2.2.). Matrix tools are preferable since they make the impact of selected parameter levels easier to see. We evaluated only one graphic tool and it underestimated most scenarios. Using such tools

TABLE 10. Summary of Findings

	Low Estimating Tools									High Estimating Tools													
Deviation	**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 Standard No. 14121-1:2007 [1] (e.g., ≥1 parameter absent)			✓														✓	✓	✓				✓
Relative weight of one parameter is too important in the resulting risk level (e.g., parameter has more weight based on tool architecture)									✓					✓		✓					✓		
<3 levels for S									✓								✓						
<4 levels of risk										✓			✓		✓					✓	✓		✓
Distribution of risk levels not uniform (e.g., construction of the tool often leads to the same risk level)		✓			✓	✓		✓	✓	✓	✓	✓		✓		✓			✓				
Discontinuities in risk matrix (e.g. leaps in risk levels)	✓				✓	✓		✓											✓			✓	
Not calibrated for safety of machinery (requires multiple deaths to achieve maximum risk)			✓				✓				✓												

Notes. Low estimating tools—tend to underestimate high-risk scenarios, high estimating tools—tend to overestimate low- to mid-low-risk scenarios.

is also complicated due to their continuous scales.

7. Provide even distribution of risk levels in the matrix (section 5.4.). This implies that each level of each parameter should ensure a number of risk levels, and that no risk level should take up most of the risk matrix.
8. Avoid discontinuities or leaps between risk levels in the matrix (no more than one level change between adjacent cells in the matrix, see section 5.4.). Such discontinuities affect the distribution of results and mean that a parameter contributes unevenly to the determination of risk.
9. Calibrate the tool for analyzing risk of machinery safety (section 5.5.) when selecting or constructing a risk estimation tool. Tools derived from major risk industries are usually not appropriate for common analysis of machinery risk even if their scope states the opposite.

6. CONCLUSION

In this article, we studied the results of using various tools estimating risk in machinery safety in the same hazardous situations. We investigated how the types of risk estimation parameters used in the construction of the tools, the number of levels of parameters, and of the number of risk levels influenced the results.

Consequently, we selected 31 risk estimation tools based on predefined criteria and compared them by estimating risk levels in 20 hazardous situations. The results showed large differences between the tools in evaluating the same situation. The scope of a tool and its construction seemed to be important in this variation of results. Tools that followed the two standard configurations produced similar average risk levels even though both configurations included tools under- or overestimating risks associated with hazardous situations. This leads to the conclusion that a simple two-parameter tool can be as effective as a more detailed four-parameter tool. Observing the operation of different tools led us to propose a series of recommendations for constructing balanced tools without bias that over- or underestimates risks. Those recommendations could help users choose or design a risk estimation tool. Future work includes validating the most promising tools by a large sample of different users from various industries.

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