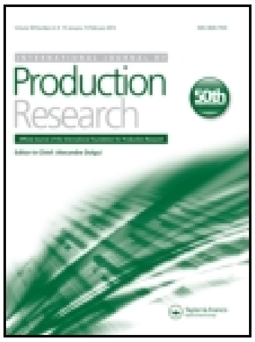

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A proposed occupational health and safety risk estimation tool for manufacturing systems

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There are numerous hazards to be found in almost any workplace. Annually, millions of workers die, are injured or become ill as a result of these occupational hazards. Industrial machines are often involved in these occupational accidents. Because of the demands of regulatory compliance, and the potentially high cost in terms of human suffering and lost production, businesses should place particular emphasis on safety measures. Risk is defined as a combination of the probability of harm and the severity of its consequences. Generally, risk estimation involves examining the hazards associated with a situation or with the use of a machine. A large number of techniques have been proposed for risk estimation, and recent studies have revealed that some of them have serious flaws. The main objective of this paper is to develop a proposed risk assessment tool based on the findings of an earlier study. Our research results constitute a first step towards the integration of occupational health and safety (OHS) concerns into facility planning models which traditionally do not consider OHS. The proposed risk estimation tool is developed based on the characteristics, strengths and weaknesses of 31 existing risk estimation tools, and is then applied to 20 scenarios representing different hazardous situations. To evaluate the performance of the proposed tool, the results were compared with those of other risk estimation tools and confirmed its proposed ability to estimate risk relative to other risk estimation tools.

Keywords: occupational health and safety (OHS); risk estimation tools; manufacturing systems

1. Introduction

Competition in the global marketplace has driven improvements in production systems in the manufacturing companies, and these improvements steer performance factors, including production capacity, work in process and cost efficiency (Neumannr et al. 2002). It remains the case, however, that the manufacturing industry is one of the most dangerous sectors for employees, given the frequency and severity of occupational accidents (Silvestri, De Felice, and Petrillo 2012). As a result, health and safety at work is one of the most important areas for targeted action in social policy, in both the European Union and the USA. Work-related injuries can compromise industrial competitiveness (Arne 1994; Hendrick 1996), owing to the costs related to labour turnover, absenteeism, and spoiled and defective goods, all of which reduce productivity (Andersson 1992). Also, the quality of the work of employees is strongly related to the level of concern for occupational health and safety (OHS) issues in the manufacturing context, i.e. in terms of employee performance and the efficiency of work systems (Erdinç and Yeow 2011). OHS contributes to product conformity by ensuring that the conditions necessary for thoroughly carrying out tasks are met (De Oliveira Matias and Coelho 2002). The Occupational Safety and Health Administration, the European Committee for Standards and the International Organisation for Standardisation (ISO) define recommended limits of exposure to some hazards in the workplace to reduce work-related injuries, and set out the responsibilities organisations have to protect the health and safety of their employees (Mutlu and Özgörmüş 2012). Protective action in the form of design changes, the use of safeguards and the implementation of safe procedures in the workplace will substantially reduce the probability of occurrence of harm and the severity of harm. Risk is the means for collecting and evaluating data on severity of an injury or probability of harm occurring in the workplace and an important tool for managers to use to analyse the potential impacts of any risks identified in the organisation (Lee, Lv, and Hong 2013).

Ideally, a facility layout should be designed to be efficient over time (Krishnan, Jithavech, and Liao 2009) and to ensure employee OHS. The physical arrangement of the components of the facility layout, referred to as the 'shop floor', includes the assignment of departments, machines and equipment to the most appropriate locations in the workspace to allow greater efficiency (Deb and Bhattacharyya 2003). A physical arrangement, which minimises the movement of personnel and material between departments, could decrease material handling costs, increase system

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effectiveness and productivity and enhance safety by reducing the risks associated with production activities. In practice, many more factors need to be considered in addition to monetary costs, an important one, being the maintenance of a safe and pleasant environment for the employees (Tompkins 2010).

The relationship between facility layout design and OHS has not been researched extensively. Chang and Liang (2009) developed a model based on a three-level multi-attribute value approach to evaluate the performance of process safety management systems at paint manufacturing facilities. Fernández-Muñiz, Montes-Peón, and Vázquez-Ordás (2007) developed a Safety Measurement System Scale based on the results of a survey of 455 Spanish companies to be used as a guide for managing the safety activities of organisations. Much earlier, Penteado and Ciric (1996) had presented a mixed-integer non-linear approach to optimising process plant layout which integrates safety and economics. Their approach identifies safe and economical layouts designed to minimise the overall cost of operating a chemical plant. Broberg (2007) refers to the concept of workspace design as a potentially new approach for ergonomists and other OHS consultants to consider. In the 1990s, Hinze and Wiegand (1992) had investigated whether or not designers were concerned with the safety of construction workers in their survey of major US design firms conducted to determine the extent to which design decisions are made, with specific emphasis on the safety of these workers. Shikdar and Sawaqed (2003) identify factors that affect worker productivity and OHS. It can be concluded from these studies that facility planners lack a tool for integrating OHS into models as one of the variables to optimise in addition to the traditional elements. It is also the case that OHS is basically a qualitative measure and cannot be included in facility planning models directly, unless safety issues can be quantitatively measured and compared with other important variables, such as cost. The main focus of this research is on introducing a scheme for quantifying OHS.

Specifically, this study is aimed at developing a risk estimation tool for OHS in a manufacturing company. The research methodology is based on a sample of risk estimation tools that have been devised in a previous study (discussed in Section 2.3), comparing their characteristics and then identifying the parameters that must be included in a proposed tool. In addition, risk scenarios that were developed in the study discussed in Section 2.3 were evaluated, using the proposed tool, and the results were compared with those of other risk estimation tools.

The outcome of this research is a risk estimation tool that includes some of the desirable traits in terms of architecture and parameters. The tool calculates a risk value using a numerical approach, which is believed to facilitate the integration of OHS into facility planning models. OHS will be one of the inputs to these facility planning models along with costs and space constraints.

2. Risk estimation in machine safety

Generally, improving workplace safety begins with a risk assessment, which consists of a series of steps to examine potential hazards. The process includes a risk analysis, followed by risk estimation. ISO 12100 describes risk analysis as comprising three stages: determining limitations, identifying hazards and estimating risk.

Methods for identifying hazards and estimating risk take many forms. Wassell (2008) presents a coherent and concise description of current methods for risk identification, and describes their limitations. Etherton (2007) reviews risk assessment concepts and methods which involve linking current risk theory to machine risk assessment, as well as exploration of how various risk estimation tools translate into decisions on industrial machine design and use. Anderson (2005) explores the risk analysis techniques applied during the design and use of industrial machines. The report by Parry (1986) describes the underlying principles and philosophy of hazard identification techniques, and discusses their use and limitations. In it, he reviews various techniques that are available for identifying hazards associated with the processing, storage and handling of dangerous substances, namely: HAZOP, checklists, FMEA, Fault Tree Analysis, Event Tree Analysis and Cause-Consequence Analysis.

2.1 *Risk estimation tools*

As noted by Main (2004), Worsell and Wilday (1997) and Worsell and Ioannides (2000), although many tools and methods have been proposed for estimating risk in companies, it is not easy to choose the tool that is best adapted to a particular company's needs. Risk estimation tools make it possible to qualify or quantify the risks inherent in various hazardous situations, in order to quickly distinguish high-risk situations from low-risk ones (Etherton 2007). These tools can be classified according to a number of criteria. The most notable aspects are addressed in Chinniah et al. (2011) as: diversity in the nature of each risk estimation tool; how to describe and define each parameter; the number of parameters; how to calculate, quantify and qualify risk; how to classify or evaluate the final result, etc.

Qualitative tools use at least two parameters. The severity of harm is represented, as is the probability of occurrence of harm. It is important to recognise that even traditional safety analyses must deal with the frequency of occurrence of harm, although these probabilities are not quantified, as they are in quantitative risk estimation. The outputs of risk estimation tools are relative rather than absolute, and so risks estimated using one tool cannot be directly compared to those estimated using another tool (ISO/TR 14121-2 2012).

The majority of qualitative risk estimation tools are either risk matrices or risk graphs. A risk matrix is a multidimensional table in which any class of severity of harm can be combined with any class of probability of occurrence of harm (Clemens 2000). Numerous research studies have used a risk matrix structure to introduce their risk estimation tools; e.g. BT, Kazer, Raafat Matrix and Wells SCRAM presented in Worsell and Wilday (1997); and US CPSC, HSE Construction and Australia Environment presented in Main (2004).

A risk graph has a tree structure, configured from left to right (ANSI/RIA-R15.06 1999). Two examples of applying the risk graph structure in risk estimation tools are the MEP risk graph (Worsell and Wilday 1997) and the risk graph used by the CSST (Occupational Health and Safety Commission) in Quebec, Canada (2006).

Quantitative risk estimation tools can be thought of as numerical scoring tools and quantified risk assessment. Quantified risk estimation tools calculate the probability of a specific outcome occurring during a specific period of time (Etherton 2007). Numerical scoring tools have between two and four parameters which are broken down into a number of classes, similar to risk matrices and risk graphs. However, instead of a qualitative term, a numerical value is associated with a class (Manuele 2001). One application of numerical scoring tool is the SUVA risk assessment method presented by Bollier and Meyer (2002).

2.2 *Risk estimation parameters*

Differences in the number of parameters, the types of parameters, the number of levels and the definitions of the parameters contribute significantly to the variations found in risk estimation tools.

In ISO/IEC Guide51 2005, risk is interpreted as comprising two parameters, severity and probability, and these form the basis for the risk estimation techniques that are popular for evaluating workplace risks (ISO/IEC-Guide51 2005). ISO 12100 (2010) states that the probability of occurrence of harm is itself made up of a number of parameters. These are the frequency and duration of exposure, the probability of occurrence of a hazardous event and the possibility of avoiding or limiting the harm that results (ISO 12100 2010).

(1) The severity of harm can be estimated by taking into account:
- The severity of injuries or damage to health; e.g. slight, serious or fatal,
- the extent of harm; e.g. to one person or to several people,

(2) *Probability of occurrence of harm* can be estimated by taking into account:
  (a) Nature of the exposure of people to the hazard:
  - reason to access the hazard zone, e.g. for normal operation, correction of a malfunction, maintenance or repair,
  - nature of access; e.g. manual feeding of materials,
  - time spent in the hazard zone,
  - number of people requiring access,
  - frequency of access.

  (b) Occurrence of a hazardous event:
  - reliability of statistical data,
  - accident history,
  - history of harm to health,
  - risk comparison.

  (c) Technical and human possibility of avoiding or limiting the harm:
  - the people involved, i.e. who may have been exposed to the hazard (skilled or unskilled workers),
  - how quickly the hazardous situation could lead to harm, e.g. suddenly, quickly or slowly,
  - awareness of risk, e.g. generally available information, user manuals, direct observation, warning signs and warning devices on the machinery,
  - the human capacity to avoid or limit harm, e.g. reflexes, agility and possibility of escape,
  - practical experience and knowledge, e.g. knowledge of the machinery or of similar machinery, or the absence of experience or knowledge.

The risk assessor is required to select the probability of occurrence of harm and the severity of harm from a fixed number of levels. There are generally three or four levels for each parameter (Charlwood et al. 2004). Chinniah et al. (2011)

define equivalence scales for the parameters in risk estimation tools, as well as including their risk levels. Their definitions are used in this paper, and further explained in Section 5.2.1.

2.3 *Comparison of risk estimation tools involving machinery*

Since the information presented in the research by Chinniah et al. (2011) is extensively used in this paper, a summary of their research is provided here.

In Chinniah et al. (2011), the authors study 31 risk estimation tools which follow the ISO 12100 (2010) guideline for estimating the risks associated with industrial machinery. They do so by comparing the risk estimation parameters as well as by applying various tools to estimate the risks associated with 20 hazardous scenarios. The study theoretically compares the performances of these tools in estimating risks, and evaluates whether or not the tools estimate risk uniformly.

The 20 scenarios depict a number of real-life hazardous situations that could occur in different industries and with different perceived risk levels. A list of these scenarios is presented in Appendix 1.

The results show significant differences among the tools in terms of estimating the risks associated with the same hazardous situations, i.e. risk is tool-dependent. The scope of the tool and its construction, or architecture, seems to be one of the contributing factors in the variability of the results. Tools that follow the two configurations proposed in ISO 12100 (2010) produce similar average risk levels, but tools in both configurations will underestimate or overestimate the risk associated with hazardous situations. They also observe that the 31 estimation tools could be classified into three groups: 9 low-risk estimating tools, 8 intermediate-risk estimating tools and 14 high-risk estimating tools. Moreover, there are tools that are not appropriate for risk estimation involving machinery, even though it is often claimed that they are. The authors propose a series of construction rules for the tools, in order to alleviate most of the problems associated with the variability in the risk estimations (Chinniah et al. 2011). The 31 risk estimation tools and the 20 hazardous scenarios are used in this study.

3. Research objective

Risk estimation can be carried out using a wide variety of tools, depending mainly on the nature of the hazards and on user preference. However, previous research has revealed that many risk estimation tools contain flaws which can be biased towards high- or low-risk estimates, which, if they are systematic, can lead to incorrect prioritisation of risk reduction activities or inappropriate risk reduction measures. Some variability in the risk estimation process can be expected, but a wide discrepancy in the results may lead to loss of credibility in the process.

3.1 *Research contributions*

The new risk estimation tool is based on the findings of previous research, and is designed for integration into facility planning models. The integration stage will be addressed in future research. The proposed risk estimation tool quantifies OHS, and its output is a suitable input for a facility planning model with other inputs, such as cost and space constraints.

In this paper, the proposed risk estimation tool is described and its results are compared with that of other risk tools.

4. Research methodology

This paper focuses on presenting a risk estimation tool that can be used for estimating risk. The overall research methodology is as follows:

(1) Use previous studies on risk estimation tools as the starting point.
(2) Apply the desirable traits of these tools in terms of the number of risk parameter levels and definitions.
(3) Study numerical tools (5 out of 31) suitable for designing an equation for calculating the risk value.
(4) Test the proposed tool by applying it to 20 hazardous scenarios.
(5) Evaluate the proposed tool by verifying how it performs compared to other tools, based on the average results for each scenario with the application of the 31 tools, i.e. rank the scenarios from lowest to highest risk, using the ranks established in the previous study.

5. The proposed risk estimation tool

In this section, the phases for developing the proposed risk estimation tool are discussed.

5.1 *Equation-based risk estimation tools*

Various risk estimation tools were studied to identify their characteristics, such as the risk parameters, the number of risk levels, the equations and the approaches they follow to assess risk. These tools were mainly adapted from Chinniah et al. (2011) and Gauthier, Lambert, and Chinniah (2012), in which the authors analysed 31 qualitative and quantitative tools.

The 31 tools were studied in detail and that number was narrowed down to five tools that calculate risk, as presented in Table 1.

The five tools introduced in Table 1 are not the only risk estimation tools available to estimate risk; however, they are well-known tools that calculate risk using an equation.

5.2 *Proposed risk estimation tool*

The proposed risk estimation tool uses the severity (S) of harm and the probability of occurrence of harm (Ph), the latter comprising:

Table 1. Summary of the five risk estimation tools selected.

Tool	Parameters (# of levels)	Risk calculation equation
BT (Worsell and Ioannides 2000)	• Potential to cause harm (3) • Likelihood of causing harm (3)	Risk = Hazard * Likelihood
Company A	• Severity (3) • Probability of occurrence of a hazardous event (3) • Frequency of exposure to a hazard (3)	Risk = Severity + Probability + Frequency
SUVA (Bollier and Meyer 2002)	• Severity (5) • Probability of occurrence of harm (5) • Frequency and duration of exposure to a hazard (5) • Probability of occurrence of a hazardous event (5) • Technical/human possibility of avoiding/limiting harm (3)	Risk ~ F (Severity; Probability of harm) Probability of harm = Frequency and duration + 2 * Probability of hazardous event + Avoidance
NORDIC (Mortensen 1998)	• Severity (4) • Probability of occurrence of harm (4) • Frequency of exposure to a hazard (5) • Probability of occurrence of a hazardous event (5) • Technical/human possibility of avoiding/limiting harm (3)	Risk ~ F (Severity; Probability of harm) Probability of harm = Frequency + Probability of hazardous event + Avoidance
Gondar (Design 2000)	• Severity (3) • Probability of occurrence of harm (3)	Risk = Severity * Probability of harm

- Frequency of exposure to the hazard (Exf).
- Duration of exposure to the hazard (Exd).
- Probability of occurrence of a hazardous event (Pe).
- Technical and human possibility of avoiding or limiting the harm (A).

In the literature, frequency and duration are often combined into one risk parameter: the exposure of people to the hazard (e.g. Mortensen (1998), ANSI/RIA-R15.06 (1999)). This research is based on four-parameter categorisation for Ph.

Definition of the proposed risk estimation model The proposed risk estimation model was based on the identified parameters. The mathematical relations between the parameters, as well as the weight assigned to each of them, have been adjusted according to the approach taken in the five selected tools. The equation was developed as follows:

$$\text{Risk value }(\text{R}) = \text{Severity of harm }(\text{S}) * \text{Probability of occurrence of harm }(\text{Ph})$$

$$\begin{aligned}\text{Probability of occurrence of harm }(\text{Ph}) = {} & \text{Frequency of exposure to the hazard }(\text{Exf}) \\ & + \text{Duration of exposure to the hazard }(\text{Exd}) + 2 \\ & * \text{Probability of occurrence of a hazardous event }(\text{Pe}) \\ & + \text{Possibility of avoidance }(\text{A})\end{aligned}$$

The proposed equation is a combination of the approaches described above. It includes all the risk parameters highlighted in ISO 12100, and is used to calculate the risk value for each scenario. Risk is calculated by multiplying the qualitative value of S by the qualitative value of Ph. This function is similar to the approach used in the BT and Gondar tools.

To calculate a numerical value of the probability of occurrence of harm (Ph), an approach similar to that applied in SUVA, NORDIC and Company A was used. Four parameters are added: frequency of exposure to the hazard (Exf), duration of exposure to the hazard (Exd), probability of occurrence of a hazardous event (Pe) and possibility of avoidance (A). In this function, the weight for the Pe value is considered to be twice that of the other parameters. This is because the likelihood of occurrence of a hazardous event, which may be of a technical nature (e.g. system reliability) or caused by a person (e.g. error, fatigue, etc.), has a higher rank than the other parameters (Bollier and Meyer 2002).

5.2.1 *Proposed risk estimation parameters and levels*

Since the proposed risk parameters are qualitatively scaled, so that they can be transformed into quantitative measures, a rating system is used by which quantitative values are assigned to the levels of each risk parameter. These values are based on a numerical rating scale of 1–5, where 1 is the lowest risk and 5 is the highest importance of risk. The number of levels for each parameter is determined from the equivalence scales which were formed by considering all 31 tools and matching their individual levels against one another, as explained in Chinniah et al. (2011). It is believed that the proposed tool will effectively discriminate among the various parameter levels and offer the desirable granularity if its five risk estimating parameters have a similar number of levels, as identified in Chinniah et al. (2011). These parameters, their risk levels and the corresponding quantitative values are presented below.

(1) *Severity of harm (S)*: The severity of harm parameter is defined as a hazard with the potential to cause harm. The likely effect of a hazard can be rated as in Table 2.
(2) *Probability of occurrence of harm (Ph)*: Ph is estimated by four parameters. These parameters and their risk levels are listed in Tables 3–6.

(A) Frequency of exposure to the hazard (Exf).
(B) Duration of exposure to the hazard (Exd).
(C) Probability of occurrence of a hazardous event (Pe).
(D) Technical and human possibility of avoiding or limiting the harm (A).

Table 2. Severity of harm.

Severity of harm (S)	Rank
Slight injuries (bruises) requiring no first aid or injuries requiring first aid but without lost time	1
Injuries requiring more than first aid (assistance) and with lost time or when there is irreversible harm and slight disability, but the employee is able to return to the same job	2
Serious disability, the employee being able to return to work, but perhaps not to the same job	3
Permanent disability, and the employee can no longer work	4
One or more deaths	5

Table 3. Frequency of exposure to the hazard.

Frequency of exposure to the hazard (Exf)	Rank
Less than once per year	1
Annually	2
Monthly	3
Weekly	4
Daily to continuously, i.e. several times per hour	5

Table 4. Duration of exposure to the hazard.

Duration of exposure to the hazard (Exd)	Rank
<1/20 of work time	1
1/10 of work time (45 min per 8 h shift)	2
1/5 of work time (90 min per 8 h shift)	3
Half of work time (1/2) (4 h per 8 h shift)	4
Continuously during work time	5

Table 5. Probability of occurrence of a hazardous event.

Probability of occurrence of a hazardous event (Pe)	Rank
Negligible	1
Unlikely	2
Possible	3
Likely	4
Significant	5

Table 6. Technical and human possibility of avoiding or limiting the harm.

Technical and human possibility of avoiding or limiting the harm (A)	Rank
Highly significant	1
Significant	2
Somewhat likely, with some conditions	3
Unlikely	4
Nil	5

These are the parameters that were used to model the proposed risk estimation tool. The quantitative values assigned to the risk levels make it possible to calculate a risk value, after which it is a simple matter to evaluate the risk inherent in the scenarios.

5.2.2 *Proposed risk estimation model*

The steps outlined below should be followed for each hazardous scenario to determine the phases required to evaluate OHS in a company using the proposed risk estimation tool. This model will not only identify OHS deficiencies, but also guide facility planners when designing a new layout.

Step 1: Identify the qualitative risk level for each of the five risk parameters.
Step 2: Assign a quantitative value (1–5) corresponding to the risk levels identified in Step 1.
Step 3: Calculate the risk values:

$$\text{Risk value (R)} = \text{Severity of harm (S)} * \text{Probability of occurrence of harm (Ph)}$$

$$\begin{aligned}\text{Probability of occurrence of harm (Ph)} = {} & \text{Frequency of exposure to the hazard (Exf)} \\ & + \text{Duration of exposure to the hazard (Exd)} + 2 \\ & * \text{Probability of occurrence of a hazardous event (Pe)} \\ & + \text{Possibility of avoidance (A)}\end{aligned}$$

6. Validation of the risk estimation tool

The proposed risk estimation tool is applied to the 20 hazardous scenarios in order to compare the risk values obtained with those attained from other risk assessment tools for the same hazardous scenarios. Figure 1 shows an example of one of these scenarios.

In the analysis by Chinniah et al. (2011), the average risk for each scenario was computed. Then, the scenarios were classified in terms of risk level from low to high (A to T), according to the average of risk values obtained from the 31 risk estimation tools.

The following sections discuss how the tool proposed in this research would assess the risk associated with the scenarios, and where it stands compared to the other risk estimation tools. This analysis and comparison was conducted by the authors of this paper.

6.1 *Estimating risk for scenarios*

The 20 risk scenarios were evaluated using the proposed tool (Figure 2). For each scenario, the qualitative values of S, Exf, Exd, Pe and A were determined. Then, the corresponding quantitative values were found, and a risk value was calculated for each scenario using the following equation: $R = S * (Exf + Exd + 2 * Pe + A)$. Figure 2 shows these analyses. Applying this tool, the overall average risk for the scenarios is 38.9%, with a standard deviation of 23.3.

For example, for scenario R (Figure 1), the severity of harm is considered to be injuries requiring more than first aid (medical assistance), with lost time, and so it was assigned a rank of 2 in the table. For the frequency of exposure to the hazard, scenario R is subject to exposure continuously, and so is assigned a rank of 5 in the table. Similarly, the duration of exposure to the hazard is considered to be continuous, and so is assigned a rank of 5. The probability of occurrence of a hazardous event is significant and is also assigned a rank of 5; and the possibility of avoidance appears to be unlikely, and so is assigned a rank of 4.

Consequently, the risk value is calculated as follows: $R_{\text{Scenario R}} = 2 * (5 + 5 + (2 * 5) + 4) = 48$.

6.2 *Evaluation of the proposed tool*

In order to evaluate the proposed tool, the sequence of scenarios is assessed based on the risk values of the individual scenarios, which are shown in Figure 3. The risk values are rounded to their upper bounds, while their equivalent percentage values are used for comparing the sequences. These values are as follows:

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 1. Example of a hazardous scenario – from Chinniah et al. (2011).

- Ranks between 1 and 25–20%.
- Ranks between 26 and 50–40%.
- Ranks between 51 and 75–60%.
- Ranks between 76 and 100–80%.
- Ranks between 101 and 125–100%.

For example, for scenario R, the calculated risk value is 48. This value is in the 26–50 range, which corresponds to 40%.

The risk values for the scenarios should follow the order A to T, or be close to it. The sequence of scenarios is compared by counting the number of intervals (i.e. the distance) between their current position and where their actual letter (A to T) must be situated. If a scenario is considered to have a lower risk, the number is shown with an asterisk.

With our proposed tool, scenarios H, M, N, O, P and R are considered to have lower than expected risk levels. As a result, the tool is a low-estimating tool. Based on the report by Chinniah et al. (2011), a low-estimating tool gives a lower average risk than the overall average for the scenarios (48.8%). With an overall average of 38.9%, the tool proposed in this paper is, in fact, a low-estimating tool.

Figure 3 also shows that scenarios G, L and Q are considered more risky than they actually are. However, this would not be an issue when assessing risk in real-life situations.

SCENARIOS	S	Ph				Risk Value R=S*(Exf+Exd+2*Pe+A)
		Exf	Exd	Pe	A	
S	5	5	1	1	4	60
G	2	5	1	3	1	26
A	1	5	1	4	3	17
B	2	5	1	2	2	24
R	2	5	5	5	4	48
N	3	4	1	4	3	48
O	5	4	1	1	2	45
E	2	3	1	1	3	18
H	1	5	1	5	5	21
M	4	4	1	2	2	44
K	3	3	2	1	3	30
L	5	3	1	2	3	55
I	2	5	3	2	1	26
P	2	5	5	4	4	44
J	3	5	5	2	1	45
F	1	5	3	2	5	17
C	1	5	5	1	2	14
D	1	5	5	5	4	24
T	5	5	5	4	5	115
Q	3	5	3	4	3	57

Figure 2. Estimating risk for the scenarios.

20	20	20	20	20	20	20	40	40	40	40	40	40	40	40	40	60	60	60	100
A	B	C	D	E	F	H	G	I	J	K	M	N	O	P	R	L	Q	S	T
0	0	0	0	0	0	1*	1	0	0	0	1*	1*	1*	1*	2*	5	1	0	0

Figure 3. Sequence of scenarios to which the proposed tool is applied.

6.3 *Comparing scenario sequences*

The sequence of scenarios for the proposed tool was compared with that used for each of the five selected tools. This comparison is shown in Figure 4. Chinniah et al. (2011) categorised scenarios in terms of their risk values: low risk (A to C), medium-low risk (D to J), medium-high risk (K to P), and high risk (Q to T). Their categorisation was based on the number of times a scenario was evaluated as having the lowest or highest risk values. A similar categorisation scheme was applied in this research.

Each of the five tools, as well as the proposed tool was used to generate a sequence of the scenarios based on an increasing risk value. Then, the sequence of scenarios for each tool was compared to the original order of A to T. The number of intervals between their current and original positions was counted, and the Sum of Differences was calculated, whether the scenario was considered a lower risk or a higher risk.

The colour codes in Figure 4 show the scenarios in their original four categories of low to high risk. In evaluating the performance of the tool in this research, it is not critical if a scenario is not in its original location, as long as it is still in its original risk category.

The comparison demonstrates that the sequence of scenarios obtained using the proposed tool is very similar to the original A to T sequence. Disregarding the fact that some of the scenarios have been placed in their risk categories incorrectly, the only scenarios that do not follow the sequence are R and L. Scenario R, with a 2-interval difference, is considered a medium-high-risk scenario, instead of a high-risk scenario. In fact, we observe that the risk associated with this scenario according to the assessment tool results is lower than it actually is, which could make the evaluation incorrect. However, the extent of this misplacement is only marginal and can be overlooked.

Scenario L is considered more risky than it actually is, as it had been assigned to the high-risk category instead of the medium-high risk-category. Although this can divert attention away from more risky scenarios, the interval difference is low, and only marginally affects the performance of our proposed tool.

When the Sum of Differences is calculated, the value obtained for the proposed tool is lower than the value obtained for the other five tools. This value gives the difference between the current scenario order and the original scenario order of A to T.

TOOLS	LOW			MID-LOW							MID-HIGH						HIGH				SUM of DDIFFERENCES	
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	Lower	Higher
	20	20	20	20	20	20	20	40	40	40	40	40	40	40	40	40	60	60	60	100		
Proposed	A	B	C	D	E	F	H	G	I	J	K	M	N	O	P	R	L	Q	S	T		
	0	0	0	0	0	0	1	1	0	0	0	1	1	1	1	2	5	1	0	0	7	7
	16.7	33.3	50	50	50	50	50	50	50	50	50	50	50	50	83.3	83.3	83.3	83.3	83.3	100		
BT	B	F	A	C	D	E	G	H	I	J	K	L	O	R	M	N	P	Q	S	T		
	1	4	2	1	1	1	0	0	0	0	0	0	2	4	2	2	1	1	0	0	11	11
	26.7	73.3	73.3	73.3	80.0	80.0	80.0	80.0	80.0	80.0	86.7	86.7	86.7	86.7	86.7	93.3	93.3	93.3	93.3	100.0		
Company A	A	D	E	K	H	L	M	N	O	S	C	F	I	J	P	B	G	Q	T	R		
	0	2	2	7	3	6	6	6	6	9	8	6	4	4	1	14	10	1	1	2	49	49
	33.3	33.3	33.3	33.3	33.3	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	100.0	100.0	100.0		
SUVA	A	D	F	G	H	B	C	E	I	J	K	L	M	N	P	R	S	O	Q	T		
	0	2	3	3	3	4	4	3	0	0	0	0	0	0	1	2	2	3	2	0	16	16
	33.3	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	100.0	100.0	100.0	100.0	100.0	100.0		
NORDIC	D	A	G	H	B	C	E	F	I	J	K	L	M	N	O	P	Q	R	S	T		
	3	1	4	4	3	3	2	2	0	0	0	0	0	0	0	0	0	0	0	0	11	11
	33.3	33.3	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3	100.0		
Gondar	B	M	C	E	F	I	J	K	L	O	A	D	G	H	N	P	Q	R	S	T		
	1	11	0	1	1	3	3	3	3	5	10	8	6	6	1	0	0	0	0	0	31	31

Figure 4. Comparison of the scenario sequences.

The Sum of Differences for each of the scenarios considered less risky is compared with that of the proposed tool and the other 31 tools. This comparison is illustrated in Figure 5. The first row in Figure 5 demonstrates the tool presented in this paper as well as the 31 tools which are referred to with a number and can be found in Gauthier et al. (2012).

All the eight tools that are positioned ahead of the proposed tool are of the risk matrix structure type, although this does not necessarily mean that the risk matrix tools are more precise than the proposed risk estimation tool because tools such as BT, SUVA and Gondar, which are positioned later in the sequence, are also risk matrix tools. Moreover, risk graph tools (e.g. tools 19 and 91) and numerical scoring tools (e.g. SUVA and tool 53) appear later in the sequence than the proposed tool.

6.4 *Correlation analysis*

A correlation analysis was performed to determine the degree of the relationship between the proposed risk estimation tool and the five selected tools. This analysis would specify the extent to which changes considered in the structure of the proposed tool is associated with other risk estimation tools.

The average risk values of the 20 scenarios assessed for the 31 tools, as well as for the proposed tool, were calculated. The analysis was performed on the 32 tools with a confidence level of $\alpha = 0.05$ and 30 degrees of freedom. The null hypothesis is as follows:

H0: There is a correlation between the structures of the proposed tool and those of the other risk estimation tools.

Even though all 31 tools were considered in the correlation analysis, the behaviours of the five selected tools and that of the tool proposed in this paper will be discussed. Figure 6 summarises the results of this correlation analysis.

To determine the likelihood that the correlation coefficient values occurred by chance, the Critical Value Table for Pearson's Correlation Coefficient from Siegle (2009) was used. Correlation coefficient values above 0.349 would indicate a statistically significant relationship between the respective risk estimation tools.

Results show that all the correlation coefficient values are above 0.349 for every tool, which means that there is a significant relationship between the proposed tool and the five selected ones, and H0 is accepted.

In this analysis, values higher than 0.6 are assumed to indicate a high correlation (shown with an asterisk in Figure 6), and those below 0.6 indicate a moderate correlation. Correlations between the proposed tool, and the BT tool and the SUVA tool are high (0.704 and 0.65, respectively). In support of these results, the risk estimation in the case of the BT tool was performed by multiplying the severity of the harm and the likelihood of harm, which is the same methodology as we use in our proposed tool. In the SUVA tool, the probability of harm is calculated by adding the following parameters: frequency and duration, probability of a hazardous event and avoidance of a hazardous event. These parameters are similar to those applied in the proposed tool. Moreover, the SUVA tool assigns a weight of 2 to the parameter: probability of occurrence of a hazardous event, which is similar to the approach taken for our proposed tool.

None of the selected tools uses all five parameters that were included in the proposed tool. The NORDIC tool is the most similar to the new tool in terms of the risk parameters used. With regard to the risk levels assigned to each parameter, the NORDIC and SUVA tools use the same number of levels (5) for the parameters: probability of occurrence of a hazardous event and frequency of exposure to a hazard as in the proposed tool. Also, the number of risk levels (5) in the SUVA tool is the same as in the proposed tool for the parameter: severity of harm.

These similarities justify the high degree of correlation between the proposed tool and the five selected tools. Therefore, it can be concluded that the proposed tool not only has similar functions to those in other risk estimation tools, but also is an improvement on those tools. The benefits and limitations of this tool are explored in the following section.

TOOL #	44	35	48	46	41	66	7	89	Proposed RA	3	17	33	57	BT	NORDIC	94	85	19	6	58	45	SUVA	55	24	34	114	10	Gondar	69	49	91	Com A
LOW (DIFFERENCE)	0	1	1	1	2	4	5	6	7	7	10	10	10	11	11	12	13	13	14	15	16	16	19	21	22	30	30	31	32	42	46	49

Figure 5. Positioning of tools.

	Proposed RA	BT	SUVA	Gondar	Company A	NORDIC
Improved RA	1.000	0.704*	0.650*	0.382	0.334	0.359

Figure 6. Correlation analysis.

7. Benefits and limitations of the proposed tool

To highlight the contributions of this research, the main benefits and limitations of the proposed tool are explored in this section.

The benefits of the proposed tool include the following:

(1) *It is functionally similar to other risk estimation tools*: The functions of the proposed tool have a similar theoretical foundation to that of most of the other tools currently in use; the risk matrix tools, for example. One of the tool's main benefits is that the analysts working with it do not need to understand the underlying theory.
(2) *It is applicable to any sector*: The proposed tool can be used for estimating risk in general and is not specifically designed for a particular situation, that is, it is not industry-specific. Consequently, it can be widely applied in the manufacturing sector.
(3) *It covers different areas of OHS*: This tool can be used for an initial risk for the purpose of prioritising interventions. If required, more specialised tools can be used for specific hazards or particular OHS issues, like ergonomics, and environmental issues, like fatigue (physical or mental), incorrect posture and chemical hazards.
(4) *It defines detailed risk parameters*: Five risk parameters have been defined for assessing hazardous scenarios in this tool: severity of harm, frequency of exposure to a hazard, duration of exposure to a hazard, probability of occurrence of a hazardous event and the technical and human possibility of avoiding or limiting the harm. These risk parameters are carefully differentiated; for example, the frequency and duration of exposure are considered as two separate parameters in the risk estimation approach as it is believed that doing so better captures the nature of the exposure to the hazard. Often, these two parameters, although different, are lumped together in one parameter in risk estimation tools or, worse still, only one of them is considered. The use of detailed risk estimation parameters makes it possible to consider, and document, all the factors at play in estimating risk, as well as identify potential risk reduction measures which could act on those different factors.
(5) *It defines detailed levels of risk estimation parameters*: The levels for each parameter are precisely defined in such a way that subjectivity is minimised. This helps to prevent disagreements among analysts, while at the same time, producing more consistent results. Five levels for each parameter are used, with no gap or discontinuity between them.
(6) *It includes sufficient levels of risk*: The proposed tool has four or five levels of risk, ranging from very low to very high. This is consistent with the majority of risk estimation tools, but the number is small enough that risk does not tend to be overestimated.
(7) *Its risk estimation formula has been configured to include weighting*: The risk estimation equation takes into account differences in the degree of importance of the parameters by assigning weights to them. This helps to prevent one parameter overly influencing the risk level. For example, the parameter: likelihood of occurrence of a hazardous event, which can be technical in nature or based on human element, has a higher rank than the other parameters. In the proposed tool, its weighting is double that of the other parameters. It is believed that estimating residual risk after the implementation of safety measures will be more realistic.
(8) *It takes a pseudo-quantitative risk estimation approach*: The proposed risk estimation tool is pseudo-quantitative, which makes it simple to incorporate into quantitative analyses. Because models for solving facility layout problems do not directly address safety issues, OHS features are rarely investigated in facility planning in terms of exposure to risk for work-related injuries. This tool can be used to integrate OHS into the next generation of facility planning models.

The 20 hazardous scenarios in this paper refer to both real and potential applications of risk estimation tools to manufacturing and production systems. The ability to represent the risk posed by every hazardous scenario with a quantitative risk value will enable facility planners to design the most appropriate layout based not only on cost, flow, etc., but on safety factors as well. The contributions of the new risk estimation tool are its ability to deliver improved safety using more precise risk parameters and levels, its comprehensiveness in terms of applicable situations and OHS features, and its pseudo-quantitative and balanced risk estimation formula. It is believed that the proposed risk estimation tool will provide more accurate results than the risk tools currently in use.

7.1 *Limitations*

One limitation of the study is that the proposed tool needs to be tested by different practitioners. So far, it is confirmed that the tool has all the theoretical characteristics of a well-balanced tool; its parameters are well defined; and it contains all the parameters required for risk estimation. The equation it uses appears to yield good results in terms of discriminating among the scenarios and in identifying the scenario sequence from low risk to high risk.

While the scenarios for this paper were mostly taken from the manufacturing sector, hazardous scenarios from the services sector can be developed and the applicability of the model in this context tested.

The proposed tool can require more time than some of the simpler existing techniques since one has to consider more parameters, more levels for each parameter as well as to calculate risk using an equation. Besides, it could require more than one analyst to evaluate the risk scenarios; therefore, fair assignments of ranks to the risk parameters are assured.

8. Conclusion

There are a number of methods for estimating risk, and choosing the tool that best suits a company's needs can be a challenge. This paper has presented a proposed tool for risk estimation, which will be able to enjoy general use in a wide range of industrial contexts. The proposed tool is intended to facilitate the integration of OHS into the design of a plant layout.

Twenty risk scenarios have been assessed based on five risk parameters, and the results used to calculate a risk value based on the risk estimation model were considered. The risk values were evaluated based on the degree of risk, from low to high, assigned to each scenario. Furthermore, the performance of the proposed tool was compared with that of the other risk estimation tools considered. The sequence of scenarios for the proposed tool turns out to be very close to their original order of A to T. Also, the Sum of Differences in considering a scenario shows it to be less risky than it actually is, and this risk is much lower with the proposed tool than with most of the other tools evaluated.

Future research will be aimed at proposing a methodology by which facility planning models and risk estimation tools can be integrated in order to better meet the safety requirements of companies. This means that it will be possible to design a facility layout in the form of a mathematical model while considering OHS issues as constraints of the model. Therefore, the output from the proposed tool in this paper can be used as an input to a facility planning model in which OHS is considered as important a factor as other factors in facility layout problems, such as cost, proximity, material flow, flexibility, and material handling system concerns.

Combining the risk estimation concept with the literature on organisational knowledge can be another interesting line of future research. For instance, Bohn (1994, 2005) provides a framework of the stages of technological knowledge. In the initial stages, there is an organisational unawareness of the risks inherent in manufacturing processes. Therefore, protective action should be taken at the initial stages (e.g. using robots) in cases where risk has not been identified, assessed and quantified. In the final stages, preventive actions will be more important.

The research can also be enriched by evaluating the proposed tool in real case studies. This could support validation of the practicality of the tool, with regard to its generalisability to many situations and its independence of the nature of those situations.

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Appendix 1. The 20 Hazardous Scenarios

Scenario number – hazard type	Activity	Hazard	Hazardous situation
A – mechanical hazard	Functional demonstration of a punching machine during a commercial show/expo. The punching machine is in automatic mode	Lateral movement of the table holding sheet metal to be punched	A person is located near the moving table
B – mechanical hazard caused by electrical fault	Tool (whisk) change on a food mixer	Rotary movement of the whisk	The worker is in contact with the whisk
C – radiation hazard	Luggage inspection	Electromagnetic radiation (X-rays)	The worker functions within a 5-m parameter of the X-ray machine
D – ergonomic hazard	Loading a new roll of polythene netting on a hay baling machine	Posture, constructing position, dangerous access (steps/platform)	The workers have to manually handle a roll of polythene weighing approximately 25 kg and load in upper part of machine indicated by arrow. Steps are provided but not suitable considering person in balancing heavy and awkward load. They therefore just get in the way
E – materials/ substances hazard	Lubricating a moving chain with the guards removed	Toxic material (oils)	Worker is situated close to the oil and moving parts
F – material substance hazard	Sanding panels within a body shop	Dust inhalation	The dust accumulation is apparent within the immediate vicinity of the worker
G – mechanical hazard	A self-guided vehicle moves through a workshop	Movement of the self-guided vehicle	Self-guided vehicle operates in same area where several employees walk
H – ergonomic hazard	The workers are threading paper into the feed rollers	Poor posture, constrained	The workers are leant forward in an unstable and uncomfortable position
I – pressure hazard	De-icing an airplane prior to take-off in sub-zero weather conditions	Pressurised water/glycol solution (approx. 40 bar) at high temperature (150–180°F)	The activity requires the worker to manually handle the high pressure hose
J – noise hazard	Operating large-panel press	Ambient noise is above 85 dB	Workers are in the vicinity
K – slips, trips and falls hazard	Repair of conveyor drive mechanism. The conveyor is stopped	Electricity	Proximity to live parts
L – mechanical hazard	Inspection and maintenance of the pulley drive mechanism	Movement of the drive pulley of the belt being drawn into in-running nip	Being in contact with the belt and pulley near a drawing-in point
M – mechanical hazard	Removing the torn/damaged parts from rollers in pulp and paper industry. The reel is in manual mode	Drawing in by large roller	The hands of the two workers are near the drawing-in point
N – thermal hazard	Working on a conveyor for carrying food	Presence of molten metal and sparks	Welding in the proximity of sawdust
O – slips, trips and falls hazard	Releasing a trapped log from a conveyor. The worker is situated on the conveyor 3 m above the ground	Bad stability – gravitational force	Working at height

(*Continued*)

Appendix 1. (*Continued*).

Scenario number – hazard type	Activity	Hazard	Hazardous situation
P – vibration hazard	Cutting car body panels using a pneumatic reciprocating saw	Hand-arm vibration (HAV) from the saw	Prolonged exposure to vibration generated by reciprocating saw
Q – mechanical hazard	Operation of circular saw to cut large and unusual shapes	Spinning saw blade	Operator hands in vicinity of blade when removing the work piece
R – thermal hazard	Cutting out thermo-formed panel	Elevated temperature of cut panel (60 °C)	Worker in the proximity of the panel
S – mechanical hazard	Tooling change on a robot-fed CNC lathe	Movement of the robot	The worker is situated in the trajectory of the robot. Robot is currently in home position and still energised
T – material substance hazard	Cooling of plastic extrusions	Legionella bacteria	Warm water recycled from sump, debris and dust are able accumulate within cooling water