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Proposal of a risk-factor-based analytical approach for integrating occupational health and safety into project risk evaluation

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ABSTRACT

Excluding occupational health and safety (OHS) from project management is no longer acceptable. Numerous industrial accidents have exposed the ineffectiveness of conventional risk evaluation methods as well as negligence of risk factors having major impact on the health and safety of workers and nearby residents. Lack of reliable and complete evaluations from the beginning of a project generates bad decisions that could end up threatening the very existence of an organization.

This article supports a systematic approach to the evaluation of OHS risks and proposes a new procedure based on the number of risk factors identified and their relative significance. A new concept called risk factor concentration along with weighting of risk factor categories as contributors to undesirable events are used in the analytical hierarchy process multi-criteria comparison model with Expert Choice© software.

A case study is used to illustrate the various steps of the risk evaluation approach and the quick and simple integration of OHS at an early stage of a project. The approach allows continual reassessment of criteria over the course of the project or when new data are acquired. It was thus possible to differentiate the OHS risks from the risk of drop in quality in the case of the factory expansion project.

1. Introduction

Industrial accidents continue to cause human suffering, capital losses, environmental destruction and social problems (Duijm et al., 2008; Kartam, 1997; Li et al., 2009; Shikdar and Sawaqed, 2003). In recent years, accidents in construction and industry have occurred in spite of rigorous management of projects and robust occupational health and safety (OHS) management systems (Makin and Winder, 2008) in all phases of project lifecycle (Li et al., 2009).

The explosion of a power plant in the start-up phase while testing a gas line in a populated region (43,000 inhabitants) of Connecticut (USA) on February 7, 2010 is reminiscent of a series of similar industrial accidents over the decades in terms of gravity and consequences. In most cases, inquiry into the causes of the accident revealed failure in the identification and evaluation of the impending risks, placing at peril the health and safety of human beings on site and in the surrounding areas. This was the case notably at Bhopal (1984) and at Chernobyl (1986).

In general, risk is evaluated in terms of its consequences with respect to project performance and rarely in terms of human suffering. Smallwood (2004) confirmed that quality, planning and costs are the parameters given the greatest consideration. This is reflected in the decision to install many high-risk production plants near or in densely populated areas (e.g. the AZF chemical plant in Toulouse, France; the now closed Sigma-Lamaque mine in Val d'Or, Quebec). In Quebec, high-risk installations still get the go-ahead in spite of the efforts by the Environmental Public Hearings Office to provide transparent information and to consult citizens.

The aim of this paper is to present a new systematic approach to the evaluation of OHS risks and proposes a new procedure based on the number of risk factors identified and their relative significance. This approach is able to overcome the difficulties of current tools in the manufacturing industry. The proposed approach is based on known techniques and tools, such as multi-criteria analysis techniques (e.g. analytic hierarchy process), expert judgment and the analysis of accidents and incidents. The analytic hierarchy process is selected to minimize the inconsistencies in expert judgments (Fera and Macchiaroli, 2009) and to support approaches that use mixed qualitative–quantitative assessment data (Chao et al., 2005).

This document is structured as follows. In Section 2, we begin by discussing the relevant tools and approaches used to manage project risk in different industrial sectors. We also give an overview of the use of qualitative and quantitative tools in various industries. Section 3 presents the methodology, including the conceptual model of the systematic approach to the evaluation of OHS risks. Given its importance in the approach proposed, the AHP method

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is outlined in Section 4. The proposed approach is then described in detail in Section 5 and a case study of a factory extension is presented to test the proposed approach. Section 6 follows with discussion and suggests possible directions for future research and a conclusion is provided in Section 7.

2. Literature review

Industrial work is risky in many economic sectors, in particular the construction industry (Fung et al., 2010), chemical plants (Vernero and Montanari, 2010), nuclear power plants (Young, 2005) and the mining industry (Hermanus, 2007). Safety problems can result from any of several combinations of causes, which vary from one industry to another. The high level of risk in the construction industry is explained by the nature and characteristics of construction work, low educational level of workers, lack of safety culture and communication problems (e.g. Fung et al., 2010; Gambatese, 2000b). In the mining sector, increasing numbers of subcontractors working in mines, the emergence of new mining ventures and recognition of small-scale mining pose new challenges to the practice of risk control (Hermanus, 2007).

The most effective way to improve OHS performance is to identify and eliminate hazards at the source (Glickman and White, 2007). Risk identification and assessment thus become primary tasks that are part of hazard prevention (Manuelle, 2005). Risk analysis is the foundation of the risk management process (Fung et al., 2010; Liu and Guo, 2009) and presents several challenges (Hagigi and Sivakumar, 2009).

OHS has not always been a preoccupation of process engineers (Hassim and Hurme, 2010). The motivations for integrating OHS risk management into engineering have been discussed recently. These include legislation (Gambatese, 2000b; Zachariassen and Knudsen, 2002), awareness of the importance of protecting workers (Gambatese, 2000a) and in some cases perceived potential to increase profitability and remain competitive (Sonnemans et al., 2002).

Industry has attempted to adapt engineering tools and methods to the assessment of OHS risks. These include quality management tools (e.g. failure methods and critical analysis (FMECA), "What If" analysis and check lists) and other industrial safety approaches (e.g. fault tree analysis (FTA), event tree (ET) and human reliability analysis (HRA)). Several authors have developed OHS risk reduction tools and models used in conjunction with historical data and shop floor know-how (e.g. Cameron and Hare, 2008; Ciribini and Rigamonti, 1999; Fung et al., 2010; Gibb et al., 2006; Hare et al., 2006; Kartam, 1997; Saurin et al., 2004; Suraji et al., 2001). It is important to note that the abovementioned tools are used alone rather than integrated into other types of risk management by an organization.

Quantitative methods of risk management are widely used in many industrial fields (Fera and Macchiaroli, 2009), for example the aerospace and nuclear industries (e.g. Skelton, 2002). These methods generally use equipment and software to analyze data. Quantitative methods are generally expensive and require specialized analysts (Restrepo, 1995). One of the best-known methods is that of the safety review and hazard and operability study (HAZOP) (Calixto, 2007). This method allows assessment of complex situations based on knowledge of several key parameters of a system.

In many industrial fields, the data and information used to assess risk are imprecise and incomplete (Ferdous et al., 2009). Quantitative approaches do not give reliable results when data are lacking (Pinto et al., 2010). Acquiring useful information using quantitative risk assessment based on probabilistic models is not yet possible (Jabbari Gharabagh et al., 2009). In the petrochemical industry, Jabbari Gharabagh et al. (2009) attributed the current difficulties in risk assessment to the complexity of the current quantitative methods. These problems are more significant in the design stage of industrial projects (e.g. Pinto et al., 2010).

Pinto et al. (2010) proposed a qualitative model for health and safety risk assessment based on available data and using a fuzzy logic approach. They concluded that qualitative approaches for human-centered problems are flexible enough to assess risk. Another method worth mentioning was developed by Hassim and Hurme (2010) for assessing the health risks of a chemical process during the design phase. The method takes into account both the hazard associated with the presence of the chemicals and the potential for the exposure of workers to them. An "Inherent Occupational Health Index" has also been proposed to conduct the risk evaluation early in the design phase. Jabbari Gharabagh et al. (2009) concluded that the use of historical data is not only important in risk management, but is also helpful in risk evaluation as an indicator of acceptable risk criteria.

Neglecting the consideration of human factors in risk analysis is due in part to the difficulty of quantifying many of them (e.g. Human risk-taking behavior in Kotani et al., 2007). In addition, human behavior cannot be predicted from analysis of accident and incident histories alone. Evaluation based solely on historical information always runs into difficulties in meeting the challenge of the proactive treatment of risks.

It is always more effective and profitable to integrate risk evaluation beginning at the project design phase (Charvolin and Duchet, 2006). Complete and accurate evaluation will contribute to reducing risks as well as justify monitoring of workers and residents of the surrounding community in the event of damage to the installation, whether caused by an industrial accident or a natural event (Pérusse and Bernier, 2009). Determining the risks and measures for dealing with them before setting the project in motion is without question the wisest course to follow (Gray and Larson, 2006).

Starting from the need to create an appropriate and effective approach that integrates the management of all project risks in the manufacturing sector, our paper explores the possibility of creating such a model for industrial projects using an approach based on mixed techniques.

The proposed approach allows quick prioritizing of identified risks and allows evaluators to identify additional potential causes of undesirable events without nullifying the previous risk element compilation effort. The simplicity of the procedure should facilitate its use in small and medium-sized businesses without requiring a major investment.

3. Methodology

Based on the literature (Aubert and Bernard, 2004; Curaba et al., 2009; Freivalds, 1987; Henderson and Dutta, 1992) and on continuous risk management standards (Dorofee, 1996), this paper proposes a conceptual model for integrating occupational health and safety into project risk evaluation based on multi-criteria comparison (AHP). We have considered a model of risk composed of three elements detailed below and the conventional steps of risk management.

In order to propose a conceptual framework for identifying and assessing risks, we began by tracing the elements of risks that are used for the identification steps. Once the elements of risk are identified, the causality links form the basis of the evaluation and the control steps.

Our analysis is based on a model of risk composed of three principal elements (Fig. 1), namely the risk factors, the undesirable event, and the impact of the undesirable event. In order to control risk, all of the elements must be identified and the various causal

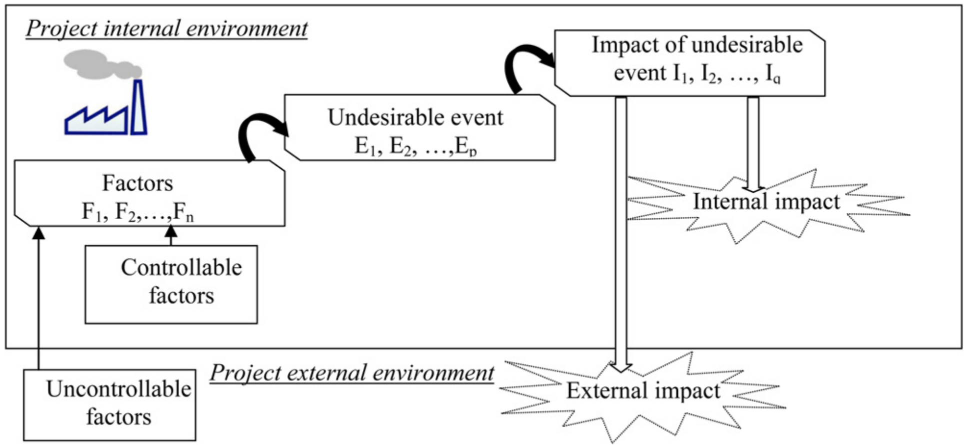

Fig. 1. Modelling of risk and its influence.

links likely to appear in a field or area of study must be clarified as well as their mechanisms and the conditions that trigger them.

It should be noted that the project internal environment is made up of controllable variables such as the effectiveness of health and safety measures. The variables of the external environment (e.g. weather-related) are always the most difficult to control or modify.

The proposed approach is based on a risk factor approach (Fig. 2). This is an original approach to risk evaluation, since it is based on a novel parameter expressed as a fraction and representing the presence or likely appearance of the risk factors that trigger an undesirable event, or more specifically the direct influence of the number of risk factors present on the probability of occurrence. This new concept is called the "risk factor concentration". When this concentration increases, there is a greater chance of triggering the associated undesirable event.

Aubert and Bernard (2004) present a similar approach without specifying that the impact of an undesirable event may include several types of loss. The causality links are identified by the evaluators and determine how the potential impact of a risk will be evaluated. Each link (i) between a factor, an event and an impact thus defines a possible route of concretization of a risk as an event having a negative impact.

4. The analytical hierarchy process (AHP)

The AHP (Saaty, 2000) method is a structured multi-attribute decision method used in complex decision making and is the most widely used of the multi-criteria comparison methods. Developed in the USA by Saaty in the 1970s (Simei et al., 2009), this method is based on three fundamental principles: decomposition of the structure, comparison of judgments and hierarchical composition (or synthesis) of priorities. AHP is applicable to decision situations involving subjective expert judgments and uses both qualitative and quantitative data (De Steiguer et al., 2003). This method creates a priority index for each expert decision or judgment. AHP summarizes these judgments by ensuring their consistency.

The proposed approach involves the AHP method for the paired comparison of the risk factors, which was carried out using the decision aid software Expert Choice©. The AHP method is used in project management as a decision aid in order to choose a project on the basis of company objectives. Al-Harbi (2001) discussed this method in the context of the pre-qualification of construction contractors.

In the OHS field, attempts to use AHP began in the context of ergonomic analysis done by Henderson and Dutta (1992) and the comparison of ergonomic standards by Freivalds (1987).

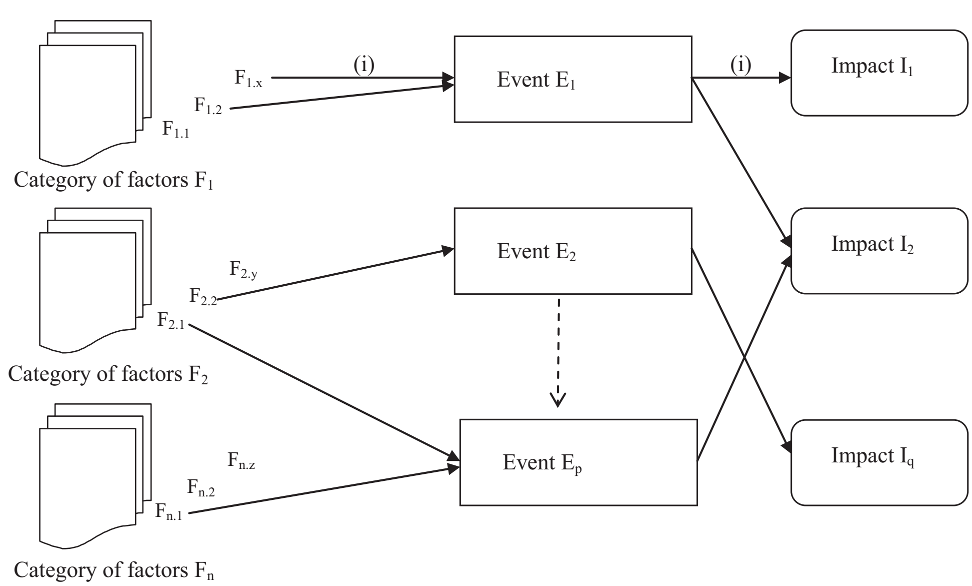

Fig. 2. The links in a risk factors approach to risk analysis; example inspired from Aubert and Bernard (2004).

Henderson and Dutta (1992) compared NIOSH recommendations with those of the ECSC for the two-handed handling of loads in the sagittal plane. In this study, 11 risk factors were compared using the AHP model. These factors, namely frequency, distance, height, dimensions, load shape, position of the load center of gravity, anthropometric dimensions, gender and age of the individual and limited biomechanical and physiological criteria, were proposed in a previous study by Freivalds (1987). Using AHP, Freivalds (1987) showed discrepancies between NIOSH and ECSC standards, which were attributed to differences in the respective equations, hypotheses and concepts.

Padma and Balasubramanie (2008) used AHP to develop a decision aid system that draws on a knowledge base in order to rank risk factors associated with the occurrence of musculoskeletal problems in the shoulder and neck. Another system using AHP to compare risk factors associated with human error and with the causes of accidents in the maritime transport sector was developed in a study by Zhang et al. (2009). Topacan et al. (2009) used AHP to evaluate a health information system with the aim of investigating the factors that influence user preferences in the selection of health services. Fera and Macchiaroli (2009) have selected AHP for their model of industrial risk assessment to identify major events and validate the actions taken.

In ergonomics research, AHP has been described as a reliable method for comparing risk factors, evaluating risks, defining priorities, allocating resources and measuring performance (Henderson and Dutta, 1992). The use of AHP to analyze human factors should make the hierarchical model more clear, simple and practical (Zhang et al., 2009) and should also allow more structured discussion and easier examination of relevant information (Larson and Forman, 2007). AHP reduces the inconsistency of expert judgments and appears acceptable in terms of reliability (Fera and Macchiaroli, 2009). This multi-criteria method allows incorporating both objective and subjective considerations into the decision process (Forman and Selly, 2002).

In conclusion, the feature of combining both quantitative and qualitative data and controlling the consistency of expert judgments makes AHP the most applicable to the proposed approach. We will provide objective judgments and reliable prioritization of risks.

4.1. The theoretical background of AHP (Nguyen, 2009):

Given n alternatives $\{A_1, A_2, \ldots, A_n\}$ from which a selection is to be made, the expert attributes a numerical scale a_{ij} from the scale of binary combinations (Table A.1 in Appendix A) to each pair of alternatives (A_i, A_j). The term a_{ijk} expresses the individual preference of expert k regarding alternative A_i compared to alternative A_j.

Once the overall expert judgments are created and computed using the geometrical mean (1), they are inserted into the comparison matrix D (2):

$$a_{ij} = \sqrt[n]{a_{ij1}, a_{ij2}, \ldots, a_{ijn}} \tag{1}$$

$$D = \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ a_{n1} & a_{n2} & \ldots & a_{nn} \end{bmatrix} \tag{2}$$

Matrix D is a comparison matrix with inconsistent judgments and has the following properties:

$$a_{ij} > 0; a_{ij} = \frac{1}{a_{ji}} \forall i \quad \text{where } j = 1, 2, \ldots, n \tag{3}$$

Matrix D is considered consistent when its elements meet conditions (4) and (5):

$$a_{ij} \cdot a_{jk} = a_{ik}; \forall i, j, k \quad \text{where } i, j, k = 1, 2, \ldots, n \tag{4}$$

$$a_{ij} \cdot a_{ji} = 1 \quad \text{where } i, j = 1, 2, \ldots, n \tag{5}$$

The ordering of alternatives is taken as a result of the approximation of comparison matrix D using matrix P:

$$P = \begin{bmatrix} p_{11} & p_{12} & \ldots & p_{1n} \\ p_{21} & p_{22} & \ldots & p_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ p_{n1} & p_{n2} & \ldots & p_{nn} \end{bmatrix} \tag{6}$$

The elements of which are consistent judgments presented in the form of weight ratios among alternatives:

$$p_{ij} = \frac{p_i}{p_j} \quad \text{where } i, j = 1, 2, \ldots, n \tag{7}$$

p_i signifies the weights of the alternatives of the order vector p:

$$p = (p_1, \ p_2, \ldots, \ p_n)^T \tag{8}$$

We obtain the standardized order vector after the arithmetic normalization:

$$p^* = (p_1^*, \ p_2^*, \ldots, \ p_n^*)^T \tag{9}$$

where

$$p_i^* = \frac{p_i}{\sum_{i=0}^{n} p_i} \tag{10}$$

Saaty (2000) uses the maximum eigenvalue method to approximate the judgment matrices:

$$D.p = \lambda_{\max} p \tag{11}$$

where $\lambda_{\max}$ is the maximum eigenvalue of matrix D.

For reliable comparison, it is important to note that the inconsistency of the comparison matrix D must be less then 10%. This condition means that the number of times that condition (4) is not met must be below 10%.

5. Results and analysis

5.1. The proposed risk-factor-based analytical approach

The proposed approach is divided into three phases and each phase is divided into steps. This approach outlines all phases of risk management including: (1) risk identification; (2) risk assessment and (3) actions.

The approach uses several methods and tools such as systematic observations, interviews, multi-criteria analysis (AHP), analysis of accidents and incidents and the new concept of risk factor concentration. In Table 1, we report the tools and methods used for each phase and step.

The model is based on teamwork and knowledge of multi-criteria analysis techniques. The purpose of this model is to integrate OHS risk with operational risk without creating a conflict and without complicating the process for the risk management team. It should be noted that multi-criteria analysis is used partly to compare the risk factors, not to compare the risks identified.

Like any approach to risk management, the model gives appropriate consideration to the phase of identifying risk elements (risk factors, undesirable events and impact of undesirable events). The risk assessment phase uses multi-criteria analysis, expert judgment and the new concept of risk factor concentration. The analysis is made according to the causal links between elements of identified risks. The action phase is based on risk prioritization. This step can

Table 1
Details of the proposed approach by risk factors.

Phase	Step	Description	Method
1	1	Identification of risk elements (on the shop floor)	Observations Interviews
		Identification of risk elements (historical data)	Analysis of accidents and incidents
	2	Identification of causal links between the risk elements	Expert judgment
2	3	Paired comparison of categories of risk factors	AHP
	4	Estimation of the probabilities of occurrence	Concept of risk factor concentration Eq. (13)
	5	Evaluation of the impact of undesirable events	Expert judgment Eq. (14)
	6	Evaluation and prioritization of identified risks	Eq. (12)
3	7	Action prioritization	AHP
	8	Action monitoring and control	Prevention plan

be assigned to the project manager, who will plan the project risk evaluation review.

In the following subsections of the paper, we describe and analyze in more detail the eight steps of the proposed approach used to manage OHS risk.

5.1.1. *Phase 1: risk identification*

Risk identification necessarily involves identification of the elements of the risks. The risk model includes three elements: (1) risk factors, (2) undesirable events and (3) the impact of undesirable events (Aubert and Bernard, 2004). Once the risk elements are identified, experts with the collaboration of workers involved trace the possible causal links between these elements. This work simplifies the conceptualization of the various risks identified in order to trace their possible impact on project progress. In our model, industrial expertise is crucial to identifying causal links.

The main objective of this step is to establish an OHS database. To collect the data needed to establish this OHS database, the model uses several tools such as analysis of documentation (identifying events and sources of hazards in historical data), field observations (identifying operations, work methods, equipment and risky behaviors) and interviews with workers. Interviews are also used to confirm the presence of sources of industrial hazards gleaned from the database of Curaba et al. (2009). The use of expertise (interviews, expert opinion and teamwork) can avoid the problem of lack of historical data especially in startup organizations. This database also facilitates access and use of data required for project risk management in more and more competitive environments, in which pressures that mount following delays often undermine the quality of the analysis and the evaluation.

Historical data have not been used for direct estimation of the risks, unlike in several other studies (e.g. Furukawa et al., 2009; Liu et al., 2007; MacNab, 2004). The historical portion is rather a grouping of sources of information (Fig. 3) that includes the elements necessary for identifying the causal links and evaluating the possible impact of each risk.

5.1.2. *Phase 2: risk assessment*

Based on Eq. (12), which combines the probability of occurrence and the impact of an undesirable event taken from the literature (Aubert and Bernard, 2004; Fung et al., 2010), estimates of these two parameters are needed in order to assess risk. The direct cause of an undesirable event is the activation of one or more categories of risk factors:

$$\text{Risk}_{(i)} = P_i \cdot I_i \tag{12}$$

where P_i is the probability of an undesirable event E(i) and I_i is the impact of an undesirable event E(i).

The multicriteria comparison used in the first step of the risk assessment phase is to quantify the importance of risk factors identified in the first phase of the process. This comparison is used to estimate the weight of the influence of each category of risk factors. These weights give the categories more credibility as contributors to an undesirable event.

In the majority of cases analyzed in the OHS field, risks and accidents arise from human behavior or an organizational problem (Saurin et al., 2008). Using historical data to estimate probabilities supposes that human behavior and organizational constraints are characterized by linear continuity. This hypothesis is far from reality, since both of these parameters depend on several latent and sometimes non-probabilistic phenomena, which are difficult for analysts to identify and monitor (Molenaar et al., 2009; Saurin et al., 2008).

In the second step of the risk assessment phase, the new concept highlighted in this research, namely risk factor concentration, is applied to estimate probabilities of occurrence. The probability that an undesirable event will occur depends primarily on the number of the risk factors in the risk categories linked with the event in the situation under study (link "(i)" in Fig. 2).

The concentration is calculated as follows:

$$C_{ij} = \frac{x_i y_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} x_i y_{ij}} \tag{13}$$

where x_i is the number of risk factors by category Fi and y_{ij} is the weight of risk factor category Fi causing an undesirable event Ej estimated by AHP. $i \in \{1, 2, \ldots, n\}$ and $j \in \{1, 2, \ldots, m\}$.

Once the concentration is calculated, a scale is used to convert this concentration to probability. In the proposed approach, two categories of conversion (numerical or qualitative) can be used. This conversion does not affect the linearity of the results.

The reasoning applied here to risk level estimation emphasizes that the probability of occurrence is influenced by the presence of risk factors (Coppo, 2003; McLeaod et al., 2003; Rosness, 1998). Since the probability of occurrence is generally not available and no statistics exist for its direct estimation (Aubert and Bernard, 2004), evaluators use indirect estimates with relative scales (e.g. Hallowell and Gambatese; Restrepo, 1995).

The proposed approach allows identification of risk factors and calculation of the concentration of these factors in relation to each identified undesirable event. The conversion of these factors (which form the basis of the estimated probabilities) does not distort the calculations or change the philosophy of risk assessment and therefore has the advantage of allowing the organization to act according to its risk tolerance or perception (e.g. Ewing and Campbell, 1994; Frank, 2010; Hallowell, 2010; Marszal, 2001) and change the scale levels to suit the levels of risk factor concentration that it finds acceptable.

The third step of the assessment phase is used to estimate the impact of each undesirable event on the progress of a project. The list of impacts is determined and causation connections are made from the identification phase (Fig. 2). The model uses a grid to estimate the magnitude of the loss suffered by the company.

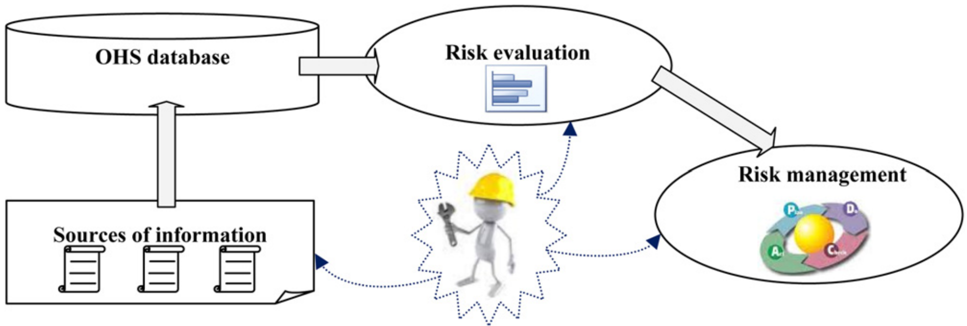

Fig. 3. The role of information sources and risk evaluation in risk management.

The impact of an undesirable event is calculated as follows:

$$I_i = \text{Max}_{\text{impacts set by the organization}\,(i)} \tag{14}$$

Once the level of each identified risk has been calculated (Eq. (12)), the fourth step of the evaluation phase is undertaken to prioritize the risks.

5.1.3. Phase 3: actions

The selection of actions to manage identified risks will depend on risk prioritization and multi-criteria analysis (AHP), taking into account technical and economic constraints. The main purpose of this phase is to eliminate, reduce or make available the necessary means for workers to protect themselves from hazards. Actions involving monitoring and controlling must be in line with the principle of continuous improvement in quality (ISO 9000), safety (OHSAS 18000) or environment management systems (ISO 14000). The prevention plan includes prevention actions that must be assigned to individuals who have knowledge and expertise in the field and who must: (1) take responsibility, (2) choose the best approach to resolve the danger and (3) define its scope of intervention (Dorofee, 1996).

5.2. Application of the proposed approach

5.2.1. Case study background

Industrial relocation is a form of globalization. The emergence of offshoring is caused by two factors: technological progress and international agreements that promote trade. Faced with fierce competition, businesses turn to outsourcing, which has become one of the most common ways to reduce production costs and expand into new markets. Manufacturers choose the least developed countries for several reasons, but especially because of the availability of cheaper labor. Relocation involves many challenges, including dealing with a lack of safety culture, a condition encountered in many developing countries. In addition, the chosen project management approach often gives priority to increased productivity and reduced delays at the expense of the health and safety of workers.

Society in developing countries is often unfamiliar with worker health and safety protection culture (Baram, 2009) and supports 80% of the global burden of accidents and occupational diseases (DCPP, 2007). The transfer of production from developed to developing countries is increasing (Hämäläinen et al., 2009). Poorly trained and sometimes illiterate workers are exposed to new risks and environments (Baram, 2009).

The present study is focused on a major expansion of a factory for assembly of mechanical parts. This expansion is intended to double production capacity and improve workshop organization. The project includes all fields of activities, in particular architecture, structural and mechanical processing and all related systems. The case study is limited to installation of the new production line and the various facilities in the new building without considering construction aspects. Our primary concern is identifying the elements of OHS risk. This theoretical example was chosen to demonstrate the novel aspect of the proposed approach to risk analysis and to test its conceptual model in the hope of providing small-to-medium-sized businesses (involved in relocation projects) with a simple and inexpensive tool for integrating OHS risk management.

5.2.2. Phase 1: risk identification

Risk identification was done using the know-how of the project team and experts and the accident and incident history of the company or of a similar company (same trade, environment, etc.). An initial consultation of the database tables allowed the team to narrow down its research.

In order to identify the risk factors, the team used adapted tables of industrial risk factors. These were developed with the aid of the MOSAR method (organized systematic method of risk analysis) and on the basis of the industrial risk records in the INRS Guide (INRS, 2004) to help evaluators detect risks in small businesses and institutional organizations (Curaba et al., 2009). The team then selected, depending on the type of risk, the factors judged as capable of having an influence on the course of the project. Appendix B summarizes the corresponding details for each risk factor (Tables B.1–B.4).

Table 2 summarizes the undesirable events identified in the case of the factory expansion project. Table 3 lists the aspects of the project that could suffer negative impact.

The causal links are shown schematically in Fig. 4, in which each link (arrow) represents possible risk.

Example:

Table 2
Case study: undesirable events in OHS.

Code	Undesirable event
E1	Work-related illness
E2	Drop in productivity
E3	Drop in quality
E4	Inadequate design
E5	Pollution
E6	Explosion and fire

Table 3
Case study: aspects vulnerable to negative impact.

Code	Impact
IP	On performance
IC	On cost
ID	On delays
IE	On the environment

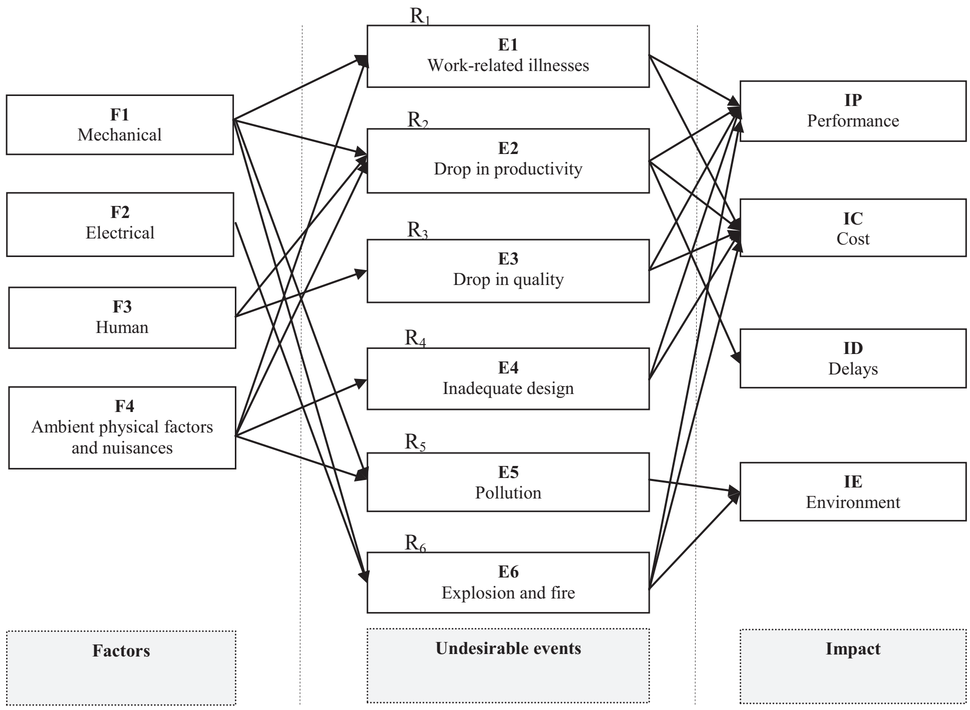

Fig. 4. Case study: links between undesirable events, their risk factors and their impact.

- R1 is the risk of work-related illness caused by mechanical factors (MF) and by ambient physical and other nuisance factors (AF).
- The impact of R1 could affect two aspects of the project: performance and cost.

5.2.3. *Phase 2: risk assessment*

Based on binary comparisons, the relative significance of each risk factor is calculated using the AHP method. Table A.1 in Appendix A provides the basis of the calculation, attributing a numerical value to each verbal decision. Once the relative significance is calculated for each factor, the overall significance of each category of risk factors is evaluated in order to assign weighting factors. The overall significance is determined by calculating the relative significance of each category of factors using Expert Choice© software. Expert Choice© allows identification of data entry errors and thus eliminates one of the most frequent causes of inconsistent judgments. The instant control of inconsistency of Expert Choice© allows experts to avoid having to provide arbitrary judgments.

Table 4
Ranking by the influence level of risk factors (AHP).

Code	Undesirable event	Influence of the risk factor			
		++	+	–	––
E1	Work-related illness	F4 0.56	F1 0.28	F3 0.1	F2 0.06
E2	Drop in productivity	F3 0.52	F4 0.29	F1 0.14	F2 0.05
E3	Drop in quality	F3 0.61	F1 0.22	F4 0.11	F2 0.06
E4	Inadequate design	F1 0.51	F2 0.31	F3 0.12	F4 0.06
E5	Pollution	F1 0.54	F4 0.3	F2 0.11	F3 0.05
E6	Explosion and fire	F2 0.57	F1 0.25	F3 0.11	F4 0.07

Table 5
Case study: assignment of risk factor category weighting.

OS rank	Weighting assigned
1	4
2	3
3	2
4	1

Based on binary comparison matrices for each category of risk factor in relation to various undesirable events (Appendix C), Table 4 highlights the weight of influence (relative significance value) estimated by AHP. It should be noted that the consistency of each comparison matrix is verified each time the team renders a decision.

To determine the overall significance (OS) of each category of risk factors, multiplication of its relative significance value for each undesirable event is done. This calculation is used to assign the weighting value to each risk factor category.

Results:

$$\sqrt{OS_{F1}} = 0.0246$$
$$\sqrt{OS_{F2}} = 0.0019$$
$$\sqrt{OS_{F3}} = 0.0046$$
$$\sqrt{OS_{F4}} = 0.0047$$

Table 6
Case study: assignment of weighting to risk factor categories.

OS rank	Risk factor category	Weighting
1	Mechanical factors (F1)	4
2	Ambient factors and other nuisances (F4)	3
3	Human factors (F3)	2
4	Electrical factors (F2)	1

Table 7
Case study: calculation of the risk factor concentrations for each undesirable event.

Undesirable event Ej	Linked risk factor category (Fig. 4) Fi	Factors in the category (Tables B.1–B.4) x_i	Weighting (Table 6) y_{ij}	$x_i y_{ij}$	Fraction of total Eq. (13)
E1	F1	7	4	28	–
	F4	7	3	21	–
			Sub-total E1	49	0.23
E2	F1	7	4	28	–
	F3	3	2	6	–
	F4	7	3	21	–
			Sub-total E2	55	0.26
E3	F3	3	2	6	–
			Sub-total E3	6	0.03
E4	F4	7	3	21	–
			Sub-total E4	21	0.10
E5	F1	7	4	28	–
	F4	7	3	21	–
			Sub-total E5	49	0.23
E6	F1	7	4	28	–
	F2	2	1	2	–
			Sub-total E6	30	0.14
			Total	210	100%

Table 8
Case study: table of conversion of risk concentration to probability of occurrence.

Relative concentration of risk	Probability of occurrence
0–0.15	0.1
0.16–0.25	0.3
0.26–0.5	0.5
0.56–0.75	0.7
0.76–0.9	0.9

Table 9
Case study: estimation of the probability of occurrence of each undesirable event.

Undesirable event	Relative concentration of risk	Probability of occurrence
E1	0.23	0.3
E2	0.26	0.5
E3	0.03	0.1
E4	0.10	0.1
E5	0.23	0.3
E6	0.14	0.1

Weightings are assigned to each of the risk factor categories as a function of their overall significance (OS) ranking, based on the values in Table 5. The weighting thus increases the numerical value of the risk factor categories having greater influence on the occurrence of undesirable events.

In the present case, Table 6 summarizes the assignment of weighting to risk factor categories.

For each type of undesirable event, there is a concentration of risk that is calculated as shown in Table 7 using the number of factors and the weighting associated with each risk category that is linked according to Fig. 4 and Eq. (13). The risk concentration for each event is thus proportional to the number of linked risk categories and to the number of factors and the weighting associated with each of these.

Table 11
Case study: calculated levels of risk or risk index.

Undesirable event	Max (IP, IC, ID, IE)	Probability of occurrence	Level of risk (i) Eq. (12)
Work-related illness (E1)	7	0.3	2.1
Drop in productivity (E2)	9	0.5	4.5
Drop in quality (E3)	7	0.1	0.7
Inadequate design (E4)	6	0.1	0.6
Pollution (E5)	9	0.3	2.7
Explosion and fire (E6)	8	0.1	0.8

The probability that an undesirable event will occur is determined from the concentration of linked risk factors calculated for that event type. For example, Hallowell and Gambatese (2008) used data from American industry to convert the impact of accidents into probabilities in construction projects. We used Table 8 as a numerical scale for the conversion of risk factor concentration to probability of occurrence of the event.

Based on Table 8, Table 9 provides the probabilities of occurrence of each of the undesirable event types considered.

The impact on performance, cost, delays and the environment are evaluated on the basis of a scale corresponding to the magnitude of the losses suffered by the company (Table 10):

- Minor impact: [1, 2 or 3]
- Moderate impact: [4, 5 or 6]
- Strong impact: [7, 8 or 9]

The level of the risk or risk index (Table 11) associated with each undesirable event is calculated using Eqs. (12) and (14).

Finally, Table 12 summarizes the hierarchy and prioritizing of the risks based on the values obtained in the previous step. This prioritizing will allow the project team to control the risks in a stepwise manner.

Table 10
Case study: estimation of impact of undesirable events on the project.

Undesirable event	Impact on performance IP	Impact on cost IC	Impact on delays ID	Impact on the environment IE
Work-related illness (E1)	7	7	3	1
Drop in productivity (E2)	9	7	6	1
Drop in quality (E3)	7	6	6	1
Inadequate design (E4)	6	6	4	5
Pollution (E5)	7	5	2	9
Explosion and fire (E6)	7	7	7	8

Table 12
Case study: ranking of the risks by priority.

Undesirable event	Level of risk (i)	Priority
Drop in productivity (E2)	4.5	1
Pollution (E5)	2.7	2
Work-related illness (E1)	2.1	3
Explosion and fire (E6)	0.8	4
Drop in quality (E3)	0.7	5
Inadequate design (E4)	0.6	6

6. Discussion

The simulation illustrates the use of the proposed approach, which ranks risks as a function of their impact in terms of undesirable events. In the example studied, the calculation allowed us to differentiate the OHS risks from the risk of drop in quality. For the paired comparisons of the identified risk factors we chose Expert Choice© software, based on the following advantages (Al-Harbi, 2001; Larson and Forman, 2007):

- Minimizing difficulties associated with calculation and verification of the logical consistency of the judgments.
- Avoiding influence of experts and domination by a single group member.
- Facilitating modification of judgments and data updates.
- Possibility of voting when no consensus can be reached.
- Calculating and displaying the sensitivity analysis used to test the robustness of the judgments.
- Documenting the decision process and allowing the traceability of modifications.

The verbal judgments (Table A.1) supported by Expert Choice© were important in the decision-making process. Forman and Selly (2002) note that humans are comfortable using words to measure the intensity of feelings and comparing two entities. This scale allows reliable comparison without specifying the exact value of the significance of one entity compared to another.

The proposed approach allows the combination of several tools used in practice, namely know-how and feedback from experience to fill databases and to some extent the AHP method for comparing categories of risk factors. In evaluating risks, the proposed approach uses the new concept of concentration of risk factors for estimating probabilities of occurrence of events. The risk management team can calculate the concentration of factors and do the paired comparison of risk factor categories quickly and with ease.

The AHP model offers the advantage of decomposing a complex system into a hierarchical structure showing the links between risk factors, undesirable events and their impact, allowing lucid evaluation of dangers. The possibility of managing conflicting criteria using AHP also allows a more realistic evaluation of OHS risks. The AHP method reduces the inconsistency of expert judgments and appears acceptable in terms of reliability (Fera and Macchiaroli, 2009). The feature of combining both quantitative and qualitative data and controlling consistency of expert judgments makes AHP the most applicable to the proposed approach.

The proposed approach is iterative, which allows modifications and revision of weighting criteria and of judgments based on project advancement and also supports testing of the measures taken to reduce or eliminate identified and prioritized OHS risks.

7. Limitations and recommendations

Given the complexity of judging and comparing OHS risk factors, we grouped them into categories in an attempt to simplify the paired comparison. This allowed us to compare risk factors initially using a combination of empirical data and subjective judgments. This evaluation was limited to the causal links that we identified in the first phase of the proposed approach without evaluating reinforcement effects between risk factors. We will present in a future article paired comparison of risk factors in an attempt to identify and evaluate reinforcement effects.

Several authors have criticized the constraining of evaluators to predefined choices of comparison criteria, the inversion of the coefficient of comparison, the use of the interval scale and especially the lack of theoretical bases of the AHP method (Al-Harbi, 2001; Belton and Gear, 1983; Dyer, 1990; Harker and Vargas, 1987; Perez, 1995). We agree with the conclusions reached by Forman and Selly (2002) that AHP "*is not a magic formula or model that finds the* '*right*' *answer. Rather it is a process that helps decision-makers to find the* '*best*' *answer*". The AHP model also does not exclude inconsistent judgments. When such inconsistency occurs, it may contaminate the entire series of judgments. Its causes are listed below (Forman and Selly, 2002):

- Data entry errors, especially when filling the judgment matrices (the most frequent cause).
- Missing information: if judgment is based on incomplete information and knowledge, it becomes random and potentially inconsistent.
- Poor concentration: evaluator fatigue and motivation are factors to consider.
- Modeling problems: the underlying model and hierarchical structure must be representative of reality.

Expert Choice© allows identification of data entry errors and thus eliminates one of the most frequent causes of inconsistent judgments. This tool also allows us to monitor the degree of inconsistency by providing an instantaneous display of the compatibility index of each comparison matrix. We consider the generalized use of AHP as a decision aid in industrial practice to be proof of its success and reliability. In future work, we shall use other multi-criteria decision aid methods such as MACBETH, ELECTRE and PROMOTHEE in order to expand the range of potential users of the proposed approach.

In this article, the final phase of the proposed approach, called "action", is not included in the case study, since it is based on a list of actions and a preventative plan is generally implemented on the shop floor. In this plan, each action will be grouped into one of four strategies, as presented in part by Aubert and Bernard (2004):

- Mitigation is concerned with the measures implemented in order to reduce the probability of occurrence of an undesirable event.
- Deflexion consists of changing the direction of the impact of an undesirable event.
- Establishment of a contingency plan consists of implementing measures that have the effect of decreasing the impact of an undesirable event.
- Assuming or accepting the risk.

An OHS database corresponding to the field must be created in order to facilitate faster identification of the elements of risk using the approach devised in the present study. The resulting increase in the responsiveness of the approach at this stage will save time and thus allow the group of experts and project manager to concentrate more on identifying the causal links with greater reliability and realism.

We plan to consolidate our approach by examining several industrial fields in order to upgrade the input data with observations, interviews and analysis of performance obtained from a variety of project teams. Once the database containing the elements of risk has reached a sufficient level of completeness, risk (or danger) sequences will be taken into consideration. OHS risk will be considered primarily as an entity interacting with other types of risk that must be managed in an organization.

8. Conclusion

Numerous industrial accidents have exposed the ineffectiveness of conventional risk evaluation methods as well as negligence with respect to factors having major impact on the health and safety of workers and nearby residents. Lack of reliable and complete evaluations from the beginning of a project will generate bad decisions that could end up threatening the very existence of an organization.

This article presents a novel risk-factor-based approach comprising eight steps and allowing the integration of OHS risks, based on identifying elements of risk and on a new concept of risk factor concentration weighted by multi-criteria comparison using the AHP method and Expert Choice© software. This OHS risk identification and evaluation is integrated upstream in the risk analysis process in order to increase the effectiveness of preventative measures undertaken at the outset of a project.

The proposed approach allows quick prioritizing of identified risks and allows evaluators to identify additional potential causes of undesirable events without nullifying the previous risk element compilation effort. The simplicity of the approach should facilitate its use in small and medium-sized businesses without requiring a major investment.

The practical use of the approach was tested using a simulated case study and the results of the paired comparison step were calculated using the decision-aid software Expert Choice©. We were thus able to determine, by applying more rigorous evaluation of factors associated with human health and safety and integrating these into the risk analysis, that the business in this case study was more exposed to the OHS risks than to the risk of drop in quality.

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Appendix A.

See Table A.1.

Table A.1
AHP scale of binary combinations, from Wang et al. (2008).

Numerical scale	Definition	Verbal explanation
1	Equal significance of the two elements	Two elements contribute equally to the property
3	Low significance of one element compared to another	Experience and personal assessments favor one element slightly over another
5	Strong significance of one element compared to another	Experience and personal assessments favor one element strongly over another
7	Confirmed dominance of one element over another	One element is strongly favored and its dominance is borne out in practice
9	Absolute dominance of one element over another	The evidence favoring one element over another appears irrefutable
2, 4, 6, 8	Intermediate values between two neighboring levels	The assessment falls between two levels
Reciprocals (1/x)	A value attributed when activity i is compared to activity j becomes the reciprocal when j is compared to i	

Appendix B.

See Tables B.1–B.4.

Table B.1
Mechanical factors contributing to OHS risk.

Mechanical factors (F1)	
Code	Designation
F11	*Moving elements*: Chucks, tools, robots, turntables, grinders, conveyer belts
F12	*Handling*: Bridge crane, forklift, stacker, motorized trailer
F13	*Physical explosions*: Dust, gas, vapor, tank depressurizing, liquid on very hot surfaces
F14	*Heights*: Ladders, staircases, catwalks
F15	*Movement*: Obstacles on the ground, slopes, openings in the ground
F16	*Devices and elements under pressure*: Compressors, gas cylinders, hydraulic or pneumatic lines
F17	*Elements under strain*: Structures, slings, pulleys, loaded racks, piping

Table B.2
Electrical factors contributing to OHS risk.

Electrical factors (F2)	
Code	Designation
F21	*DC or AC electrical current*: Electrical room, electrical cabinet, transformer, wiring, overload of outlets
F22	*Static electricity*: Accumulation of charge on insulating materials; sparks in the presence of inflammable liquid transfer operations

Table B.3
Human factors contributing to OHS risk.

Human factors (F3)	
Code	Designation
F31	*High-risk behavior*: Alcohol, narcotics, tobacco, ignoring safety measures, ignoring safe limits/protection
F32	*Stress*: Work pace, work overload
F33	*Harassment*

Table B.4
Physical ambience factors contributing to OHS risk.

Physical ambience and other nuisance factors (F4)	
Code	Designation
F41	*Ambient lighting*: Work station lighting, glare, luminosity
F42	*Video screens*
F43	*Ambient noise*: Infrasound, ultrasound, blowers, machinery
F44	*Vibrations*: Machines, motorized trailers
F45	*Contact temperature*: Hotplates, composting machine, Bunsen burner, hot surfaces, piping
F46	*Work station design*: Work posture, repeated movements, human-machine interface, station arrangement
F47	*Hostile environments*: Asphyxia caused by displacement of air by gas, work in isolation, physical aggression

Appendix C.

Case study: The paired comparison matrices

Work-related illnesses (E1)

	F1	F2	F3	F4
F1	1	5	3	0.50
F2	0.20	1	0.50	0.13
F3	0.33	2	1	0.14
F4	2	8	7	1

Inadequate design (E4)

	F1	F2	F3	F4
F1	1	2	4	7
F2	0.50	1	3	5
F3	0.25	0.33	1	2
F4	0.14	0.20	0.50	1

Drop in productivity (E2)

	F1	F2	F3	F4
F1	1	3	0.25	0.50
F2	0.33	1	0.11	0.14
F3	4	9	1	2
F4	2	7	0.5	1

Pollution (E5)

	F1	F2	F3	F4
F1	1	6	8	2
F2	0.17	1	3	0.33
F3	0.13	0.33	1	0.17
F4	0.50	3	6	1

Drop in quality (E3)

	F1	F2	F3	F4
F1	1	4	0.33	2
F2	0.25	1	0.13	0.50
F3	3	8	1	7
F4	0.50	2	0.14	1

Explosion and fire (E6)

	F1	F2	F3	F4
F1	1	0.33	3	4
F2	3	1	5	7
F3	0.33	0.20	1	2
F4	0.25	0.14	0.20	1

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