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Article

Integration of OHS into Risk Management in an Open-Pit Mining Project in Quebec (Canada)

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Abstract: Despite undeniable progress, the mining industry remains the scene of serious accidents revealing disregard for occupational health and safety (OHS) and leaving open the debate regarding the safety of its employees. The San José mine last collapse near Copiapó, Chile on 5 August 2010 and the 69-day rescue operation that followed in order to save 33 miners trapped underground show the serious consequences of neglecting worker health and safety. The aim of this study was to validate a new approach to integrating OHS into risk management in the context of a new open-pit mining project in Quebec, based on analysis of incident and accident reports, semi-structured interviews, questionnaires and collaborative field observations. We propose a new concept, called hazard concentration, based on the number of hazards and their influence. This concept represents the weighted fraction of each category of hazards related to an undesirable event. The weight of each category of hazards is calculated by AHP, a multicriteria method. The proposed approach included the creation of an OHS database for facilitating expert risk management. Reinforcing effects between hazard categories were identified and all potential risks were prioritized. The results provided the company with a rational basis for choosing a suitable accident prevention strategy for its operational activities.

Keywords: occupational health and safety (OHS); risk management; industrial projects; action research; analytical hierarchy process (AHP); open-pit mine

1. Introduction

Canada is a world leader in the mining industry and among the largest producers of minerals and metals [1]. The mining industry is a major contributor to the Canadian economy, employing 351,000 people in mineral extraction and related sectors and contributing $40 billion to the GDP in 2008 [1]. According to a recent study by the Quebec Mining Association [2], mineral extraction contributed $7 billion or 2.4% of the GDP of the province of Quebec in 2008, employing over 52,000 people earning total wages estimated at $1.9 billion.

In Canada, statistics published recently shows that the mining industry is among sectors with the highest injury incidence rate (IIR) [3]. The four most hazardous industries are classified according to the IIR as follows: Longshoring (20.34), Energy and Mining (17.64), Air Transport (14.39) and Bridges and Tunnels (11.67). According to recent CSST statistics based on five industrial sectors, the mining sector is ranked fourth with 792 job-related accidents and second with 156 cases of job-related illness [4]. In comparison, the construction and civil engineering sector is ranked first with 6,881 job-related accidents and 298 cases of job-related illness. It is noteworthy that mining accidents have been reduced by 76% over the past 20 years [5]. Despite this remarkable performance in Quebec and the positive trend in Canada, the mining industry has experienced several serious and fatal accidents. Among these are the incidents in the Stobie mine near Sudbury (Ontario), in which a muck slide killed two experienced miners (June, 2011), and the Lac Bachelor mine in Desmaraisville (Quebec), in which three workers died at the bottom of a flooded shaft (October, 2009). It is cold comfort that the number of victims was fewer than in the Ferderber mine accident in Val d'Or in 1980, resulting in eight deaths and at least 16 serious injuries [6], or in the Westray disaster in Nova Scotia in 1992, which killed 26 coal miners.

The OHS performance of the mining industry varies from one country to another and does not reflect the current trend in Quebec. In the United Kingdom, quarries are considered the most dangerous industrial sector, with injury and accident rates far exceeding those of the construction industry [7]. It is important to note also that miners are four to five times more likely to die in South African mines than in Australian mines [8]. In the USA, the mining sector performance is clearly improving, despite production growth under unfavorable operating conditions and changes in methods and mining equipment [9]. China also suffers from frequent serious mining accidents. A recent statistical study ranked Chinese coalmines among the top three sources of fatalities (37.26% between 2001 and 2008) [10]. Data for other developing countries are not available, but the mass media provides some indication of the current status of the global mining industry, painting a rather dismal picture.

The mining industry is currently experiencing a period of intense activity and growth with new projects and increasing numbers of workers [5]. Increasing metal prices have increased profit margins and are making production and exploration more worthwhile. The recent launch of the "Plan du Nord" program in Quebec, which includes several planned mining projects with anticipated investments totaling $80 billion, is an indication that the trend is expected to continue. In this favorable economic situation, the renewal of the aging workforce, the scarcity of workers and the arrival of a new diverse workforce (immigrants, First Nations people, *etc.*) represent significant OHS challenges [5,11].

The skill and the means used in risk management vary from one industry to another. The construction industry is among the most developed in this area in North America. Sectors such as nuclear energy, aviation and chemical industries are leaders in the use of sophisticated and advanced tools of risk identification and assessment [12,13]. However, integration of OHS into risk management remains incomplete and the methods and tools being used are poorly suited [14].

The aim of the proposed approach was to manage and evaluate the integration of OHS risks with other types of risk in the context a new mining project. Several risk identification techniques and multi-criteria analysis were adapted for this purpose and a new concept called hazard concentration was developed. This concept represents the weighted fraction of each category of hazards related to an undesirable event. The weight of each category of hazards is calculated by the AHP method. When the hazard concentration increases, the probability of an undesirable event increases [15]. In an earlier study, the example of the expansion of a manufacturing facility revealed that the proposed approach achieves the goal of integrating OHS into risk management. In this article, we present a preliminary validation of the proposed approach in the mining sector, based on action research with the active involvement of the industrial partner. We start by discussing in Section 2 the current level of integration of OHS and the tools used to manage risks in the mining industry. Section 3 presents the action research methodology adopted for the study. In Section 4, we summarize the risk-factor-based approach and important points to retain. Section 5 presents the implementation of the results of this approach in the case of the open-pit mine. In Section 6, we discuss the results, the impact of our study and the opportunities for future research in order to generalize our concepts to Quebec's gold-mining industry. Finally, Section 7 presents our conclusion.

2. Literature Review

OHS is gaining importance in the field of industrial projects management. Thanks to legislation [16,17], improvement of several management standards [18], development of a culture of safety [19-21], better organization of tasks and responsibilities [22], improved communication [23] and the emergence of several new decision support tools and approaches [18,24-27], OHS is becoming a major criterion in project management alongside quality, cost and delays. Being able to offer work in safe environments is becoming essential for attracting and retaining skilled labor [28].

The level of integration of OHS varies from one industry to another. The methods and criteria for measuring this integration are not universally accepted among the different sectors. For example, petrochemicals, construction, mining and manufacturing all use different approaches to OHS integration (e.g., statistics, methods of risk assessment, involvement of design engineers and subcontractors, *etc.*) [7,8,16,29]. These differences stem from the urgency implicit in legislation and laws, the danger associated with the industry, the wherewithal to invest in the promotion of OHS and public pressure [16].

Although the mining sector is being built more and more on leading-edge technologies, the human contribution in mining operations is still prevalent. Interaction between vehicles, equipment and humans in generally limited spaces and in the presence of concentrated energies in an environment in perpetual change gives this industry a dynamic character [30] such as that seen in construction [17]. According to Hermanus [8], recent developments such as the increasing number of subcontractors, the emergence of new mining firms and the increasing presence of women place new constraints on the mining industry. Development of technical and engineering aspects such as rapid sharing of information and the use of specialized equipment with the aim of improving health and safety in mines has led to much progress [31] and the recognition of several emerging risks (e.g., noise, vibrations, ergonomic issues, *etc*.).

In view of mining project volume and the dominance of economic and budgetary factors, integration of human factors is not always considered as an important element in project evaluation [32]. Several researchers have attempted to integrate human factors and OHS risks into the management of various mining projects and several efforts have been made to improve risk comprehension and evaluation [33-36]. Jansen and Brent [33] used an integrated approach to risk management based on a human behavior study and concluded that proper organizational culture is an essential condition to promote responsible and safe behavior. Schutte [34] used participatory ergonomics intervention to eliminate OHS risks related to noise caused by mining equipment and involved legislators, mining firms, workers and equipment suppliers and concluded that in order to benefit from participatory ergonomics, all work management practices must undergo marked changes. Kumar and Paul [30] proposed an OHS risk assessment and management manual involving miners and managers based on a statistical study of work accidents occurring in open-pit mines. Terbrugge *et al*. [35] used a risk analysis approach designed with fault tree analysis (FTA) to categorize the risks associated with design problems of slopes in open-pit mines. Risk categories are identified according to their consequences for workers, equipment, production, economics, various industrial operations and public relations. Through the involvement of technical staff and the definition of the level of acceptable risk in an organization, the mining industry can improve design and make proactive decisions to protect workers [35].

Risk evaluation is based on assessing the probability (or frequency) and impact (or consequence) of one or more undesirable events [25,27]. Assessment of the probability of equipment failure is sometimes based on expert subjective judgment without checking for consistency [35]. The limitations of assessing risks associated with human factors have become obvious as a result of numerous industrial accidents over the years. To the best of our knowledge, systematic integration of OHS risk has yet to find its way into technical or environmental feasibility studies of mining projects [37]. Feasibility studies of mining projects usually integrate environmental impact without using methods for assessing the total number of identified risks overall. Risk evaluation tends to be influenced by the economic viability of a project more than by its long-term consequences for humans and the environment [38]. The mining industry is concerned primarily with chemical, mechanical, geotechnical and other immediate physical risks [39]. For many years, this industry has focused its risk reduction efforts on the improvement of procedures and the establishment of training programs [40]. However, integrated risk management has become a topic of great interest [39] and the need for adapted and appropriate approaches to integrating OHS in this sector has been confirmed [41].

Our aim is to help the mining industry benefit from certain tools, techniques and approaches that have proven efficient in the industrial sectors most advanced in OHS integration. This study is limited to risk identification and assessment. Risk identification and assessment are the most important steps towards hazard reduction [25,42] and they present several challenges [38]. We have adapted several techniques of risk identification and multi-criteria analysis (AHP) and we have developed the new concept of hazard concentration in order to manage OHS risks along with operational risks in the context of a new mining project.

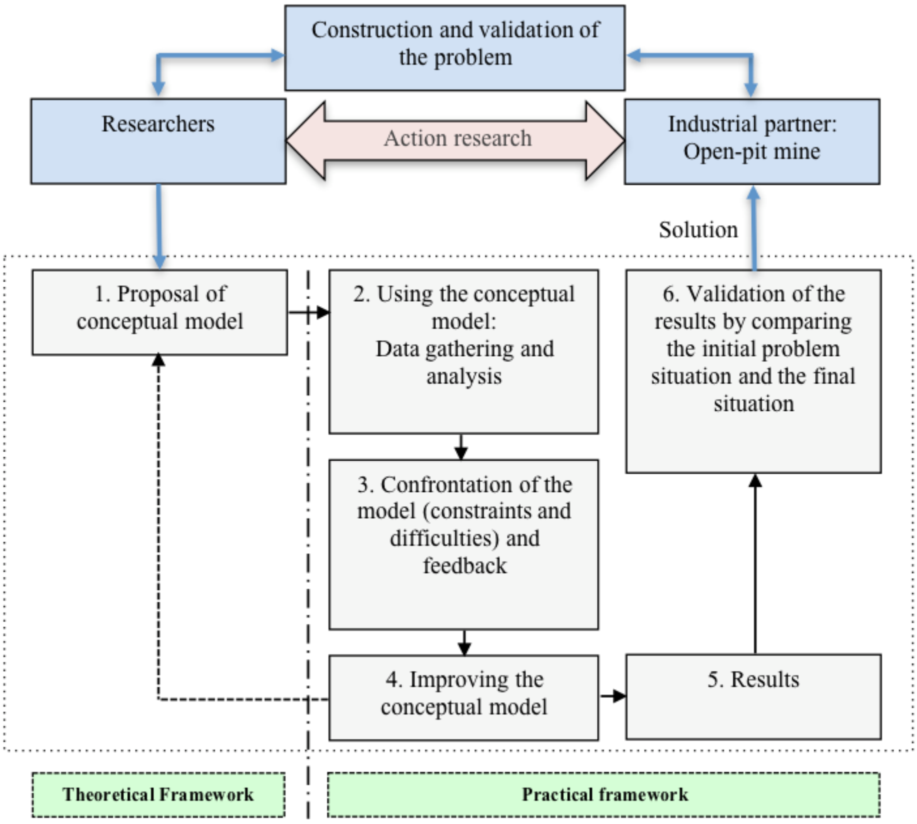
3. Methodology

The risk factor approach is designed to integrate OHS into industrial project risk management. An application of this approach has been simulated using the example of the expansion of a manufacturing facility [15]. The same approach is now being applied in the mining sector.

In this article, we apply action research methodology to improve and validate the risk factor approach. The choice of action research methodology was motivated by the participation of a mining company wishing to benefit from a support tool for the decision to integrate OHS into risk management for the purposes of a new project. Since human interaction and influences are significant in OHS, it was necessary to introduce a sociological dimension to the engineering approach in order to make the management complete. Action research is the methodology most favored by the World Health Organization and the US Centers for Disease Control because it allows commitment and involvement of the stakeholders in order to resolve problematic situations quickly [43].

Action research has been grouped into several categories [44] differentiating by degrees of participation: (1) research on action, but without action; (2) the partner exposes the problem and the researcher proposes solutions; and (3) total commitment of the partners in the research [45]. The last category is also referred to as "soft systems methodology" [46]. The action research adopted in the present study falls between these two categories: the industrial partner exposes the problem and the researchers suggest solutions. In our case, the problem arose from the lack of a tool for OHS integration into the risk management portion of the mining project and from the absence of assessment of the impact of OHS risk on the project and the organization. To propose solutions, we used the approach by risk factors based on soft systems methodology. The involvement of the industrial partner throughout the intervention improved the fit between the conceptual model underlying our approach and the reality of the constraints on the open-pit mining business. Details of the methodology are presented in Figure 1.

Figure 1. Methodology of application and validation of the proposed approach.



Data collection in this action research is mainly based on semi-structured voluntary interviews combined with questionnaires. Interviews were done using a questionnaire previously validated by the researchers and the company representatives. The questionnaire is designed using the list of occupational hazards raised by Curaba *et al.* [47]. These authors have developed lists of occupational hazards using the MOSAR method. These lists are used to achieve and improve the assessment of occupational hazards in European industry. We begin by verifying the presence of these hazards in our study and we add specific hazards identified in the open-pit mining business.

We also use collaborative observations and analysis of incidents and accidents reports. The observations were done using a checklist that describes the details to be observed in each zone of the mine. All reference material received approval from the research ethics committees (UQAT and École de technologie supérieure) before starting the project.

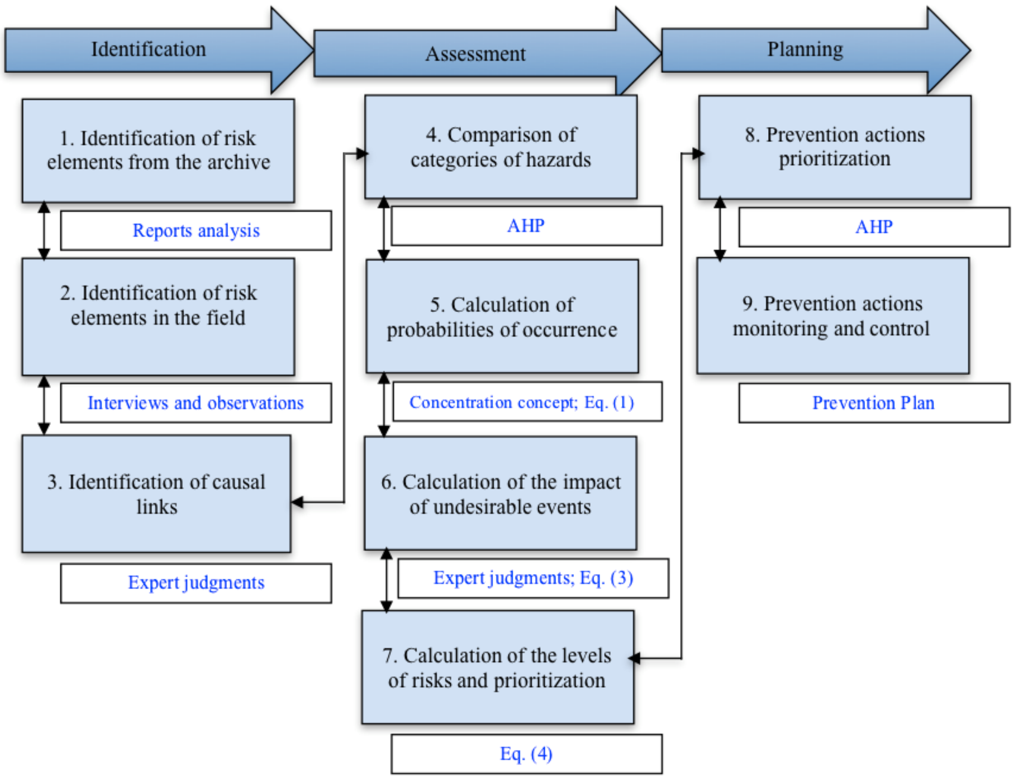
4. Results and Discussion

4.1. The New Approach Based on Risk Factors

For the purposes of the present research, the previously published risk factors approach was used [14]. This approach, based on the principle of continuous improvement, features the following steps in risk management: (1) identification of risk elements; (2) risk assessment; and (3) action planning. The important points to retain in each phase of the approach are highlighted below.

The approach uses several methods and tools such as interviews and questionnaires, observations, methods of multi-criteria analysis (AHP), analysis of incidents and accidents and the new concept of hazard concentration. Figure 2 illustrates the phases and steps of the approach and the methods and tools used in each step.

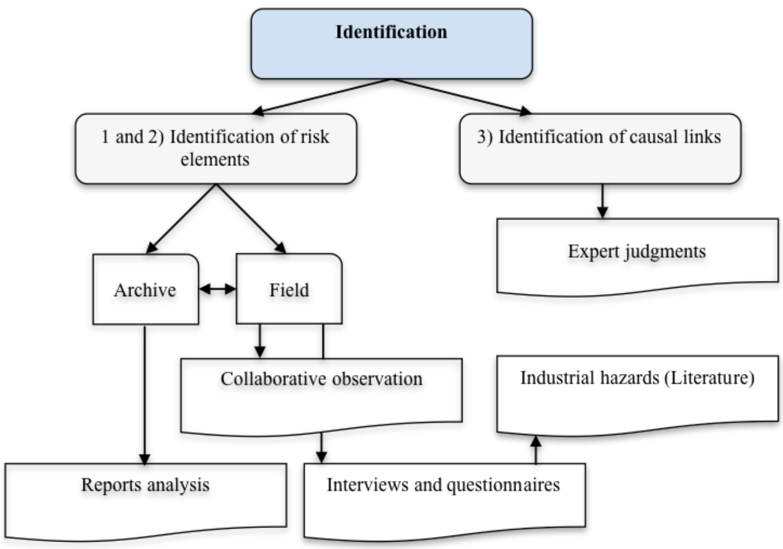
Figure 2. Details of the proposed approach based on risk factors.



4.1.1. Identification Phase

Identification (Figure 3) is the most important phase for reliable management of risk [42]. This phase requires much effort and time in order to constitute a database of risk elements in the field (hazards, undesirable events and impact).

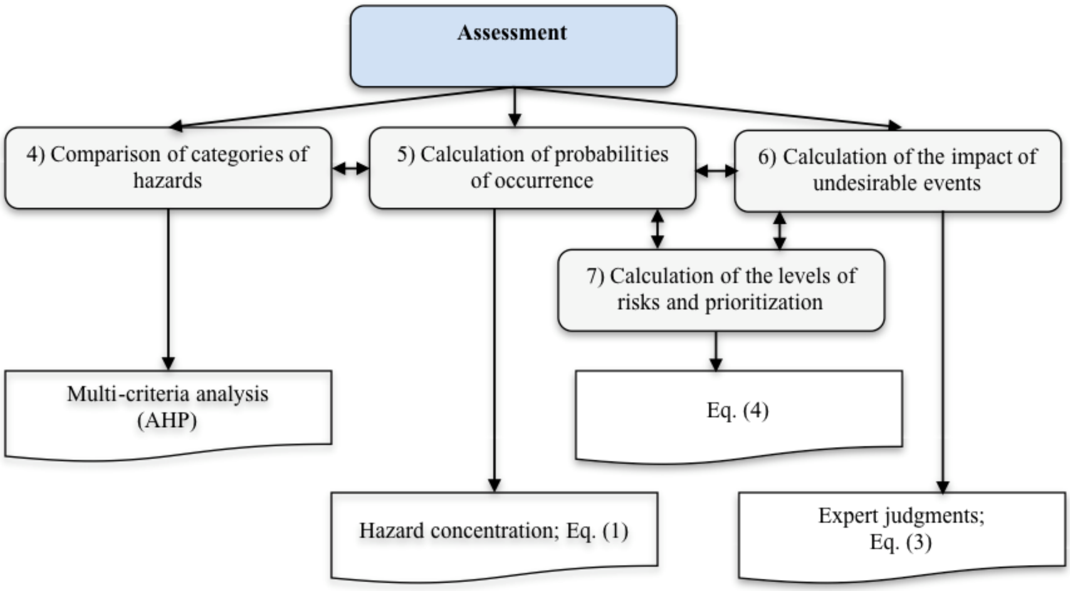
Figure 3. Identification phase of the risk-factor-based approach.



4.1.2. Assessment Phase

Assessment (Figure 4) completes identification and is based on expert opinion, multi-criteria analysis (AHP) and the new concept of hazard concentration. This phase requires complete information on the hazards, the people or equipment exposed to risk and the associated effects [39].

Figure 4. Assessment phase of the risk-factors-based approach.



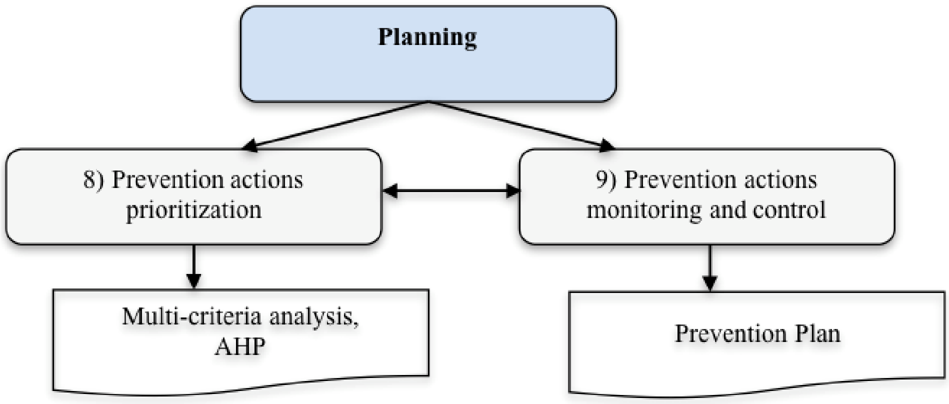
It is important to note that the proposed approach uses AHP [48] supported by Expert Choice© software. The AHP method allows instant testing of the consistency of expert judgments, thus lessening the problem of inconsistent decisions. AHP uses a fixed numerical (or verbal) scale and judgment consistency is defined only within these fixed limits. To the best of our knowledge, AHP has not been used in a study of Quebec mines.

The AHP method was introduced into the OHS field in the 1990s in the USA. This method was used in ergonomic analysis conducted by Henderson and Dutta [49]. It has also been used for ranking of musculoskeletal disorder risk factors [50] and to compare the risk factors linked to human errors [51]. Fera and Macchiaroli [14] recently introduced AHP into a model developed to evaluate risks at work in small and medium-sized industry and service businesses. Ishizaka and Labib [52] have reviewed AHP methodology, its applications and its limits. Badri *et al*. [15] explain the AHP concept and use of the method in detail.

4.1.3. Planning Phase

The planning phase (Figure 5) is crucial to the elimination of hazards. The purpose of including multi-criteria analysis in this phase is to minimize the influence of weak managerial decisions on the choice of solutions [53], through active involvement of project team members.

Figure 5. Planning phase of the risk-factor-based approach.



Finally, we emphasize that the different phases of the proposed approach converge with the majority of OHS laws and regulations (e.g., Loi sur la santé et la sécurité du travail, 2011, Québec and Construction Design and Management Regulations, 2007, UK) and that over the course of the project, the approach is compliant with the following criteria suggested by Baxendale and Jones [54]:

- Systematic consideration of health and safety from the outset of the project.
- Commitment of all workers contributing to the health and safety of people involved in the project.
- Prioritization of actions and elimination of hazards.
- Communication and sharing of information.
- Recording of information for later use.

4.2. Context

Our intervention concerned an open-pit gold mine in Quebec and began in September 2010. The mine is divided in two main areas of activity: mining operations and the processing facility, each with totally independent administration. Mining operations refer to the activities surrounding ore extraction, while processing refers to gold extraction. The research began with the direction of mining operations, which involved about 100 people, including the miners, managers and support crews, excluding subcontractors actively involved in various areas of the mine. The main activities undertaken were associated with infrastructure, establishment of crews and preparation of the main pit and residue treatment zones.

Due to constraints on the project start date, non-functional areas, time and so on, we limited our research to the main pit, primary crusher, main conveyor, mechanical maintenance workshop and explosives storage room plus some operational departments (health and safety, mining operations, engineering, maintenance, environment and geology). We defined the areas targeted for the intervention in terms of their criticality and volume of industrial activity in progress and based in part on the work of Kumar and Paul [30].

The operational departments involved are those directly related to ore extraction and main pit preparation activities. In the risk element identification step, we introduced the analysis of data relating to subcontractors. This component is very important in view of the interaction and overlap of subcontractor activities with those of the mining crews. This interaction is inevitable in starting an industrial project and presents major OHS risks [55]. Performance in health and safety of industrial projects is also influenced by the role and quality of subcontractors directly involved in operational activities [56,57].

The company gave us authorization to contact those involved and engage in voluntary discussion. We validated extracted data and submitted proposals with managers of certain departments involved. The risk management team was formed mainly of managers of these departments plus researchers. Meetings were conducted and project progress reports were shared with these managers throughout the intervention.

4.3. Risk Elements and the OHS Database

To identify risk elements, the approach provides for three methods of data collection. These are consultation of records of accidents and incidents occurring in the company, semi-structured interviews and collaborative observation in the field. Interviews were done using a questionnaire previously validated by the researchers and the company representatives. The duration of each interview and questionnaire was about one hour. Collaborative observation was done using a checklist that describes the details to be observed in each zone of the mine. All reference material received approval from the research ethics committees (UQAT and École de technologie supérieure) before starting the project. Interview results, field observations and incident and accident reports were analyzed using a macro of specific calculations in MS-Excel© and MS-Access©.

We began by analysis of accident and incident reports filed since the beginning of company activities, including data relating to subcontractors involved in installations and process start-up. For the analysis of accident records, we identified five major subcontractors (codes S-1, S-2, S-3, S-4 and S-5). These five were present in the mine for more than two years. We classified the data relating to the remaining subcontractors conducting minor operations in the field under code S-6. Data relating to mine workers are classified under the code S-Mine.

In the course of the study, a total of 346 reports of incidents and accidents covering 2009 and 2010 were analyzed. The 346 reports analyzed are those approved by the Health and Safety manager. The mining company has only given us access to approved reports. This step was performed with the involvement of the health and safety department. Discussions with workers directly affected provided better understanding of the circumstances. Reports not validated by the manager of the health and safety department were excluded.

The company data included the impact of the incidents in terms of injuries and material damages. Differentiation on this basis was subjective and often focused on material damages. Verbal descriptions of the events and depth of analysis varied widely from one report to another.

Table 1 summarizes the risk elements obtained from incident and accidents report for 2009. Analyses showed that most accidents were caused by failure to comply with working methods or instructions as well as lack of experience, training or competence. Undesirable events related to these hazards had impact on equipment (fire, collision and material damages) or on humans (foreign body in the eye, fall, injury).

Table 1. Analysis of incidents and accidents (S-Mine and Subcontractors, 2009).

S-Mine and Subcontractors: 2009				
	Hazards	**Undesirable event**	**Incidents**	**Accidents**
1	Failure to respect working methods: instructions, procedures, hazardous areas, safety equipment, inadequate equipment, locking, vehicle parking	Fire, injuries, foreign body in the eye, loss of balance, fall, collision, material damages	7	17
2	Work area constrained, closed, cluttered with obstacles or debris	Pain, jamming, loss of balance, fall, injury	6	3
3	Inattention or lack of concentration	Electric shock, injury, jamming of the body	3	5
4	Mishandling and/or poor posture	Pain, back pain, injury	1	3
5	Frost and ice	Loss of balance, fall, injury and collision	1	3
6	Communication insufficient or lacking	Body jamming or crushing	4	
7	Insufficient experience, training or competence	Injury	2	1
8	Vehicle operation on slopes	Slip, body or organ jamming or crushing, injury	2	
9	Misjudgment of distance and towing	Collision and material damage	2	
10	Maneuver in high winds	High fall, twisting of the back		2

Table 2 summarizes risk elements identified in accident and incident reports for 2010. Failure to respect working methods remained the predominant cause of incidents. New hazards related to driving vehicles appeared due to the start of activities for preparing the main pit and residue treatment areas. The number of vehicles and drivers increased during this period. Communication problems arose in association with integrating new workers and from the presence of other subcontractor crews that did not use the same means and standards of communication. New undesirable events such as pain in upper limbs (back and shoulders) and legs began to occur.

Table 2. Analysis of incidents and accidents (S-Mine and Subcontractors, 2010).

S-Mine and Subcontractors: 2010				
	Hazards	**Undesirable event**	**Incidents**	**Accidents**
1	Failure to respect working methods: instructions, procedures, hazardous areas, safety equipment, inadequate equipment, locking, driving	Injury, loss of balance, fall, collision, material damage	14	82
2	Inattention or lack of concentration	Electric shock, injury, jamming	3	33
3	Lifting or moving heavy loads	Shoulder pain, back pain, sore legs		23
4	Work area constrained, closed, cluttered with obstacles or debris	Jamming, loss of balance, fall, injury	10	12
5	Mishandling and/or poor posture	Pain, back pain	2	19
6	Lack of visibility or inattention	Vehicle accidents, damage to power lines	17	

Table 2. *Cont.*

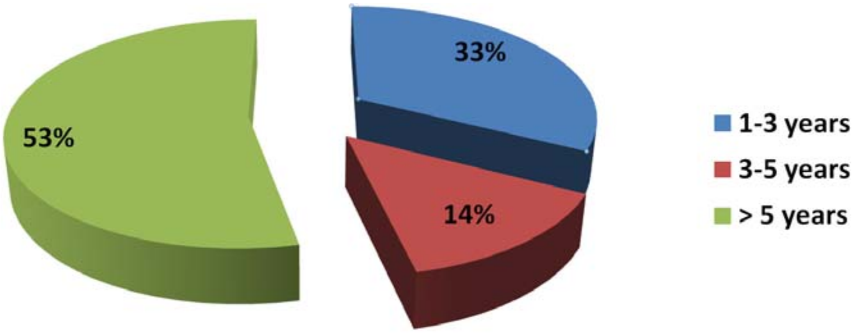
S-Mine and Subcontractors: 2010				
	Hazards	**Undesirable event**	**Incidents**	**Accidents**
7	Misjudgment of distance and towing	Collision, material damage	9	1
8	Moving or unstable part	High fall		8
9	Lack or absence of communication	Body or organ jamming	2	3
10	High falling object	Injury	2	3
11	Frost and ice	Loss of balance, fall, injuries, collision	1	4
12	Conduct not tailored to the situation or the environment	Collision, material damages	4	
13	The vehicle is operating in slope (slope)	Slip, body or organ jamming	2	1
14	Communication insufficient or lacking	Driving accident	3	
15	Sudden movement	Pain, twisting of the back, back pain		3
16	Non-compliant safety equipment, detachment of fasteners	Injury		3
17	Fire	Material damage	3	
18	Evacuation during blasting	Injury	2	1
19	Maneuver in high winds	High fall, twisting of the back		3
20	Rockslide or fall	Injury	2	
21	Heatstroke or chill	Pain, fatigue and problems concentrating		2
22	Fatigue	Driving accident	1	
23	Climatic conditions (snow)	Lack of visibility, collision, material damage		1
24	Power sources	Electric shock, burns		1
25	Use of dangerous equipment, handling without precautions	Injury		1
26	Poorly distributed load	Loss of balance, fall, injury		1
27	Bursting, explosion	Injury		1
28	Gas leak	Fire and injury		1

In 2010, most incidents caused by subcontractors were related to inattention, lack of visibility, congested areas and poor communication. Among the most frequent undesirable events were vehicle collisions and contact with high-energy devices. Lack of concentration during tasks was due to fatigue related to work overload. Failure to respect working methods (protective equipment not used, access to hazardous areas not limited, *etc*.) was also a common source of danger to all subcontractors. The undesirable events included injuries, fire, fall, electric shock and pain in upper limbs.

Subcontracting was associated with 73% of incidents and accidents, thus confirming the importance of considering and collecting risk elements related to these activities. OHS risks related to the presence of subcontractors is frequently neglected in the management of industrial projects. Grusenmeyer [58] confirmed the positive correlation between the numbers of industrial accidents and subcontracting activities. Several researchers have highlighted this problem in the construction industry and emphasize the importance of improving communication, task organization and the safety culture [20,29].

Semi-structured voluntary interviews with workers (43 in all, from all company departments involved in the research) were conducted during working hours to identify new hazards and to confirm certain observations made during the analysis of accident and incident reports, in particular regarding the presence of hazards as defined by Curaba *et al*. [47]. They were combined with questionnaires and allowed identification of potential dangers in each area of the mine. Details of the experience of these workers in the mining industry are presented in Figure 6. Among the workers with more than five years of experience, 65% had more than 10 years of mining experience in various functions.

Figure 6. Distribution of workers based on their experience in the mining industry.



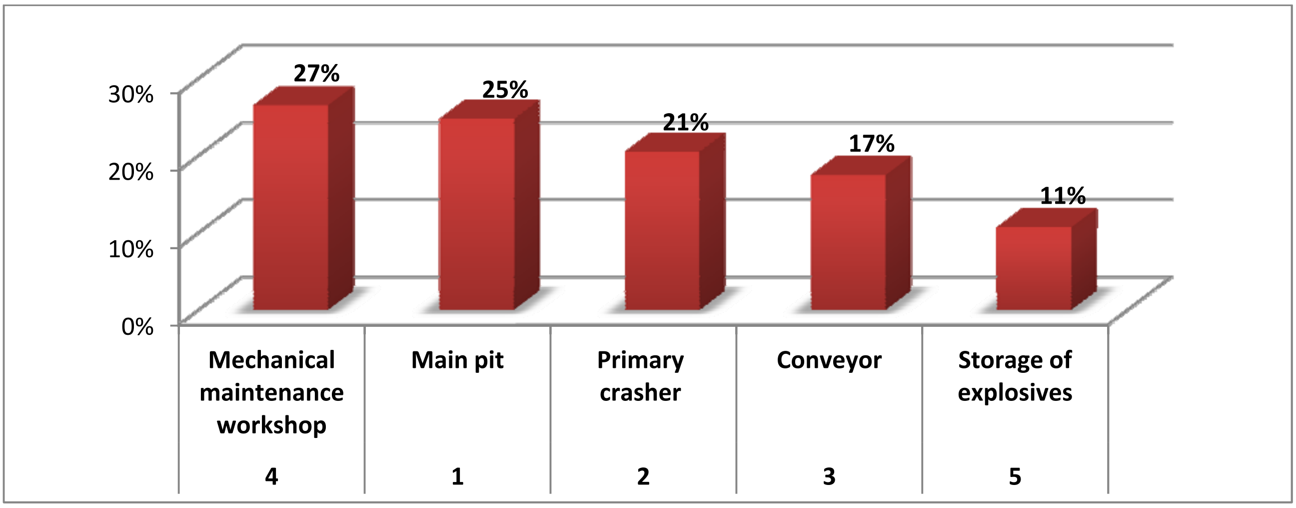
The interviews and the 35 hours of collaborative observations in the field confirmed the potential occurrence of hazards as listed by Curaba *et al.* [47]. This step allowed us to generalize a portion of these in the case of an open-pit mine. Table 3 shows the association between identified hazards and specific areas of the mine.

Table 3. Presence of hazards in specific areas of the mine, based on interviews, questionnaires and observations.

Hazard Curaba *et al*. [47] *	**Area of the mine**				
	Main Pit	**Primary Crusher**	**Main Conveyor**	**Mechanical maintenance workshop**	**Storage of explosives**
Mechanical *	✓	✓	✓	✓	
Electrical *	✓	✓	✓	✓	
Ambient physical *	✓	✓	✓	✓	
Human	✓	✓	✓	✓	✓

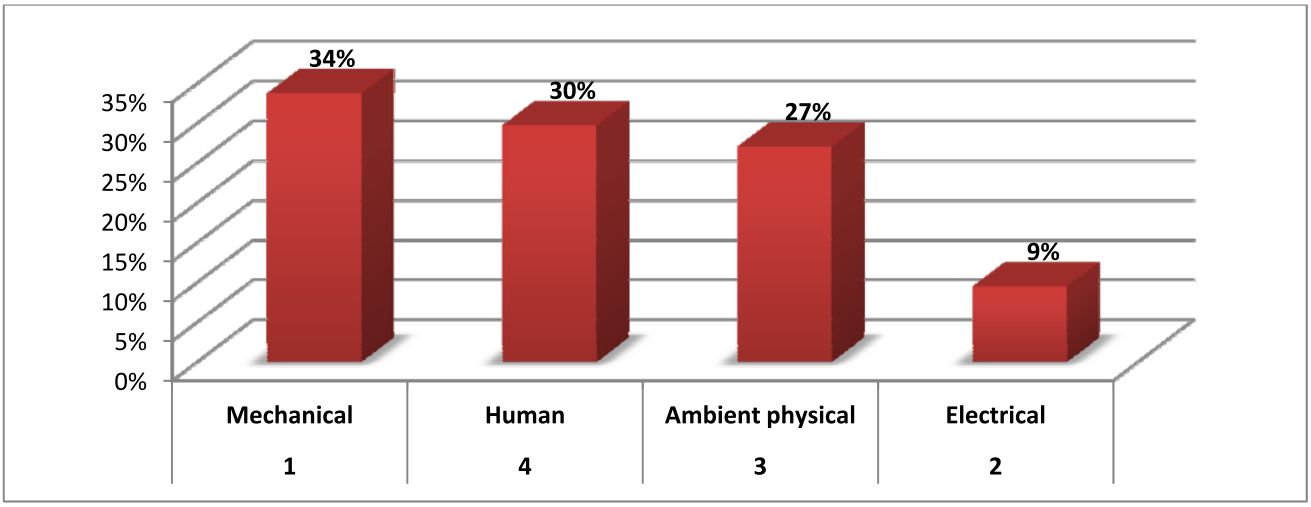
The criticality of the areas of the mine as ranked by the consulted workers is shown in Figure 7. The questionnaire allowed us to synthesize estimates of workers. Workers choose an answer on a scale of three levels of criticality (low, medium and high). Their opinions are based on their knowledge of the company and their expertise and experience in the mining industry. The mechanical maintenance workshop was ranked first, while storage of explosives was ranked last. The perception of explosives storage as less critical was explained in terms of (1) its distant location from areas of operations; (2) access limited to specialized and highly qualified staff; and (3) the rarity of human interaction and man-machine interaction in that zone.

Figure 7. Criticality of the areas of the mine as perceived by the consulted workers.



Before weighting the influence of each category of hazard to cause an undesirable event, it is important to note the criticality of these as perceived by the consulted workers (Figure 8). Their ranking was (1) mechanical; (2) human; (3) ambient physical factors; and (4) electrical (conspicuously lower than the other three). The major concerns were congestion of working areas, the presence of moving parts (tools, conveyors, *etc.*) and constraining elements (structures, pipes, *etc.*). Hazards related to ambient physical factors were emphasized, suggesting ergonomic problems in vehicle design (excavators, trucks, drills, bulldozers, *etc.*) and concern regarding the dusty environment (main pit, traffic patterns, crusher, *etc.*). Human hazards associated with the problem of communicating with new, inexperienced workers and interacting with subcontractors not knowing the safety rules of the company or not sharing safety concerns were also emphasized.

Figure 8. Criticality of different sources of hazards as perceived by consulted workers.



The OHS database (Appendix A) was thus developed to feed the model underlying our approach to integrating OHS into the risk management aspect of the mining project in progress. Identified hazards were evaluated in accordance with: (1) the consulted workers' expertise; (2) collaborative observations in the field; and (3) analyses of incident and accident reports. The OHS database allowed grouping of all possible hazards for quick integration into project risk management.

Incident and accident reports of the company were adapted as shown in Table 4. The new database allowed new hazards to be entered continuously. The proposed tables are adaptable and improve the current incident and accident monitoring system and aid the extraction of necessary data for risk assessment.

Table 4. Proposed structure for the monitoring and logging of hazards in the mine.

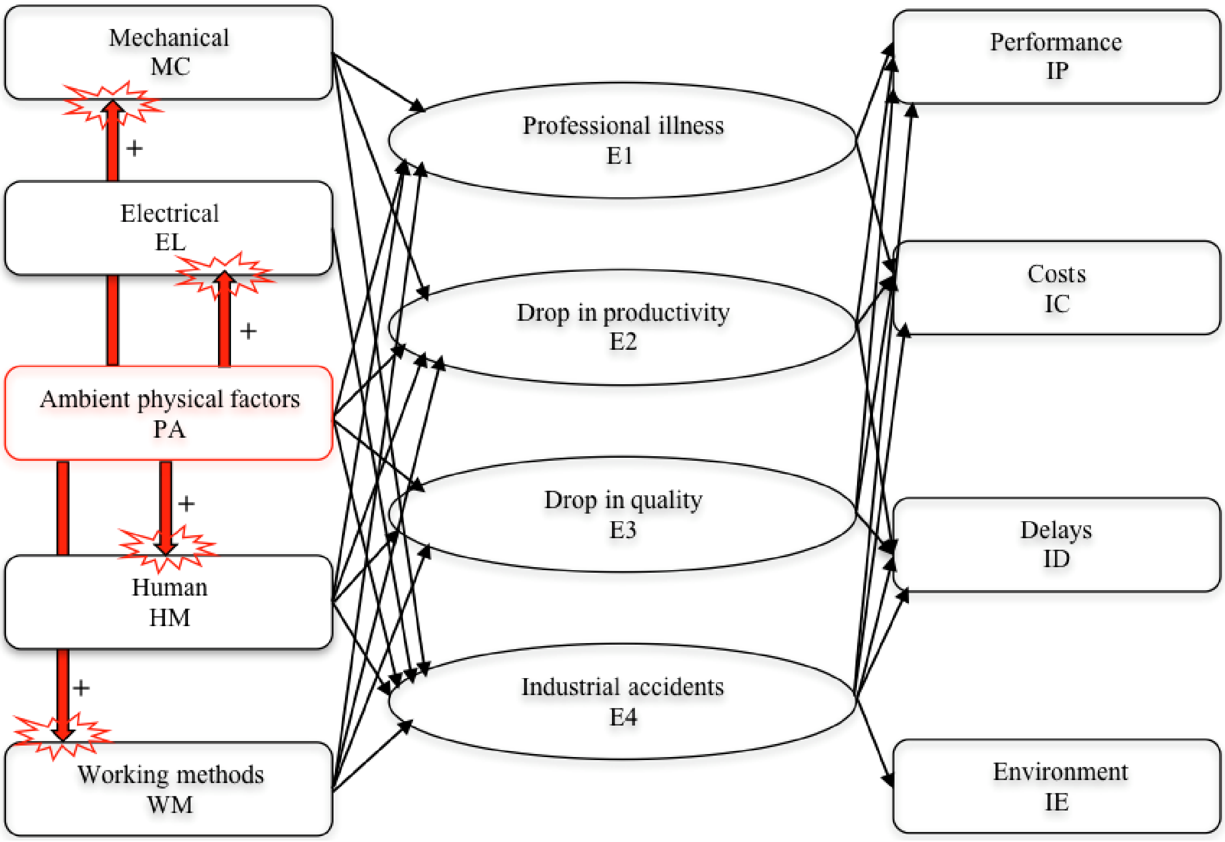
Category	Hazard	Code	Details of most recent event	Victim	Area	Impact	Number of appearance	Date of last appearance
MC	…	MC-1	…	…	…	…	…	…
HM	…	HM-2	…	…	…	…	…	…

To complete the risk element identification phase, research team members noted their preoccupation with the following undesirable events: job-related illness (E1), drop in productivity (E2), drop in quality (E3) and industrial accidents (E4). These undesirable events have negative impact on mine performance (IP), project costs (IC), project delays (ID) and the environment (IE).

These elements (undesirable events and impacts) were much simpler to identify by the team throughout the hazard identification phase. Tolerance of risks by the company may play an important role when choosing the types of negative impact. The nature of the industry also influences their choice. In the case of mining operations, final product quality (gold in the present case) is not a determining factor compared to the quality of the gold ore mining before processing.

Once the risks elements were identified, the team traced the possible causal links between hazards and undesirable events using the OHS database (Appendix A). This allowed monitoring and prediction of possible progression of risks. In view of the importance of this step, the team consulted workers having more than 10 years of experience. Figure 9 shows the final version of the causality linkage between different elements of the identified risks. During the interviews, certain reinforcing effects of ambient physical hazards were identified (red full arrows in Figure 9). For example, rain and flood hazards reinforced the effect of human hazards by subjecting the workers in the main pit to greater stress (fear of electrocution) as well as reinforcing electrical hazards. Other factors worth mentioning are snowstorms complicating vehicle use and shorter daylight hours increasing collision and injury risks.

Figure 9. Causal links between the elements of risk and reinforcing effects of ambient physical factors. [+: reinforcing effect].



4.4. Risk Assessment and Prioritization

Comparison of hazard categories was done using the AHP method, which involves the paired comparison of the five categories of hazards (MC, EL, PA, HM and WM). Comparisons were based on the influence of the hazard categories on each identified undesirable events (E1, E2, E3 and E4). The consistency of the expert judgments was verified instantly using Expert Choice© software. As obtained by Saaty [48], the consistency index (CI) of each comparison matrix did not exceed 10%.

Table 5 shows the relative and overall weights of each category of hazards, its rank and its assigned weight for the purposes of calculating the weighted concentrations.

Table 5. Weight calculation of the hazard categories.

Undesirable event	**Relative weights (AHP) of the hazard categories**				
	MC	**EL**	**PA**	**HM**	**WM**
E1	0.50	0.03	0.22	0.13	0.12
E2	0.18	0.03	0.16	0.36	0.27
E3	0.05	0.03	0.21	0.40	0.31
E4	0.52	0.19	0.06	0.13	0.09
√ Overall weight (AHP)	0.04	0.002	0.02	0.05	0.03
Rank (AHP)	2	5	4	1	3
Weight—b_{ij}	**4**	**1**	**2**	**5**	**3**
Number of hazards—a_i	10	2	10	6	4

The probability theory of risk occurrence involves the calculation of the relative concentration of each category of hazard.

As indicated above, hazard concentration (**CR_{ij}**) represents the weighted fraction of each category of hazards (**i**) containing $\mathbf{a_i}$ hazards and related to an undesirable event (**j**). The weight (**b_{ij}**) of each category of hazards is carried out according to the AHP pairwise comparison. When this concentration increases, the probability of an undesirable event increases. It is therefore more likely to trigger the associated undesirable event. Concentration was calculated as follows:

$$\mathrm{CR_{ij}} = \frac{\mathrm{A_{ij}}}{\sum_{i=1}^{n}\sum_{\mathrm{j=1}}^{\mathrm{m}} \mathrm{A_{ij}}} \tag{1}$$

With:

$$\mathrm{A_{ij}} = \mathrm{a_i b_{ij}} \tag{2}$$

Where: a_i: Number of hazards of category (i) (Level 1 in Appendix A); bij: Weight of category (i) of hazards causing an undesirable event (j). i ∈ {1, 2, ..., n} and j ∈ {1, 2, ..., m}.

Table 6 summarizes the calculation of the probabilities of occurrence based on hazard concentration and the corresponding probability conversion scale applicable in the case of this mine. The concentration conversion stems from the reasoning underlying that the probability of occurrence of an undesirable event increases with the number of hazards present [59-61]. It is important to note that the value of this probability of occurrence is difficult to estimate. According to Aubert and Bernard [62], no statistical analysis can directly assess this probability. These constraints have forced many researchers to develop intermediate conversions to estimate the probability of occurrence (e.g., frequency-probability, incidence and injury rates-probability) [17,63,64].

Table 6. Calculation of the probabilities of occurrence of hazards.

S-Mine probability scale		Probability of occurrence		
Concentration	**Probability of occurrence**	**Undesirable event**	**$CR_{(i)}$ concentration**	**Probability assigned**
0.10 to 0.25	20	**E1**	0.276	40
0.26 to 0.55	40	**E2**	0.276	40
0.56 to 0.75	60	**E3**	0.168	20
0.76 to 0.95	80	**E4**	0.281	40

The hazards concentration makes the weighting of each hazard category more realistic in terms of direct influence on the associated undesirable events. Based on this idea, evaluators no longer consider the identified hazards as entities having the same influence-weighting factor. The conversion of the measured concentrations does not introduce a bias into the calculation or change the reasoning underlying the risk estimation. This conversion has the advantage of allowing the organization to act according to its tolerance of risks [65-68], that is, to change the levels in the conversion scale to match the concentrations of hazards that it is able to tolerate.

The risks were selected for consideration on the basis of the risk management strategy of the company. Based on the loss that would be (or had been) incurred, the impact of an undesirable event associated with a given risk was judged as minor (1, 2 or 3), average (4, 5 or 6) or high (7, 8 or 9) and calculated as follows:

$$\text{Impact}_{\text{Risk (i)}} = \text{Maximum impact}_{\text{(Performance, Costs, Delays, Environment)}} \quad (3)$$

In other words, the impact associated with risk (i) was that of the event considered to have the greatest impact. In project management and according to Aubert and Bernard [62], risk is defined as the combination of the probability of occurrence and the impact of an event. The following equation was used to calculate and prioritize risks at the end of the evaluation phase.

$$\text{Risk}_{\text{(i)}} = \text{Probability}_{\text{Undesirable event (i)}} \times \text{Impact}_{\text{Undesirable event (i)}} \quad (4)$$

Table 7 shows the risks prioritized on the basis of probability of occurrence and the impact of undesirable events.

Table 7. Prioritization of identified potential risks.

Priority	**Code**	**Type of event**	**Probability of occurrence**	**Negative impact**	**Risk level** Equation (4)
1	E4	Industrial accident	0.4	9	**3.6**
2	E1	Job-related illness	0.4	8	**3.2**
3	E2	Drop in productivity	0.4	7	**2.8**
4	E3	Drop in quality	0.2	8	**1.6**

4.5. Problems and Constraints

In this study, OHS integration was limited to tasks handled by the Health and Safety department that manages and promotes worker health and safety. We assert that Health and Safety department has limited capacity for attaining health and safety objectives without the active involvement of the other operational departments, especially in the case of a project start-up, in which several latent phenomena may occur. These latent phenomena are associated with: (1) new recruited workers; (2) the presence of much machinery and new equipment; (3) communication between crews and their managers; and (4) the presence of several subcontractors in operational areas for a great diversity of tasks.

The feasibility study focused on technical, economic and environmental aspects and did not integrate OHS with conventional risks. It is important to note that the environmental aspect deals with OHS only partially. Risk management teams are usually more focused on risks that are known and require attention by law and regulations [69]. Preventing OHS risks by improving mining project design remains a goal to be achieved by researchers and practitioners alike.

Current operation of the mine is geared towards discovering OHS problems during operations (corrective vision). For example, we observed the risk of collision between the excavator and loading trucks. If the company had already developed an OHS database and implemented routine evaluation of OHS risks, this problem would have been discovered before running mobile equipment and starting work in the main pit. This example of risk management can be justified economically (material damages and shutdown) and in terms of OHS (injuries or fatal accident). In both cases, the mine could benefit from a non-negligible gain if it focused on a prevention strategy based on a rigorous evaluation of risks before the beginning of mining activities.

Companies usually benefit on the long term from accident and incident histories to formulate policy recommendations in favor of prevention. Start-up activities usually take into consideration project progress and the point at which economic profitability is expected. With the pressure of starting a new business, it is difficult to benefit immediately from the experience of the new recruits to build a usable knowledge base for the purpose of improving worker health and safety. We emphasize this observation in the present case, in which the mine had a large potential knowledge base of experienced workers oriented for technical purposes.

To make incident and accident reports reliable and more useful, they must identify clearly the risk elements (hazards, undesirable events and impact). A complete and detailed description of the risk elements provides more clarity and allows quicker use of the data when necessary. We have drawn attention to this fact and have started discussions with accident victims to improve the analysis or to complete event descriptions.

4.6. A New Approach for a New Vision

The above action research stemmed from evaluation of the overall situation in this mining company and was intended as a practical decision support tool in the specific context of integrating OHS with a new mining project.

Several hazards were identified during our presence using the proposed approach. We were able to confirm the presence of certain hazards identified in other studies of mines [34,40,70-74] and we noted in particular dangers associated with equipment and machines, worker-machine interferences, power sources, mechanical sources, driving of vehicles and ambient physical factors (dust, noise, vibrations, rain and floods, explosions, *etc*.). Kumar and Paul [30] also noted hazards such as high-risk driving behavior, failure to respect instructions and procedures, as well as work in limited spaces. We confirmed the criticality of several areas of the mine that were cited in other studies, including mechanical workshops, explosives storage areas, pits, conveyors and electrical stations as discussed by Kumar and Paul [30] and Singh [75].

The analysis of incidents and accidents, the interviews and collaborative observation all helped create an OHS database usable by the company in particular and by open-pit mines in general. Through the development of this database, we were able to utilize the mining experience of workers in support of a safety and prevention policy. The company thus benefited from the expertise of new workers during the first months of their employment.

The approach allowed prioritizing of potential risks by involvement of the crews, analysis of available data and our presence in the field. The new concept of hazard concentration added a more realistic dimension to the influence of hazards and led to the identification of certain reinforcing effects of ambient physical hazards. The use of multi-criteria analysis (AHP) allowed the combination of quantitative and qualitative data and testing of the consistency of expert judgments in order to provide consistent decisions and reliable prioritization of risks. Data collection tools were chosen to maximize the extraction of information in a relatively short period of time.

This action research has the potential to promote the convergence of OHS with all operational activities of mines. Collaboration between the researchers, the company and workers accelerates the solving of certain problems [76,77]. By applying the approach and examining the results, the mine will be able to utilize OHS data sooner. The increasing priority given to industrial accidents and job-related illness shows that consideration of OHS is gaining ground and catching up to productivity and quality. Identifying and prioritizing risks is crucial to gaining control over known hazards and avoiding their negative impact on projects in particular and on the company in general.

4.7. Limitations and Avenues of Future Research

The methodology of action research has its benefits and drawbacks. According to Hales and Chakravorty [78], advantages can be summarized as complete answers to the questions "why" and "how", which cannot be obtained through statistical analyses alone. Field study allows us to describe the actual problem and identify solutions based on the selection of data reflecting a more complete vision of the system and more realistic consideration of the interactions within it. Among the disadvantages of action research, the difficulty of generalizing the results and the influence of the corporate culture on the effectiveness of the proposed solutions should be mentioned [44].

To the best of our knowledge, no study of the integration of OHS into risk management in open-pit mining projects has been published, and meaningful comparison of our findings with those of other researchers is difficult. We use summary categories to estimate the criticality and confirm the presence of hazards. It is important to note the necessity of drilling down into the data and targeting interventions, when needed to allow the user to focus on details at the practical level of operations. Our intervention was limited to risk identification and assessment, since the company had the capability of devising a safety and prevention plan based on its risk prioritization. The medium-term impact of the intervention on the company will be the subject of monitoring and rigorous verification by the researchers. We have also planned to conduct interventions in other mines in order to generalize the approach and make it available to gold mines throughout Quebec.

5. Conclusions

In this action research involving a company exploiting an open-pit gold mine in Quebec, we used a new risk-factor-based approach to integrating OHS into risk management in the context of a new mining project. The approach has been tested previously in the simulation of a factory expansion project. The work was based on thorough analysis of accident and incident reports, interviews, questionnaires and collaborative observation in the field. A new concept of hazard concentration, based on the number and influence of hazards by category is proposed with multi-criteria comparison by the AHP method.

During this work, we created an OHS database including all the identified and confirmed hazards in the context of an open-pit mine. The database thus developed allows researchers to identify hazards sooner and apply more rigorous risk management. The proposed approach allowed the company to prioritize the potential risks and to identify reinforcing effects among hazards in order to choose the best safety and prevention strategy.

This action research involved several types of actor from the outset of the project and promoted sharing of industrial expertise. It allowed correction of biases and gathering of consistent opinions and thus allowed the company to benefit from the accumulated experience of workers in the mining industry. The study enabled the company to construct a knowledge base useful in the effort to prevent OHS problems that cause delays in the achievement of project objectives.

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Appendix A. OHS database (Summary of hazards).

Category (Level 0)	**Subcategory (Level 1)**	**Details of hazards (Level 2)**
Mechanical (MC)	MC-1	Mobile park: Excavator, drill, bulldozer, articulated haulers, truck, pickup, scraper, leveler, loader, crane
	MC-2	Equipment: Non-compliant safety equipment, dangerous equipment, ladder, stairs, gateway
	MC-3	Maintenance and installation of equipment Preventive, mechanical wear, wiring, installations
	MC-4	Moving parts: Tools, trailers, grinder, conveyor belt, working basis, moving or unstable part, vibrating object
	MC-5	Under pressure devices and elements: Compressors, gas cylinders, hydraulic or pneumatic circuits
	MC-6	Constrained elements: Structures, slings, racks loaded, pipes, tank
	MC-7	Handling: Traveling crane, pallet truck, cart, conveyor
	MC-8	Shifting and oversight: Obstacle on the ground, slope, high walls, open ground
	MC-9	Explosion-bursting: Leak, fire, smoke, dust, fuel, gas, enclosures in depression, explosives, sparks, electric arc, blasting, friction, chemical products, tires, battery
	MC-10	Fall, collapse, projection or reversal, slip: Rocks, load, object, worker, structure, open ground, blasting
Electrical (EL)	EL-1	DC or AC power: Electrical room, electrical cabinet, transformer, cable, isolation, electrical outlets overloaded, battery, electrical equipment, measurement tool
	EL-2	Static electricity: Charge accumulation on insulating materials, spark during unloading of flammable materials

Appendix A. *Cont.*

Ambient physical factors (PA)	PA-1	Light environment: Lighting of work stations, glare, brightness
	PA-2	Display screen: Computer, control interface
	PA-3	Soundscape (noise): Gussets, machines, mobile park, blasting, crushing, radio
	PA-4	Vibration: Machines, vehicles, blasting, crushing
	PA-5	Contact temperature: Heater, hot surface, gel and ice
	PA-6	Design of the workstation: Working posture, repetitive gesture, Man-machine interface, job location, ergonomics
	PA-7	Hostile environments: Asphyxia, diesel particulate, chemicals, explosives
	PA-8	Dusty environment: Ventilation, crusher, blasting, transport ore, loading, unloading, excavation
	PA-9	Limited areas: Confined space, debris, waste, obstacles, traffic patterns, parking, garage, loading area, unloading area, jamming against an object
	PA-10	Climatic condition: Frost and ice, bad weather, wet temperature, maneuver in high winds, rain and flood, snow, heatstroke, chill, fog
Human (HM)	HM-1	Risk behaviours: Alcohol, drug, tobacco, non-compliance with safety measures, non-compliance with instructions/protection, unsafe driving
	HM-2	Stress and fatigue: Work pace, overwork, inattention, lack of concentration, to sleep
	HM-3	Harassment
	HM-4	Interference: Several subcontractors, competition, cultural differences, languages, integration, pedestrian-equipment
	HM-5	Competence: Expertise, training, local knowledge, capacity for action, autonomy
	HM-6	Human error: Conduct, parking, order, working methods, safety instructions, oversight, manipulation, access to hazardous areas, decision, safety equipment (belts, harness, *etc.*)
Working methods (WM)	WM-1	Methods: Posture problems, excessive effort, sudden movement, lack of signaling, non-adapted conduct, communication, reactivity, safety equipment, lifting or moving a heavy load, improper handling, exploration
	WM-2	Risk tasks: Driving, loading shovel, drop operation, blasting, near area excavated by blasting, near a power source in the pit, near the vehicles, intervention in height, intervention in a confined space, repairing, preventive maintenance
	WM-3	Planning: Monitoring, communication, overtime, organization of work at risk, division of labor, interference
	WM-4	Execution: Tasks control, layers and ground control, site examination, emergency procedures, communication

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