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A NEW PRACTICAL APPROACH TO RISK MANAGEMENT FOR UNDERGROUND MINING PROJECT IN QUEBEC

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Abstract

The mining industry worldwide is currently experiencing an economic boom that is contributing to economic recovery and social progress in many countries. For this to continue, the mining industry must meet several challenges associated with the start-up of new projects. In a highly complex and uncertain environment, rigorous management of risks remains indispensable in order to repel threats to the success of mining.

In this article, a new practical approach to risk management in mining projects is presented. This approach is based on a novel concept called “hazard concentration” and on the multi-criteria analysis method known as the Analytic Hierarchy Process (AHP). The aim of the study is to extend the use of this approach to goldmines throughout Quebec. The work is part of a larger research project of which the aim is to propose a method suitable for managing practically all risks inherent in mining projects.

This study shows the importance of taking occupational health and safety (OHS) into account in all operational activities of the mine. All project risks identified by the team can be evaluated. An adaptable database cataloguing about 250 potential hazards in an underground goldmine was constructed. In spite of limitations, the results obtained in this study are potentially applicable throughout the Quebec mining sector.

Keywords

Mining projects; underground goldmines; risk management; occupational health and safety (OHS); multi-criteria analysis (AHP).

1. Introduction

The mining sector has been experiencing a period of strong growth over the past few years. Mining companies and subcontractors (construction, consulting engineers, equipment suppliers, etc.) are all benefiting from renewed exploration, development and start-ups (Schmouker, 2011). Governments of countries in which these projects are underway view the current boom as a lever for helping the economy out of the recession that has been hindering economies around the world for at least as many years (Humphrey, 2011). These countries, including Canada, pin much hope on the contribution of mining to economic recovery and have put many projects on the fast track by contributing to innovation and the promotion of mining entrepreneurship (e.g. MRNF, 2012).

Canada is a leader among mining nations, world leader in the production of potash and uranium, second producer of nickel and cobalt and third in extraction of several other metals (The Canadian mining journal, 2008). Like several other Canadian provinces, Quebec is benefiting from the current development of the mining industry, with numerous high-potential mineral and metal deposits, including gold, nickel, cobalt, zinc, platinum, iron, copper, lithium, vanadium and rare-earth elements (Quebec Government, 2011). This industry contributes an estimated 2.7% of the provincial GDP (QMA and QMEA, 2010), a figure growing in view of the number of mining projects underway in the context of the Plan Nord® program. There are currently 11 new projects well into the developmental phase (Rousseau, 2011).

A territory twice the size of France has been thus marked for new mining projects (Figure 1). The Plan Nord® represents investment potential valued at $80 billion, of which $33 billion will be earmarked for the mining sector, related industries and workers, including roads, housing, transportation, schools, health, telecommunications, airports and so on (Rousseau, 2011).

The development of the mining industry in sparsely populated areas lacking infrastructures poses several challenges, risks and uncertainties associated with overcoming long distances, appealing to an aging labour force, recruitment, training and keeping workers, and availability of subcontractors and suppliers (CSMOM, 2012; Doggett, 2007; Kral, 2006). Starting up several projects at the same time in a given region requires careful planning and huge efforts from both the business community and public authorities. Poor synchronisation between the development of mining projects and of the required infrastructures and labour can lead to early failure. Interruption of projects would have province-wide political and economic fallout and is not an acceptable risk. The mining industry itself will not agree to begin activities in a climate of uncertainty, given the financial burden and complexity of the projects being considered (Chinbat and Takakuwa, 2009). In addition, public pressure to ensure safe and responsible mining of deposits as well as economic benefit to the taxpayer is huge and adds considerably to the challenges of any business or government contemplating such an undertaking.

Figure 1 – The designated Plan Nord® territory (Quebec Government, 2011)

In an effervescent economy, mining companies must identify and implement risk and uncertainty monitoring and control strategies. The mining industry must also adapt and implement major measures in order to deal with a variety of problems and challenges (e.g. Rousseau, 2011). Concerns with productivity and the advantages of using innovative equipment and new methods of extraction must not be examined only from an economic perspective, nor should personnel requirements be evaluated only in terms of operational indicators. Interdisciplinary and participative evaluation of operational needs and activities throughout all project phases reduce the likelihood of overlooking relevant risks (Pal and Dewan, 2009). A mining project is by nature very complex and marked by numerous interactions between endogenous as well as exogenous factors, thus requiring major efforts in order to eliminate risks that threaten to delay or block the achievement of goals (Badri et al., 2011a).

Systematic management of risks and uncertainties remains the most effective means of ensuring maximum safety of a mining project and covering all phases of the project life cycle (e. g. Orsulak et al., 2010). For increased effectiveness, risk management should go beyond technical and environmental feasibility studies and take into consideration several types of threats often neglected, underestimated or hidden because of the complexities of the industrial context. Setting and achieving such objectives will not only improve the social capital and image of the industry, it will also increase feelings of security among workers, businesses and surrounding communities as well as throughout the mining sector in general.

This article aims to promote the use of a new practical approach to risk management in underground goldmines in Quebec. New concepts developed, validated and utilized in open-pit mining have been adapted to underground mining. This work identifies limitations, proposes improvements to implementation and considers opportunities expanding the range of applicability. This work is part of a larger research project with the aim of devising an approach suitable for managing practically all types of risks associated with mining projects.

Section 2 reviews the particularities and challenges in the mining industry and discusses risk management as well as several methods thereof in mining companies. Section 3 presents the research methodology and describes the proposed practical approach to risk management. The results are presented in section 4, while section 5 contains discussion of the value and limitations of the approach. Section 6 contains a summary of the findings as well as the conclusion.

2. The current situation

Management of mining projects is often influenced by several factors, which may be internal or external to the organization. These factors complicate the achievement of the objectives and add constraints to the daily management of operations. Among the most notable are (1) project complexity, in particular scale, duration, budget, number of suppliers and subcontractors (Chinbat and Takakuwa, 2009); (2) variability, in particular of equipment, worker experience, skill and geographic origin, management tools and methods (Kral, 2006; Rousseau, 2011); (3) interdependencies, in particular between workers, promoters, teams, relationships, organizations (Paszkowska, 2002; Radosavljevic, 2009) and (4) industrial context, that is, cooperation, competition, work environment, maturity and culture, sense of social responsibility, laws and regulations and so on (Kemp, 2010; Zhou and Zuo, 2002).

In addition to the factors listed above, there are diverse risks and uncertainties peculiar to mining. These also depend on the nature and complexity of the project and evolve throughout the project lifecycle. Several researchers have attempted to define them concisely, hoping to improve the safety of mining project operations (e.g. Atkinson et al., 1996; Chinbat and Takakuwa, 2009; Mol, 2003; Orsulak et al., 2010). The effort to date is considerable, but has stopped short of integrating the definition of risks and uncertainties into management as a whole. This deficiency is sometimes attributed to the uniqueness of the mining context, lack of data, the complexity of the task, pressure to avoid delays and insufficient risk management skill and knowledge (e.g. Badri et al., 2011a; Komljenovic and Kecojevic, 2007).

Risk analysis is nevertheless one of the biggest concerns in the mining industry (e.g. Lilic et al., 2010). In order to improve risk management, an obvious first step is reliable identification of hazards, based on analysis of the available data (Komljenovic and Kecojevic, 2007; Tchankova, 2002). Komljenovic and Kecojevic (2007) have summarized management of mining risks in terms of systematic application of procedures and standards, evaluation of hazards and consequences, qualitative and quantitative evaluation of risks, and decision-making based on results obtained. In order to meet with success, the overall aim of risk management must be clear and supported by well-defined objectives.

Data and other relevant information must be gathered in order to identify problems associated with technical, environmental or organizational aspects as well as with human nature (Gheorghe, 1996). In a complex industrial setting, identification of potential risks encounters difficulties associated with choosing sources of information and clarifying the various categories of risks. Among the best-known categories, researchers have discussed occupational health and safety (OHS), financial, economic, operational, social, technical, organizational, legal, political and environmental risks (e.g. Bhattacharya et al., 2008; Daoud et al., 2011; Kumar, 2004; Lilic et al., 2010; Pal and Dewan, 2009; Shen, 2010). In addition to risks, practitioners and researchers must enumerate and integrate the various possible uncertainties (e.g. resource estimation errors).

In general, risk management tools are not designed specifically for the mining industry. They are usually borrowed from the nuclear, petrochemical or construction industries or from military structures. In addition to mining skills, the industry also depends on several other industrial specialties. A mining project actively involves subcontractors from several fields including consulting engineering, construction, mechanics, electricity and fluid mechanics as well as equipment suppliers (machines, measuring instruments, etc.). The use of risk analysis tools borrowed from other industries is justified by the advances being made in risk management in these sectors. Development and progress of a safety culture, changes to laws and regulations, and the desire to increase resource security have all contributed to open-mindedness towards the use of these tools in the mining industry.

Komljenovic and Kecojevic (2007) have reviewed risk management practices, standards, tools and approaches used both in the mining industry and in other industrial sectors. They have catalogued risk evaluation standards and guides (e.g. ANSI/AAMI/ISO 14971: 2000; ISO-17776: 2000 and DOE-DP-STD-3023-98: 1998) and risk analysis techniques (e.g. NASA: 2002 and DOE Guidelines: 1992). Other researchers have compiled the risk analysis methods and tools most used in mines (Daling and Geffen 1983; Dhillon, 2009; Komljenovic and Kecojevic, 2007). These are summarized in Table 1.

Table 1 – Risk analysis tools

Acronym	Name
BM	Binary Matrices
CA	Consequence Analysis
CBA	Cost Benefit Analysis
ETA	Event Tree Analysis
FMEA	Fault Modes and Effects analysis
FMECA	Fault Modes, Effects and Criticality Analysis
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Study
HEA	Human error Analysis
HRA	Human Reliability Analysis
MORT	Management Oversight and Risk Tree Analysis
PHA	Preliminary Hazards Analysis

According to Daling and Geffen (1983), the six risk analysis tools most widely used in the mining sector were PHA, FMEA, BM, CA, MORT and HRA. Many years later, this list had not changed (Dhillon (2009), at least for risk analysis of mining equipments. In general, dedicated versions of these tools are used for equipment and process safety, with little adaptation to analysis of other risks of various types in specific organizational and human contexts. The CA tool is used during the design of industrial infrastructures primarily to determine the possible consequences of a particular hazard such as dust, explosion, fire or toxicity (e.g. Alonso et al., 2008; Shariff and Zaini, 2010). This tool requires quantitative data and simulation software to evaluate consequences. For example, Alonso et al. (2008) used it to estimate damage associated with an industrial explosion using over-pressure, dust and explosion distance as parameters. The CBA tool is used to analyze risks, but as a complement to other methods (Jones-Lee and Aven, 2009). Jones-Lee and Aven (2009) describe this tool as dedicated to evaluation from an economic and investment perspective in situations of uncertainty. The tools FMEA and FMECA are widely used during product and process design to anticipate possible failures (e.g. Herman and Janasak, 2011; Levinson et al., 2011). Neither of these tools can be used to analyze more than one mode of failure at a time (Dhillon, 2009). Other tools such as MORT require very much time and are quite complex (Daling and Geffen, 1983). Some tools such as HEA and HRA deal with only a single risk typology (e.g. Iden and Shappell, 2006; Nelson et al., 1994), while others provide analysis only of the impact of risks (CA and CBA).

The current industrial context and the rise in metal prices are putting additional pressure on mining companies to maximize production capacity and profits. The industry therefore needs tools that are reliable and easy to use. It would be very useful to group or adapt some of these tools in order to benefit from the advantages of each. However, this effort should not result in increased complexity and must take into consideration the particularities of the use of each tool.

Finally, the uncertainty and risky nature of mining projects and the limitations of conventional risk management tools are motivating practitioners and researchers further to design new systematic approaches better adapted to the industry (e.g. Badri et al., 2011a; Komljenovic, 2008; Orsulak et al., 2010). Proper integration of these approaches into the project risk management process will lead to (1) better protection of human capital and the environment; (2) sparing of resources (human and material); (3) reduced legal, professional and civil liabilities; (4) better public image of mining companies and (5) increased operational stability and flexibility of companies in the face of change and unexpected developments (IBC, 2010).

3. Methodology

3.1. Research continuity

This article represents the continuation of a three-year research project of which the aim is to integrate OHS into risk management in mining projects in Quebec. The work began by reviewing the literature to evaluate the relative importance of OHS in risk management in industrial projects in several fields (Badri et al., 2012a). This overview of industrial practices and research revealed the need to create or adapt methods in order to deal with constraints associated with the challenge of integrating and evaluating OHS risks and also confirmed the need to increase the consideration given to OHS. An approach to integrating OHS into industrial project risk management was then developed (Badri et al., 2011b). The work is based on best industrial practices and a body of interdisciplinary knowledge in risk management. The proposed approach is based on the number of hazards identified and the relative significance of each category. A new concept called “hazard concentration” was combined with the multi-criteria comparison method known as the Analytical Hierarchy Process (AHP) to evaluate and rank potential risks.

This approach was adapted and tested on a new open-pit mining project (Badri et al., 2011a). Researchers used an action research methodology in order to favour exchanges with industry experts and benefit from the active involvement of the industrial partner. Once adapted to the open-pit mine context, the proposed approach was used to compile an OHS database for facilitating the integration of OHS into risk management. The subject of the present study is the possibility of adapting the proposed approach and the hazard source database to the underground mining context. The potential advantages and limitations of the practical application of the proposed new concepts were thus evaluated in goldmines in Quebec.

3.2. Action research: soft systems methodology (SSM)

A research methodology favouring exchanges with the practitioners of the industrial partner was adopted. Practical application of the designed risk evaluation concepts to a human activity system remains crucial. Therefore, it was required to use a flexible and interdisciplinary approach that combines the tools of engineering, management and social sciences.

The research project was designed to meet the challenge ascertained within the theoretical framework but also expressed by the industrial partner. In addition, it quickly became apparent that the physical presence of researchers would have a direct effect on practices observed in this company. An action research methodology was therefore proposed during the initial discussions with the industrial partner. The adopted approach also converges with the definition adopted by Liu (1992), which describes action research as fundamental research in the humanities, borne of melding of "willingness to change" with a "research intention".

In summary, action research was considered as the best adapted methodology for the purposes of this project for several reasons: (1) the research must have a foot in the real world (committed mining project) to give it practical meaning; (2) the challenge of mining project risk management is recognized by the industry and by the industrial partner; (3) willingness to collaborate and participate in the research was expressed unequivocally by the industrial partner; (4) willingness to change practices through action according to objectives specified right from the beginning of the research project was expressed; (5) the interdisciplinary character of the research (using several tools from different disciplines) and (6) the research is designed to yield results potentially applicable throughout the Quebec goldmine sector.

SSM was selected (Checkland 2000; Checkland, 1991), which draws on the human activity system concept to define a challenging situation (lack of systematic integration of OHS) and propose changes (to mining project risk management). The SSM (Figure 2) consists essentially of seven steps: (1) identification of the challenge (how to integrate OHS into mining project risk management); (2) description of the challenge; (3) definition of the relevant elements of the system under study (mining company); (4) development of a conceptual model for meeting the challenge (the proposed risk analysis/management method); (5) comparison of the conceptual model to the reality of the system under study; (6) examination of the feasibility of the suggested changes to the system and (7) implementation of measures meet the challenge. Finally, the flexibility of SSM allows us to adapt in response to constraints as they arise in the dynamic environment characterizing the company and the mining industry in general.

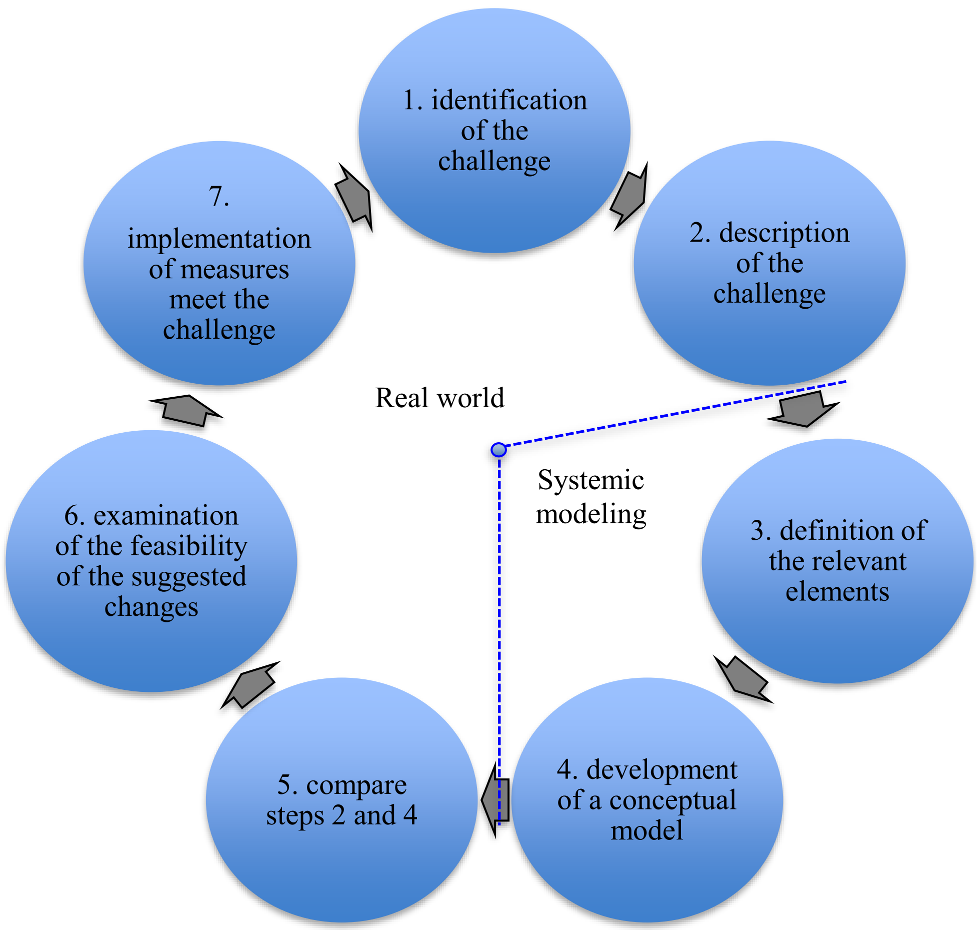

Figure 2 – The steps involved in applying SSM
(Adapted from Checkland, 2000)

3.3. The new approach to risk management in mining

Combining the tools of engineering as well as management and social sciences makes the new approach to mining project management much more effective, especially for taking into consideration greater numbers of scenarios that could be harmful to humans or the environment. A multidisciplinary method is essential in a rapidly evolving industry.

Team involvement, analysis of available data and field observations allow identification of potential hazards. The “hazard concentration” concept is used to estimate the potential for these hazards to lead to undesirable events. The AHP method is used to form and evaluate various categories of hazards and to monitor expert judgments in order to provide reliable estimates of risk.

Risk analysis is based on decomposition of risk into three essential elements: (1) hazards (causes); (2) undesirable events (caused by one or more hazard) and (3) the impact or consequences of the undesirable event (Figure 3).

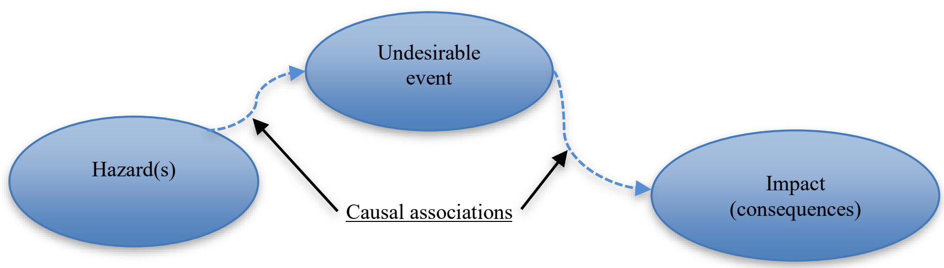

Figure 3 – Modelling of risk

The OHS database to be developed compiles the hazards identified using the chosen data-gathering tools (document analysis, observation, interviews, questionnaires). The risk management team establishes the lists of undesirable events and their impact based on the principal concerns of the company and also traces the causal associations between the elements of risk. These associations are based essentially on the judgment and experience of the workers involved. During this step, the team may consult other managers, experienced workers or experts to discuss and confirm possible causal associations.

Figure 4 shows the steps of the proposed approach to risk management in mining projects, as described previously (Badri et al., 2011a). Risk evaluation based on calculated hazards concentrations and on estimation of the impact of undesirable events is described in detail in the

Results section. Improvements or adjustments made to the approach in the context of the present research are also described in this section and in the discussion.

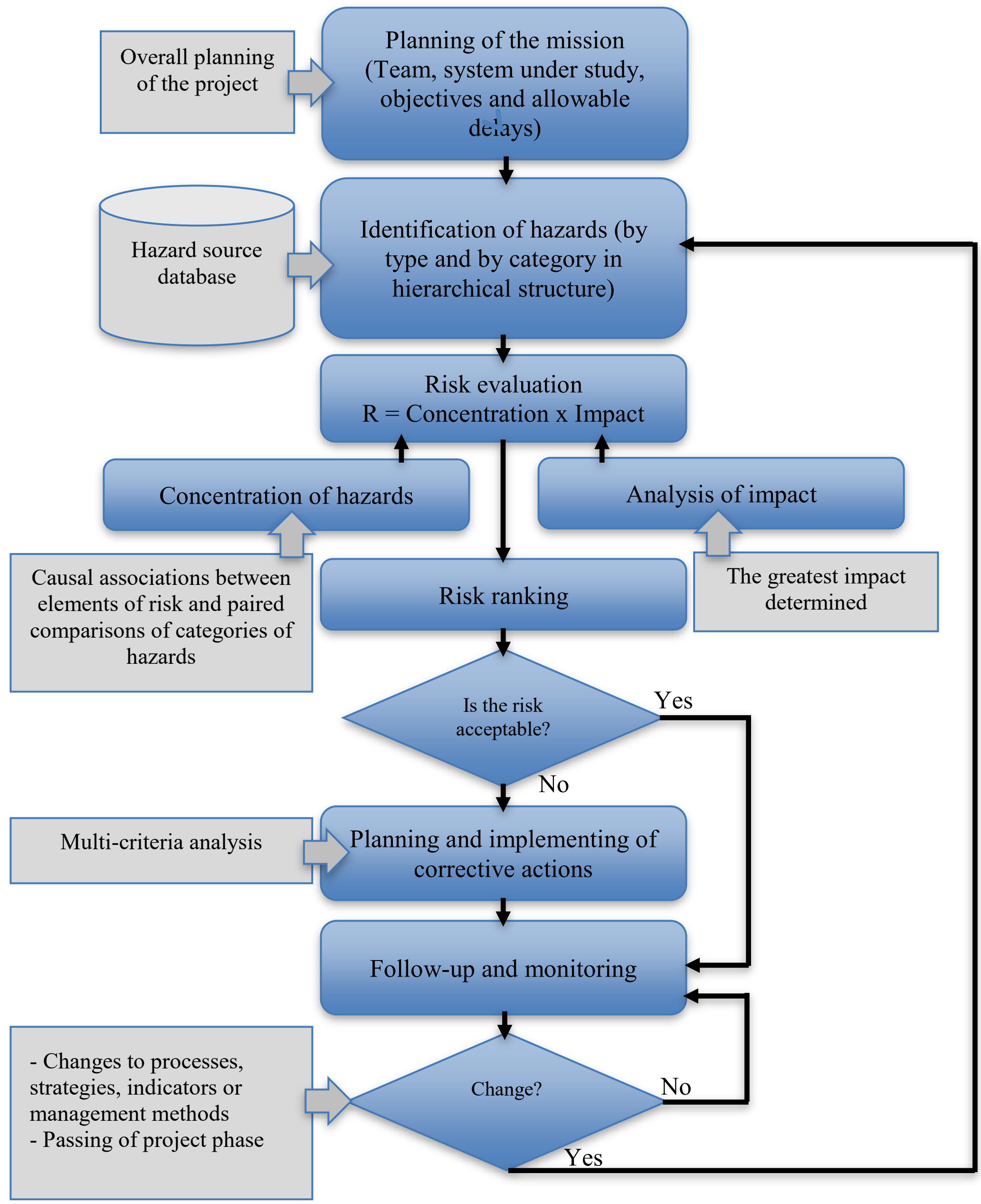

Figure 4 – The steps involved in the proposed approach to risk analysis/management

4. Results

4.1. Scope of the intervention

The industrial partner has been extracting gold from an underground mine for several years. The principal aim of the mission is to identify effective means of integrating OHS into project risk management. The proposed approach has been tested previously in an open-pit mine (Badri et al., 2011a). This change in context will test model adaptability in anticipation of extending its use to all goldmines in the province of Quebec.

The company currently operates new deposits in the same underground zone, using existing infrastructure (mineshafts, roadways, equipment, supervision, etc.). Researchers thus have an opportunity to observe several phases of various underground mining projects, namely exploration, development and commercial production. These projects are all under the supervision and direction of the same company crew.

The intervention is limited to processes and activities associated with ore extraction. In view of the scale of the work and the complexity of the processes under study, researchers did not examine ore processing. They made this same choice previously during research in the open-pit mine.

To study OHS risks, the entire ore extraction process was covered, beginning in January of 2012. The company directors saw to the involvement of all departments, workers and managers connected with the associated field operations, including the company OHS representative. Throughout the intervention, the researchers maintained direct contact with the managers and workers in order to gather all relevant information for the OHS database and risk evaluation. It should be noted that 80% of the team members had over 20 years of experience in the mining industry and that 96% were involved right from the developmental phase of the principal project of the company. Figure 5 describes the ore extraction process. These activities are carried out 380 to 840 meters below the surface.

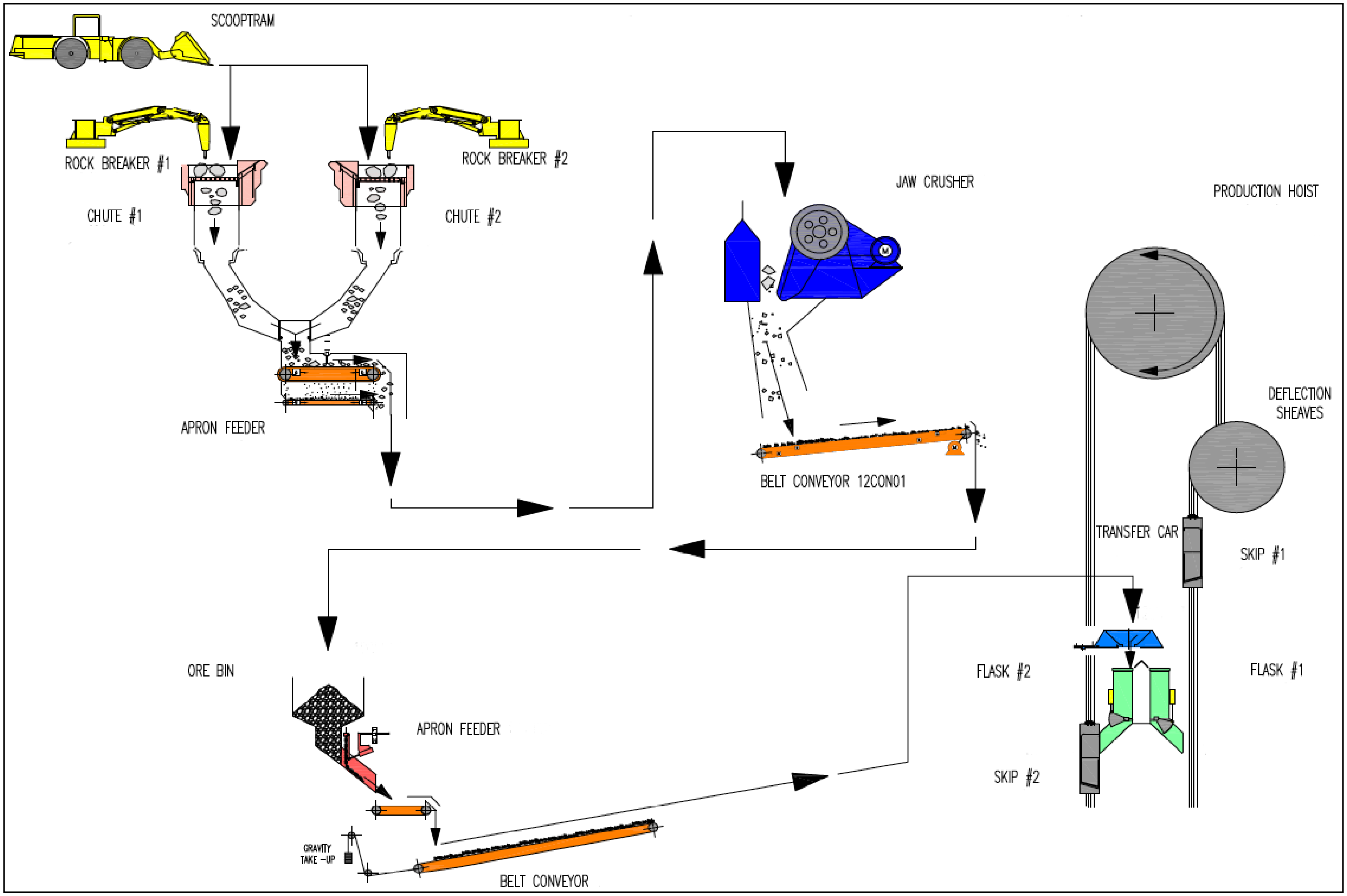

Figure 5 – Steps involved in the underground extraction of ore (company information)

4.2. Uncovering the threats (hazards)

The researchers relied on three data-gathering techniques and review of the literature. This included 35 hours of observation, interviews and questionnaires (32 persons) and two months of document analysis (Figure 6). The documents contained essentially incident and accident reports, standard work procedures, emergency measures, technical plans, and prevention or correction plans regarding various high-risk situations.

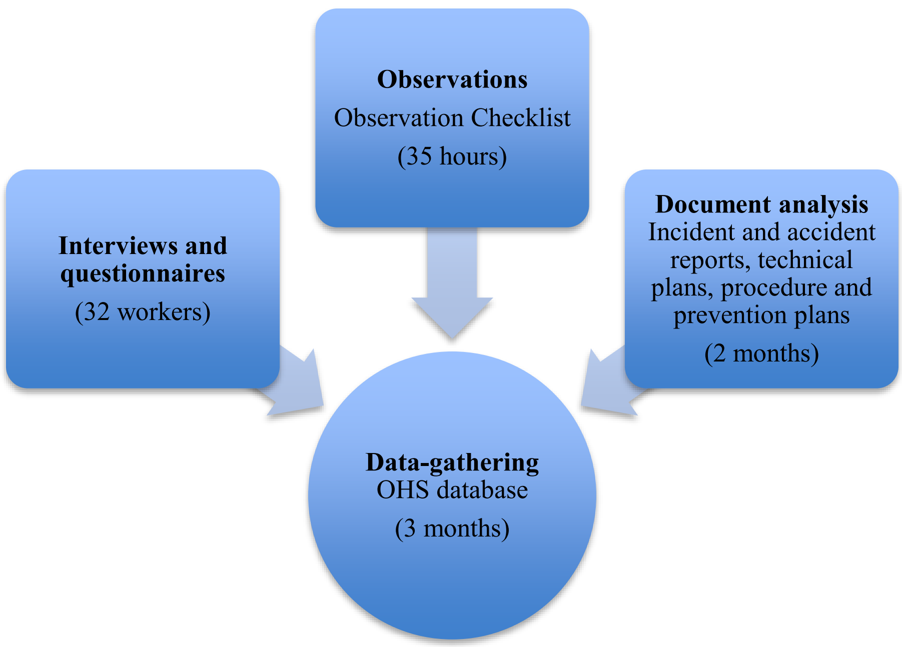

Figure 6 – Data-gathering tools used in this study

Table 2 lists some of the hazards noted during the 35-hour observation of the ore extraction process (Figure 5). These were categorized in the OHS database as mechanical, electrical, physicochemical, or method/human-related. The personnel group affected and the potential zones of impact were included. The zones of impact depend on the underground architecture of the mine. For example, a major fire or serious problem with the main extraction system (main shaft) could have a major impact on all zones of mining operations. Exposure to silica dust resulting from draw operations has only local impact thanks to various means of isolation put in place by the company (closed cabins, curtains).

Table 2 – Examples of hazards (based on observations)

Hazards	Group affected		Zone of impact	
	Miner in the zone	All miners	Local	General
Cluttered areas (with tools, cables, toolboxes, components, wastes, tool storage, etc.)	x		x	
Dynamic environment (moving, storage, traffic, frequent entry and exit of mobile equipment, interference, changes in architecture, etc.)	x		x	
Slipping or loss of balance (on ground, ramps, stairs and catwalks)	x		x	
Sharp edges, hooks (metal structures, forklifts, tools, etc.)	x		x	
Draw dust (silica, crystalline silica, others), metal filings (grindstone), moisture, cold, heat, draughts, fog, mist, steam	x		x	
Smoke, soot, gases (ammonia, carbon monoxide, sulphur dioxide, nitrogen dioxide)	x	x		x
Accumulation of ice (e.g. on head-frames)	x		x	
Visibility and lighting (control rooms, traffic zones, drilling zones, etc.)	x		x	
Noise (equipment and operations)	x	x		x
Vibrations (equipment and operations)	x		x	
Ground conditions (holes, water, bumps, rocks, slopes, etc.)	x		x	
Harmful and inflammable products near sparks or heat sources, greases, de-greasers, paint (spray and fumes)	x	x		x
Explosives (loading, blasting, residues, ignition and propagation conditions, ignition sensitivity, static electricity, transport, state of packaging, fragment shields)	x	x		x
Traces of explosives in ore and exposure to ammonia after blasting	x	x		x
Flying or falling objects, tools or equipment	x		x	
Collapsing of a roadway or area under stress	x	x		x
Moving elements (cables, conveyers, pulleys, crushers, treadmills, jacks, motors, fans, jackhammer, bolting machine, etc.)	x	x		x
Elements under stress (pipes and ducts, hoists, chains, slings, tires, wear parts, winches, cages, cables, tracks, ore loading and dumping devices, platforms, etc.)	x	x		x
Elements under pressure (hydraulic presses, ducts and pipes, 400-lb pumping station, plumbing, 120-lb compressed air, 80-lb pressurized water, jacks, pistons)	x	x		x
Reservoirs (diesel, gasoline and oil) and water basins	x	x		x
Leaks (water, gasoline, diesel, concrete, oil, compressed air or gas)	x	x		x
Things catching fire	x	x		x
Heavy equipment traffic on slopes (17-18%)	x		x	

Table 2 (*continued*)

Hazards	Group affected		Zone of impact	
	Miner in the zone	All miners	Local	General
Sources of heat (motors, pumps, oil)	x	x		x
Power supplies and electrocution (600V electrical cabinets, cables, electric motors, transformers)	x	x		x
Electromagnetic hazards (electromagnets, electric motors, electrical breaking, etc.)	x		x	
Control screens (reflections and flashes)	x		x	
Mobile equipment traffic (loaders, borers, trucks, etc.)	x		x	
Truckloads and breaking capability on slopes	x		x	
Interference among mobile equipment (loaders, borers, trucks, etc.)	x		x	
Interference between mobile equipment and workers	x		x	
Remote monitored or controlled equipment (crushers, borers and jackhammers)	x		x	
Equipment and tool ergonomics (standard design, constrained space, vibration, body shield, driving posture, etc.)	x		x	
Procedures ill-adapted to equipment design (e.g. arc-flash in the case of an electrical repair)	x		x	
Improper work posture (standing with little movement, leaning forward, crouching and leaning forward, arms above the shoulders)	x		x	
High-risk tasks (heights, in constrained spaces, enclosed or isolated spaces, in darkness, exposed to cold, dust or dampness, maintenance and inspection of moving elements, loading and transportation of explosives, blasting, drilling, handling and transporting heavy equipment, dislodging ore, worksite repairs, exposed to power sources, proximity of heavy or suspended equipment, gas burners, interference between repair crews, welding, ill-adapted tools and equipment, etc.)	x	x		x
Repetitive manual tasks requiring excessive physical effort	x		x	
Tasks requiring visual effort and prolonged concentration	x		x	
Fatigue and stress	x		x	
Subcontracted teams and tasks (exploration and construction)	x	x		x
Rigour in the use of personal protective equipment (boots, mask, safety glasses and gloves)	x		x	
Respect of procedures and rules (lock-out, maintenance, inspections, residual energy, chemicals, explosives, environmental safety, blasting zones, blasting plans, sources of ignition, handling and insertion of explosives, wearing protective equipment, safety, driving and parking vehicles, storage, drilling, blasting, emergency measures, etc.)	x	x		x
Respect of laws and regulations (explosives, ventilation, mechanical equipment, gas monitoring, etc.)	x	x		x
Competence (expertise, training, familiarity with the site, reaction capacity, autonomy)	x	x		x
Communication (with monitors, other crews, emergency measures, alarms, radio and interference)	x	x		x

Researchers compiled the elements of risk by analyzing 975 incident and accident reports filed since 2006. It should be noted that 26% of these reports involved subcontractors (e.g. construction and drilling) during 2011-2012. This is in opposition to the trend recorded previously in the case of the open-pit mine (Badri et al., 2011a) and is explained by the personnel management method adopted by the industrial partner, which favours in-house expertise (within the mining group). Subcontracting is limited to specific cases (cost savings or expertise outside the group of companies). The principal project of the mine has reached the commercial production phase, in which the need for subcontracting is minimal.

During the 32 semi-directed interviews, researchers discussed and confirmed the hazards identified in the course of observation and document analysis. Discussion with the participants revealed several constraints not noted during observation, brought to their attention by workers very familiar with the site and the nature of the various tasks. They thus learned individual strategies used to circumvent risks. The company values this type of data all the more since this highly experienced labour will be replaced over the next few years. They discussed all of the ore extraction zones (main crusher, excavator, maintenance workshop, main extraction system as well as development and production zones). Researchers reported the criticality of these zones in OHS terms as perceived by the workers and identified possible OHS hazards in each extraction process zone. The participants also compared OHS risks to other types of risks (supplier-related, internal organizational, financial, planning-related, personnel-related, logistic and regulatory). Although difficult to evaluate, several OHS-hazard-reinforcing factors were also discussed.

The participants confirmed that mechanical hazards exist in the various process zones studied. Direct-current electrical hazards other than static electricity are also present. Physicochemical hazards are potentially present and human hazards are omnipresent. The workers indicated that harassment and aggressions are currently absent but cannot be ruled out in the future. Figure 7 below shows the criticality of the studied zones. Development, production and draw zones and the main mineshaft are the most critical. Interference between workers and mining equipment (loaders, borers, conveyers, etc.) is described as frequent. Unlike in the open-pit mine situation (Badri et al., 2011a), these workers did not cite the mechanical workshop as the most significant. They felt that maintenance tasks are “organized and safe”. They also felt that mobile equipment under repair (loaders, tractors, drills, bolting machines, etc.) were of “limited height” and that the risk of tipping over as well as the risk of falling objects, persons or tools are minimal.

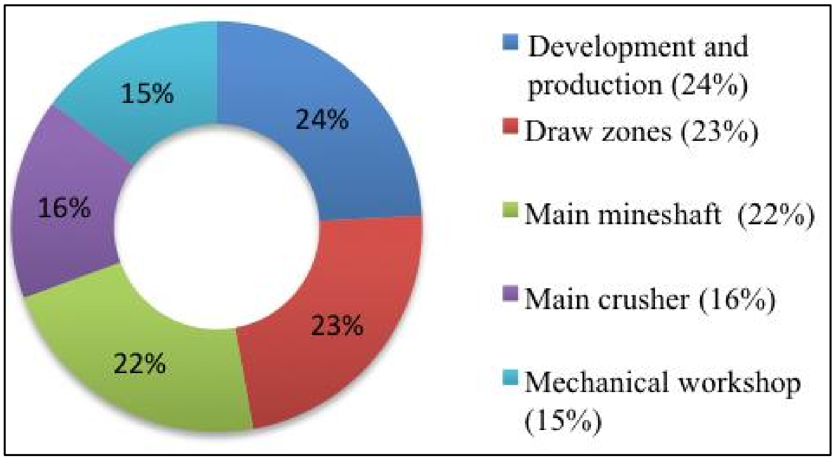

Figure 7 – Estimation of the criticality of the various zones

Table 3 shows the reinforcing factors of the hazards evaluated by most of the workers involved. The presence of these factors can activate or increase the likelihood of the manifestation of risks (indicated by the symbol '+'). The same factors may have no influence (indicated as '0').

Table 3 – Possible effects of some reinforcing factors

Hazard \ Reinforcing factor	Heat	Cold	Flooding	Work at night
Mechanical	+	0	0	0
Electrical	+	0	+	0
Physicochemical	+	+	+	0
Human	+	+	+	+

Researchers thus added potential hazards to the approximately 250 entries in the OHS hazards database (see Appendix). Before evaluating projects risks, a hazard knowledge base was needed. As mentioned above, the principal focus of the data gathering was identification of OHS hazards, which was undertaken in response to the lack of detailed OHS data available for researchers and practitioners in the goldmine context. By combining "conventional" categories of hazards documented (Badri et al., 2012b) with the results of the open-pit mine study (Badri et al., 2011a), Researchers obtained a summary of hazards judged applicable to underground mines by virtue of encompassing operational, financial, economic, legal and political risks in a macroscopic sense.

Figure 8 illustrates the hazard hierarchical network for facilitating risk evaluation and use of the "hazard concentration" concept by analysts. Hierarchical levels follow the direction of the arrows. Level 1 is made up of the hazard categories: (1) operational; (2) financial and economic; (3) OHS and (4) societal (legal and political). Each category is made up of one or more "families" of hazards (level 2), while each family is made up of several hazards (level 3). The network is based on the Causal Tree Analysis method (CTA) used to analyze in depth the possible causes of a problem or failure (e.g. workplace accident). The CTA is intended to show the combinations of causes as a whole. Researchers mapped possible hazards by category and by family to determine causal associations between these levels, facilitating both modelling and tabling of the information for the database (MS Access®). To calculate "hazard concentration", they need the number of hazards (level 3) identified per family of hazards. Weighting of each family was obtained by paired comparisons (AHP) of the families in each category connected to an undesirable event.

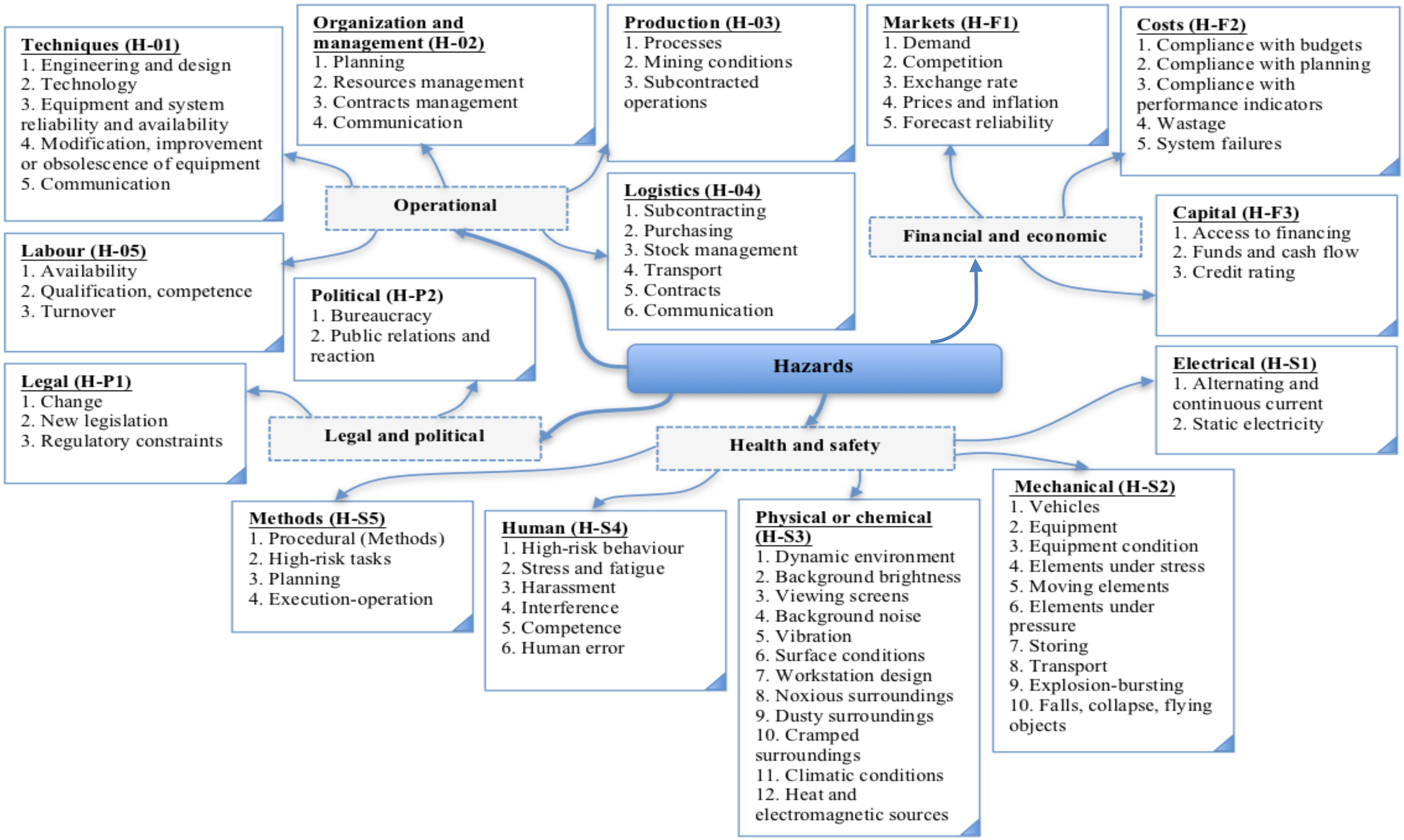

Figure 8 – Hierarchical network of hazards

4.3. A clearer view of risks: elements and causal associations

The risk stemming from a hazard is defined in terms of undesirable events and their impact. These may vary as the project advances. Causal associations must first be drawn, between (1) families of hazards, (2) undesirable events, and (3) the impact or consequences of these events (Figure 3). Table 4 below models the possible causal associations between these elements, based on the judgment of the team.

Table 4 – Risks and the associations between their constituent elements

Code	Element	Risk					
		R1	R2	R3	R4	R5	R6
IE	**Undesirable event**						
DE-1	Major industrial accident	X					
DE-2	Increased business costs		X				
DE-3	External operational difficulty			X			
DE-4	Business stoppage				X		
DE-5	Occupational illness					X	
DE-6	Spill with ecological impact						X
NI	**Negative impact on the project**						
NI-C	Cost increase	X	X	X	X	X	X
NI-D	Delay	X		X	X		
NI-P	Poor performance	X	X	X	X	X	X
HZ	**Hazards**						
H-O	**Operational**						
H-O1	Technical	X	X		X	X	X
H-O2	Organizational and managerial	X	X				X
H-O3	Production-related	X	X		X	X	X
H-O4	Logistic		X	X	X		
H-O5	Labour-related	X	X	X		X	
H-F	**Financial and economic**						
H-F1	Markets			X	X		
H-F2	Costs	X	X		X		X
H-F3	Capital			X	X		
H-S	**Occupational health and safety**						
H-S1	Electrical	X			X		
H-S2	Mechanical	X			X	X	X
H-S3	Physicochemical	X			X	X	X
H-S4	Human	X			X	X	X
H-S5	Procedural	X			X	X	X
H-P	**Societal**						
H-P1	Legal		X	X	X		
H-P2	Political		X	X	X		

For example, the risk of occupational illness (R5) is inherent in the undesirable event "occupational illness" (DE-5) and stems from the technical (H-O1), production-related (H-O3), labour-related (H-O5), mechanical (H-S2), physicochemical (H-S3), human (H-S4) and procedural (H-S5) families of hazards. Materializing of this risk has negative impact on project cost (NI-C) and performance (NI-P). The industrial partner views major industrial accidents as those having major destructive impact (e.g. serious fires or accidents with direct impact on work-crew health and safety).

4.4. Measurement of threats: evaluation and ranking of risks

To calculate "hazard concentration", a ranking of the families of hazards connected with each undesirable event is obtained using multi-criteria analysis. It is at this stage that the involvement of experienced workers and managers is particularly crucial. As much as possible, the team should also seek external expertise. The exercise can be completed in a single meeting. In this case, Expert Choice® software was used, although a common spreadsheet application could be used. This comparison provides a weighting of the capacity of each family of hazards to lead to undesirable events.

The number of hazards per family (level 3) is taken into consideration at this point. "Hazard concentration" is conceptualised as follows: A family of hazards is more likely to trigger an undesirable event (i.e. increases a risk) when it,

- contains a larger number of identified hazards
- is more heavily weighted by multi-criteria analysis

The concentration concept thus combines the weighting of the family of hazards (perceived likelihood of involvement) with the number of hazards (possibilities). Figure 9 below illustrates the comparison of two families of hazards. Family 2 is more likely to lead to the undesirable event.

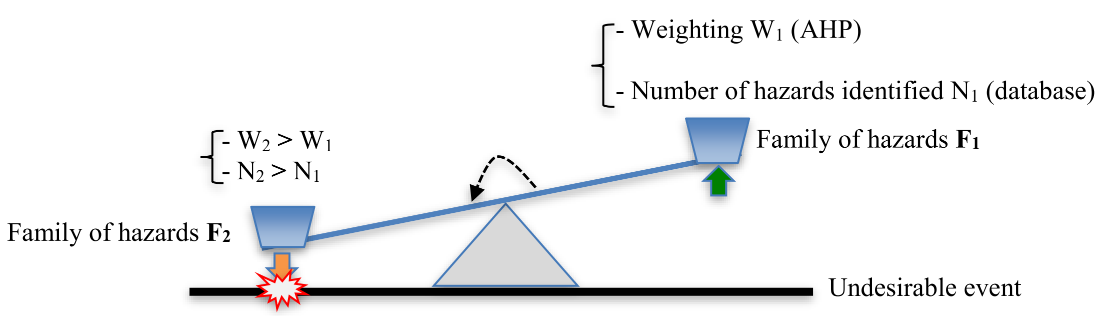

Figure 9 – The "hazard concentration" concept

According to the team (AHP), the most important “family of hazards” will have the largest weight (disturbance weight). As the “AHP ranking” and to determine the “disturbance weight, $Y_{(i)}$”, an interval scales is used. The “disturbance weight” between two adjacent families of hazards uses a scale of 1. Table 5 shows the calculation of the “relative concentration of hazards (rc(i))” for each “family of hazards (i)” using the “disturbance weight” and “number of hazards”.

Table 5 – Use of AHP weightings and number of hazards to calculate hazard relative concentration by family

Family of hazards (level 2)	H-O1	H-O2	H-O3	H-O4	H-O5	H-F1	H-F2	H-F3	H-S1	H-S2	H-S3	H-S4	H-S5	H-P1	H-P2
Number of hazards (level 3) $X_{(i)}$	5	4	3	6	3	5	5	3	2	10	12	6	4	3	2
AHP ranking (by paired comparison)	1	2	4	5	3	8	10	9	13	11	12	7	6	14	15
Disturbance weight $Y_{(i)}$	15	14	12	11	13	8	6	7	3	5	4	9	10	2	1
$X_{(i)}Y_{(i)}$ ($\Sigma X_{(i)}Y_{(i)} = 569$)	75	56	36	66	39	40	30	21	6	50	48	54	40	6	2
Relative hazard concentration by family (i) $rc_{(i)} = X_{(i)}Y_{(i)}/569$	.132	.098	.063	.116	.069	.070	.053	.037	.011	.088	.084	.095	.070	.011	.004

The total “relative hazard concentration” contributed by all “families of hazards” connected to an undesirable event (j) ($RC_{(j)}$) is shown in Table 6.

Table 6 – Hazard concentration

$Risk_{(j)}$	**Undesirable $event_{(j)}$**	**Concentration $RC_{(j)}$**
R1	DE-1	0.76
R2	DE-2	0.54
R3	DE-3	0.31
R4	DE-4	0.83
R5	DE-5	0.60
R6	DE-6	0.68

Risk is defined as the product of the concentration of hazards and the negative impact connected with an undesirable event. This is the principal innovation described in the present article. The concentration was initially converted to probability in order to combine it with the value of the impact of the undesirable event and thus evaluate risk. In the discussion section, it will be explained why the researchers now believe they can use “hazard concentration” directly to evaluate risk.

Estimation of the impact of a risk is based on the highest impact value implied by the causal associations (Table 4). The matrix in Table 7 shows the levels of impact as established using the proposed approach. The impact (consequence) of an undesirable event associated with a risk was judged as minor (1, 2 or 3), average (4, 5 or 6) or high (7, 8 or 9). In the case of risk R5 and its associated event “occupational illness (E5)”, the negative impact will manifest itself as increased cost (NI-C) or poor performance (NI-P). The value of the impact of risk R5 to take into consideration is the higher of the two, in other words,

$$\text{Impact}_{(j)} = \text{Maximum impact}_{(\text{Cost, Delays, Performance})} \quad (1)$$

Table 7 – Impact (consequence) estimation matrix

Major	7	8	9
Moderate	4	5	6
Minor	1	2	3

By multiplying the $\text{impact}_{(j)}$ by the “hazard concentration $RC_{(j)}$”, experts evaluate and rank the risks identified in the course of our study:

$$\text{Risk}_{(j)} = RC_{(j)} \text{ x } \text{Impact}_{(j)} \quad (2)$$

Given the time constraints, the present study is limited to ranking of risks. The remaining steps are devoted to implementing appropriate monitoring and control measures, based on this evaluation and ranking of the potential risks.

It was anticipated of course that the company would set its own criteria or levels of risk acceptability based on its in-house strategy. These criteria must treat federally or provincially regulated risks independently of their ranking. Risk acceptability depends principally on criteria set by decision-makers (ISO/IEC Guide 73, 2002). In the case of the industrial partner, the criteria were the result of the ranking of the risks and the value of their impact (or consequences). Table 8 shows the evaluation and ranking of the potential risks. Researchers emphasize the feasibility of evaluating all categories of project risks using the proposed approach. The company is now able to integrate OHS into its management of risks associated with projects. It is able to update its risk evaluation as a function of project phase or following changes to processes, procedures, strategies, follow-up indicators or managerial methods.

Table 8 – Evaluation and ranking of potential risks

Risk	Concentration $RC_{(j)}$	$Impact_{(j)}$	Value of the risk	Rank
Major industrial accident (R1)	0.76	9	6.84	1
Increased business costs (R2)	0.54	5	2.70	4
External operational difficulty (R3)	0.31	7	2.17	5
Business stoppage (R4)	0.83	7	5.81	2
Occupational illness (R5)	0.60	3	1.80	6
Spill with ecological impact (R6)	0.68	4	2.72	3

5. Discussion

It should be noted that the OHS database created for the underground mine is almost identical to the one used for the open-pit mine. This suggests that the identified hazards are applicable, with a few adjustments, to goldmines in general. There were some discrepancies due to process and procedure characteristics and to the type of mine as well as to differences in perception of the consequences of hazards by the workers. The managers and workers in the underground mine feared fire the most. In general, they were not afraid of mine collapses. In the open-pit mine, the workers' worries were related to traffic and interference with mobile equipment during ore loading operations and maintenance activities. They also expressed apprehension regarding high-risk behaviours. These behaviours are among the preoccupations of underground miners (e.g. Xia, 2010). Vibrations are viewed among underground miners as a long-term problem and have been examined in several studies (e.g. Kumar, 2004; Pal and Dewan, 2009). Hazards are entered into the database without evaluation or measurement of the perceived degree of associated danger. The perceived seriousness of the hazard becomes apparent only after the ranking procedure (weighting) or evaluation of impact is completed.

The database is thus used to store as many potential hazards as can be identified in the mine. The data are updated as projects advance, as processes and procedures evolve, as new strategies are implemented, as new indicators or new managerial methods are adopted, and so on. The database thus serves as a knowledge base potentially adaptable to other companies as well as new mining projects. The challenges currently facing mines in terms of demand pressure, labour shortages and the use of new means of production have a direct impact on control of project risks. With the present work, researchers are trying to limit the negative impact of these factors by providing companies with solid fundamental knowledge in the area of risk management. This study has also provided OHS and project management researchers with the opportunity to apply their knowledge in the context of goldmines. Much literature is focused on risks in coalmines (e.g. Guo et Wu, 2009; Larry Grayson et al., 2009; Torma-Krajewski et al., 2007). To the best of the researcher's knowledge, the OHS database established in the present study is the first of its kind for goldmines in the Canadian Shield. Once the proposed approach has been integrated into the company risk management process, researchers believe it will make a significant contribution to the protection of mining personnel. Sharing this evolving know-how should have a sparing effect on both human and material resources.

Integration of OHS reveals a limitation of conventional risk analysis and evaluation tools. These tools are generally derived from the analysis of the safety of technical systems. To evaluate a risk, a probability is combined with a consequence. Probability is generally estimated indirectly using measurable variables such as frequency of breakdown or failure/incident rate. In socio-technical system risk management, the challenge is often taking into consideration workers and their interactions with the technical, social and organizational sub-systems of the business under study. It should be noted that human influence is dominant. Human behaviour, thought, reaction and decision-making are all difficult to define in terms of probability (Badri et al., 2011b). The behaviour of a worker depends to a large degree on his perception of danger and is influenced by personal or professional goals and by the nature of his relationships within the organization (Nadeau, 2001). The risk management system also has a direct influence on risk evaluation. Even when rules or algorithms are applied, evaluation will always be affected by feelings, intuition, experience and the evaluator's acceptance of the risk. It is clear that the attitude of individuals towards risk evolves with the established common symbolic referential in the workplace (Duclos, 1991). Referring to the theories of modern cognitive psychology, Slovic et al. (2004) proposed two possible systems of risk appreciation. The first of these is the "analytical system", which applies rules and standard models such as stochastic calculation. The second is the "experimental system", which focuses on human intuition and emotions. In the case of simultaneous application of these two systems, the first naturally influences the second.

Researchers attempted accordingly to find a compromise between these two systems to increase the reliability of risk evaluation, especially for cases in which different types of risks are integrated. The “hazards concentration” concept begins by identifying all rational concerns. Paired comparison of the families of hazards by the AHP method allows the reaching of a compromise among the evaluators and reduces disparities in risk appreciation. As is required by the AHP method, they kept a watch on the consistency indexes of hazard family weighting to ensure reliability. This weighting and hence the value they have called “concentration” replaces the term probability used in conventional risk evaluation formulas. “Concentration” is by design proportional to the likelihood of occurrence of an undesirable event and the final value of each risk remains proportional to the total number of potential hazards. Whether probability or “concentration” is used has no impact on the ranking of risks, given the linear relationship between these two variables (Badri et al., 2011a,b).

In spite of several logistical constraints, researchers were able to involve mining operational crews in order to adapt and improve the proposed risk management technique as well as obtain an OHS database potentially applicable to other goldmines in Quebec. Using the “hazard concentration” concept and multi-criteria analysis, all forms of risk can be evaluated simultaneously and no threat to a project need be neglected. More comprehensive evaluation of risk should allow more enlightened and rational decision-making.

The proposed approach nevertheless has several limitations, which researchers will attempt to resolve in future studies. Action-research affects the practices observed in the participating companies. This may influence the course of subsequent discussions and the risk evaluation exercise. Their presence may have modified behaviours and the manner in which tasks were performed or hazards were assessed. They did not choose the risk management team. Participation in data gathering was free and voluntary. The company did make a point of involving its most experienced miners. The hazards identified were generally known to the researchers and the workers beforehand and have been cited in numerous studies. Since changing the number of hazards per family could influence the calculated concentrations, the evaluation must be updated if the hazards profile is changed. They believe that this problem will be minor as long as the data gathering process remains rigorous. When sharing the knowledge gained in the present study with new mines, effort should focus in each case on verifying the presence of the elements compiled in the database.

6. Conclusion

This article presents a novel practical approach to risk management applicable to mining projects. The aim of the study is to begin the gradual introduction of such an approach into goldmines throughout the province of Quebec. The study was carried out within a comprehensive research program intended to devise a method of managing practically all risks in mining projects and involved adapting new concepts developed in the context of open-pit gold mining to the underground context.

Thanks to extensive data gathering by several methods, including interviews, questionnaires, collaborative observation and document analysis, experts were able to identify a wide range of hazards that provided reliable evaluation of potential risks. Using the new concept of “hazard concentration” and multi-criteria analysis (AHP), it is now possible to evaluate simultaneously practically all types of risks in mining projects and thus avoid neglecting possible threats to the success of a project.

In spite of several limitations, this study involved operational crews in the mine in order to adapt and improve the procedure. Action research made possible exchanges with experienced miners, whose contribution and know-how increased the value of the study. In addition to evaluating potential risks, researchers have begun the development of a useful OHS database. This database is adaptable and could be applicable throughout the Quebec mining sector with adjustments to accommodate the unique character of each new mining project.

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APPENDIX

OHS database: Underground goldmines

Family of hazards (level 2)	Details (level 3)
Electrical H-S1	**1. Direct or alternating current** Electrical room, cabinet, transformer, cable, insulation; overloaded outlets, batteries, electrical equipment
	2. Static electricity Accumulation of charge, sparks
Mechanical H-S2	**1. Vehicles** Borer, truck, tractor, loader, interference with equipment, workers
	2. Equipment Substandard safety devices, dangerous devices, ladders, stairs, catwalks
	3. State of equipment Mechanical wear, age, reliability, operation, suspension
	4. Elements under stress Structures, pipes and ducts, hoists, chains, slings, tires, wearing parts, winches, cages, cables, tracks, ore loading and dumping devices, tanks and reservoirs, floors or roadways under stress
	5. Moving elements Tools, turntables, crusher, treadmill, work base, moving or unstable parts, vibrating objects, conveyers, pulleys, jacks, motors, fans, rock borer, jackhammer, bolting machine
	6. Devices and elements under pressure Compressors, hydraulic press, pipes and ducts, pumping stations, plumbing, jacks, pistons, tanks
	7. Material handling Rolling bridge, forklift, dollies, conveyer
	8. Transport Obstacles on ground or floors, uneven ground, openings, puddles, bumps, rocks, clutter, loading and breaking capacity, slopes
	9. Explosion/bursts Leaks, fire, smoke, dust, fuel, gases, tanks under pressure, explosives, sparks, electric arcs, dynamiting, friction, chemicals and inflammable liquids, tires, batteries
	10. Falls, collapses, splashes, spills, slipping Rocks, loading, tools, objects, workers, structures, openings in ground, dynamiting, oil, water, roadways
Physicochemical H-S3	**1. Dynamic environment** Transport, material handling, traffic, frequent entry/exit of mobile equipment, interference, changes in architecture
	2. Ambient lighting Workstation lighting; flashes, brightness
	3. Viewing screens Computer, control panel
	4. Ambient noise Equipment, vehicles, crusher, wireless, operations, blasting
	5. Vibration Equipment, vehicles, dynamiting, operations
	6. State of contact surfaces Hot or cold surfaces, ice accumulation
	7. Workstation design Man-machine interface, station surroundings (clutter), ergonomics
	8. Noxious surroundings Gases, diesel fumes and soot, chemicals, explosives
	9. Dusty surroundings Ventilation, draw, drilling, crusher, dynamiting, ore loading and dumping
	10. Cramped surroundings Enclosed spaces, debris, wastes, obstacles, traffic routes, parked vehicles, workshop; tools or materials stuck between objects
	11. Climatic conditions Ice and frost, dampness, draughts, flooding, fog
	12. Sources of Heat (motors, pumps, oil), electromagnetic fields (electromagnets, electric motors, electric breaks)
Human H-S4	**1. High-risk behaviour** Alcohol, drugs, tobacco, unsafe driving, access to danger zones, compliance with procedures and rules (lockout, maintenance, inspections, residual energy, chemical and explosives storage; securing areas, blast zones, blast plans and ignition sources; handling and insertion of explosives; wearing protective devices; driving and parking; handling materials; drilling, blasting, emergency measures), compliance with laws and regulations (explosives, ventilation, mechanical equipment, gas monitoring, etc.)
	2. Stress and fatigue Work pace, work load, inattention, poor concentration, drowsiness, visual effort, manual tasks
	3. Harassment

	Bullying, physical aggression
	4. Interference Numerous subcontractors, competition, cultural differences, integration, pedestrian-equipment conflicts
	5. Competence Experience, training, knowledge of the site, capacity for action, autonomy
	6. Human error Driving, parking, controls, work methods, safety procedures and rules, omissions, improper handling
Work methods **H-S5**	**1. Procedural (Methods)** Challenging posture (standing with little movement on cement floor, leaning forward while standing or crouching, arms above shoulders), excessive effort, sudden movement, lack of signalling, ill-adapted behaviour, poor communication or responsiveness, poor use of safety equipment, lifting or moving heavy loads, improper handling, repetitive tasks, procedures ill-adapted to equipment design
	2. High-risk tasks Vehicle driving, draw, working on slopes, at heights, in closed or cramped spaces or darkness, repairs, exposure to cold, dust or dampness, maintenance and inspection of moving elements, loading and transport of explosives, blasting, drilling, handling or moving heavy equipment, dislodging ore, worksite repairs, exposure to flashes and electric arcs, proximity of heavy or suspended equipment, work with gas burners, interference between repair crews, welding, ill-adapted tools and equipment, remote monitored or controlled equipment (crushers, drillers and jackhammers)
	3. Planning Follow-up, communication, overtime, organization of high-risk work, task distribution, interference, subcontracting
	4. Execution-operation Task monitoring, site inspection, emergency procedures, communication (with control rooms, other crews, emergency measures, alarms, radio and interference)

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