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Towards sustainability in underground coal mine closure contexts: A methodology proposal for environmental risk management

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ABSTRACT

The mining industry needs community and regional governmental support to maintain its current activities and, more importantly, to develop future projects. The failure to manage environmental risks in an acceptable manner during mine operation, closing and post-closing periods is a critical factor. The mining industry must regain its reputation that has been lost over decades and centuries of environmental degradation. Several environmental management tools (e.g., life cycle assessment, multi-criteria decision analysis, etc.) are widely applied during mine development, operation and closure periods. Nevertheless, due to uncertainties associated with the post-closure phase and the end of economic activity (implying no more revenues for stakeholders in the form of workers' salaries and municipality taxes), it is crucial to adopt sound management practices during this period to achieve sustainability in the mining sector.

As operational methodologies that can be used as a reference are lacking, the management of environmental risks during and after underground coal mine closures is, in many cases, limited or is developed without specific guidance.

This statement is supported by the fact that the European Commission, through the Research Fund for Coal and Steel, encouraged research, pilot and demonstration projects and accompanying measures within the coal sector via the coal programme priority of recent years (2012–2014), namely, the "Management of environmental risks during or after mine closure".

The aim of this paper is to provide mine operators with an organized informational framework that could be applied during future underground coal mine closures independent of the major environmental problems faced and directly connected to the types and characteristics of coal and the exploitation methods used. The investigation was conducted using a literature review and interviews with experts from European universities, research institutions and coal mining companies from Poland and Spain.

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1. Introduction

One of the objectives of the "Strategic Implementation Plan for the European Innovation Partnership on Raw Materials" (European Commission, 2013) is to mitigate the negative environmental impacts of the European raw materials sector. Based on inputs from stakeholders and policymakers, possible actions that should be taken have been grouped under five frameworks called Work Packages. The third one ("Regulatory framework, knowledge and infrastructure base") calls for the improvement of environmental impact assessment methodologies. Not long ago, after reviewing the literature on mining sustainability, Laurence (2011) argued that limited guidance for mine operators can be achieved to put sustainability frameworks into action.

Some environmental management tools focused on mine development, operation and closure periods are widely used:

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- Life Cycle Assessments (LCAs) can be used to determine (among alternatives) which approach has the least environmental impact and its corresponding land-use impact category (Durucan et al., 2006; Reid et al., 2009)
- Multi-criteria Decision Analysis (MCDA) allows one to couple environment, social and economy criteria (Roussat et al., 2009) to assess the value of various options
- Risk evaluations (the final step of the risk assessment process) involve comparing estimated levels of risk with risk criteria that will be defined.

Nevertheless, due to uncertainties associated with the post-closure phase and the end of economic activity, implying an end to revenues in the form of workers' salaries and municipality taxes for stakeholders, it is crucial to adopt sound management practices during this period to achieve sustainability in the mining sector. Sustainable development is a multi-dimensional problem that involves achieving balance across three main dimensions: economic, social and environmental (Bluszcz, 2015). Thus, post-closure phases should place special emphasis on the remaining dimension.

Until now, several specific tools and techniques have been developed to facilitate the management of environmental risks within a mine closure context. At the European level, an administrative French tool integrates mining and post-mining risks in land-use management, as it is the state's responsibility to evaluate residual risk and to integrate it in the management of regional planning. This tool is referred to as the "Mining Risk Prevention Plan" (MRPP), and it was designed to evaluate and map risks linked to pollution generated from historical mining activities, thus providing an assessment of the extent of soil and water contamination in surrounding mining site areas. Levels of contamination are determined through a risk assessment approach, but due to a lack of operational methodologies available, environmental hazard assessments have been limited. Only several specific cases of MRPP have generated environmental hazard maps (Didier, 2009).

In Finland, a TEKES (Finnish Funding Agency for Technology and Innovation) funded project called "Environmental Techniques for the Extractive Industries" was undertaken as a joint research project between agencies and industry and provides mine operators, regulatory authorities and industry consultants with guidelines relating to the planning and implementation of mine closure strategies (Heikkinen et al., 2008).

Among the different research projects financed by the European Union, various tools and techniques have been developed to enable the assessment of individual environmental impacts:

- MANAGER (Bondaruk et al., 2013) and WATERCHEM (Pastor et al., 2008) on mine water discharge optimization;
- PRESIDENCE (Herrero et al., 2012), which focuses on subsidence hazard prediction and monitoring;
- FLOMINET (Klinger et al., 2011), which focuses on flooding management in regional mining networks, etc.;
- ESIAS (Durucan et al., 1995), the only project that directly addresses the development of an impact assessment system while conducting environmental simulations in two European metal mines that consider groundwater, river, air, soil pollution, noise and vibration impacts.

In South Africa, the Department of Water Affairs and Forestry and the mining industry have made major strides in developing principles and approaches for the effective management of water within the mining industry. These entities have developed a series of Best Practice Guidelines (BPGs) on water management strategies, techniques and tools (Pulles, 2008b). These BPGs aim to provide a logical and clear process that can be applied by mine operators to allow for proper mine closure planning. They also allow for the mine closure transfer of water-related residual environmental and financial risk to the state and citizens, presenting an impact assessment and prediction framework and methodology based on risk assessment principles (Pulles, 2008a).

Australia uses a Strategic Framework for Mine Closure that is designed to encourage the development of comprehensive closure plans that help restore mine sites to self-sustaining ecosystems whenever possible. The Strategic Framework also holds that closure plans must be adequately financed, implemented and monitored within all jurisdictions, and it is focused mainly on reducing financial burdens associated with mine closure and rehabilitation. The Strategic Framework is structured based on a set of objectives and principles grouped under six key areas: stakeholder involvement, planning, financial provision, implementation, standards and relinquishment, but detailed guidelines are not provided (Australian Department of Industry, Tourism and Resources, 2006).

Finally, closure guidelines used in Canada and the United States employ a similar approach to mine reclamation (Cowan et al., 2010). Such legislation is found in multiple legislative acts that govern mining with a strong emphasis on financial assurance components.

2. Research methodology

This paper seeks to propose an environmental risks management methodology for an underground coal mine closure context. To achieve this goal, the authors first analysed peer-reviewed academic literature available through the Web of Knowledge ^{SM} (WOK). The authors searched for "mine closure", "mine sustainability", "mine pollution", "environmental impact assessment" and "risk management" search terms with and without using "coal" and "mine" search terms when applicable. A second web search was conducted with a focus on legislative or regulatory bodies and private companies based around the world using the same keywords.

Finally, the authors extended their search to CORDIS (Community Research and Development Information Service), the European Commission's public repository on European Union-funded research projects and results.

The employed methodology adheres to the following international standards: ISO 31000 (2012) "Risk Management, Principles and Guidelines" and IEC/ISO 31010 (2009) "Risk Management, Risk Assessment Techniques". According to these standards, the risk management process is defined as shown in Fig. 1; context establishment, risk assessment and risk treatment, and communication and consultation with stakeholders (both internal and external) must be undertaken throughout the entire process in addition to monitoring and review.

After compiling all of the data collected and structuring them according to the risk management process, the authors obtained feedback on the methodology from experts based at universities and research bodies across Europe (United Kingdom, Czech Republic, Poland, Spain, France and Germany) and from Polish and Spanish underground coal mine specialists.

3. Establishing the context

As specified in IEC/ISO 31010 (2009), establishing the context defines the basic parameters needed to manage risk while setting both the scope and criteria to be applied during the process, including external and internal parameters that are relevant and any risks that should be addressed.

As described by Didier (2009), during the Information Phase, a

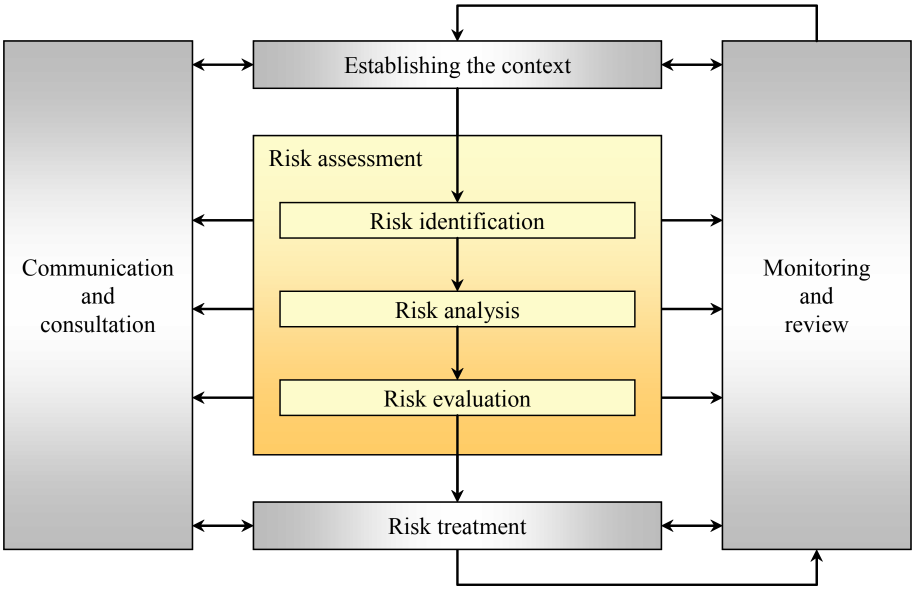

Fig. 1. Risk management process (ISO 31000, 2012).

Mining Risk Prevention Plan should be designed to summarize any disorders or harmful effects of the past to generate an informative map. This plan must also involve collecting all available information together with the results of further investigations if necessary. Pulles (2008b) specifies crucial information for correctly establishing assessment objectives as follows: a land use plan that complements the area development plan, any known or suspected interactions with other mines and mineral reserves and resource quality objectives for catchments that may be impacted. Another variable must also be taken in to account; Rodríguez et al. (2011) stated that for closed mining sustainability, environment and safety must be considered in consideration of any known related financial factors.

According to these parameters, in establishing the contexts of risk management processes based on internal and external parameters, it is necessary to:

- Consider all international, national, regional and local environmental regulations that affect or may affect the external environment in which the mine is situated, as well as the social issues and economic aspects of the community. IEC/ISO 31010 (2009) also refers to cultural factors when applicable;
- Obtain a full description of the mine assessed through the collection and synthesis of existing data of mining, geological, geo-chemical, hydro-geological and geo-mechanical characterizations of the mine, as well as data related to air pollution issues and historical pumping data. This description must also include any known or suspected interactions with other open or closed mines;
- Collect all historical environmental and safety incidents related to the mine area during past activities and all economic costs of these incidents for the company. This information will also be used when evaluating the financial feasibility of proposed risk treatment alternatives;
- Acquire complementary data needed to propose risk criteria, such as the land use plan, and for the acquisition of new information that is typically required for the complete identification of relevant characteristics (e.g., climatology and the quantity and quality of river flow rates, springs and underground water and aquifers);
- Collect experiences on similar mine closures and literature on inputs to address various situations and to establish a list of key assumptions that may prove crucial for establishing risk criteria.

All collected information should be introduced through a data management and visualization tool or geographic information system (GIS) developed based on specific mining and abandoned mining needs (e.g., including specific mine map support, etc.), as this will facilitate interpretation and process-based risk assessment (Duzgun et al., 2011).

To validate the methodological proposal, a case study is analysed: the Pumarabule mine property of Hulleras del Norte, S.A. (HUNOSA) in Asturias, Spain, which since its closure has been undergoing flooding. A scheme of existing interconnections with the Mosquitera mine is presented in Fig. 2, and two other mines in the surrounding area that may be influenced by various interactions.

Fig. 3 presents a three-dimensional view of the Pumarabule galleries.

A GIS image with historical incidents of the Pumarabule mine area is presented in Fig. 4. The different colours correspond to the following:

- Red: present and future compensation; the company recognizes damages and provides compensation after the claimant has signed a resignation document stating that he will not ask for any more compensation for the same property;
- Blue: present compensation; the company recognizes damages made and provides compensation to the claimant who is free to make another claim if more damages are incurred;
- Yellow: the company does not recognize any damages;
- Green: in process; typically, some information from the claimant is missing, and the company is not able to settle the record (e.g., property rights were not presented by the claimant).

Each coloured area includes a complete file with all pertinent information (technical, legal and economic) on the given incident and a photographic report.

Using this integrated approach, significant improvements in terms of data availability, access and visualization can be achieved,

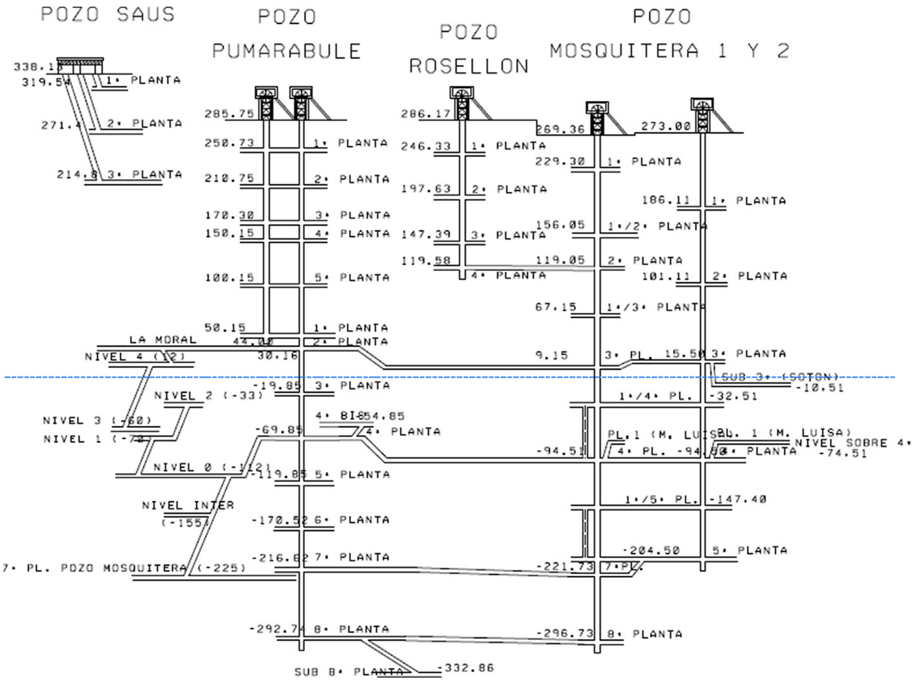

Fig. 2. Scheme of existing interconnections between the Pumarabule and Mosquitera mines; Hulleras del Norte, S.A. (HUNOSA).

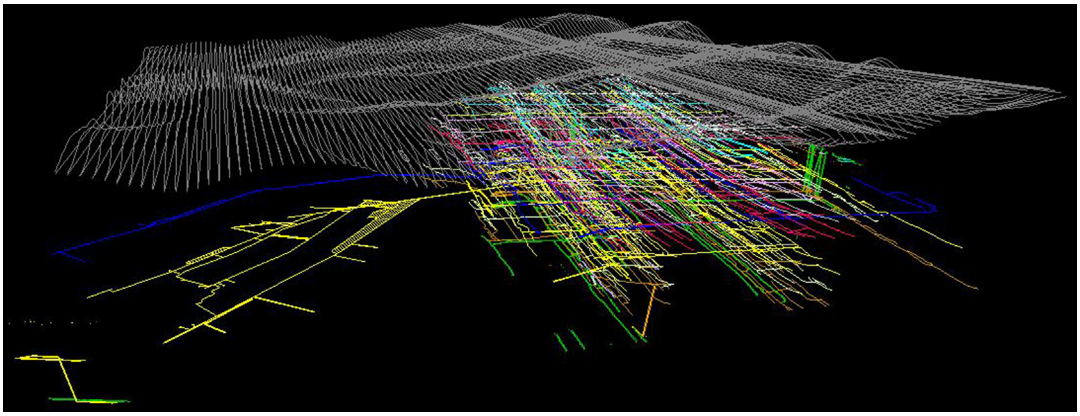

Fig. 3. Three-dimensional view of the Pumarabule galleries; Geomatics Research Group, University of Oviedo.

allowing for an integrated approach to the analysis of heterogeneous data sources and methods that provide sufficiently complex information on occurring phenomena. Dutta et al. (2004) developed a cumulative impact assessment methodology for the scoping phase based on a questionnaire checklist and GIS tool, and Pavloudakis et al. (2009) integrated a Geographic Information System with Multi-criteria decision-making methods to select appropriate land uses for a post-mining area. Geographic information analyses and related GIS operations (e.g., querying, overlaying, distance transformation, neighbouring, rating, multivariate analysis and geostatistics) may allow one to identify certain patterns that will prove difficult to discover or manage based on different managing information.

Another exemplary approach to data integration and data mining provided by Benecke and Zimmermann (2011) involves conducting a multi-layer GIS analysis based on measured surface movements with persistent scatter radar-interferometry (PSI), mining maps and geologic information to identify subsidence patterns and areas potentially rendered vulnerable due to abandoned mining activities in the Ruhr region of Germany (Fig. 5).

4. Risk identification

Risk identification is the process of finding, recognizing and recording risks (IEC/ISO 31010, 2009), and according to ISO 31000 (2012), its aim is to generate a list of risks that must be comprehensive and based on events that have influenced the achievement of objectives (creating, enhancing, preventing, degrading, accelerating or delaying their achievement). It should involve the examination of knock-on effects with particular consequences and both cumulative and cascade effects.

4.1. Environmental risk factors

The most commonly used risk identification methods are the following: failure mode and effects analysis (FMEA), evidence

Fig. 4. Geographic Information System (GIS) with historical incidents of the Pumarabule mine area; Hulleras del Norte, S.A. (HUNOSA).

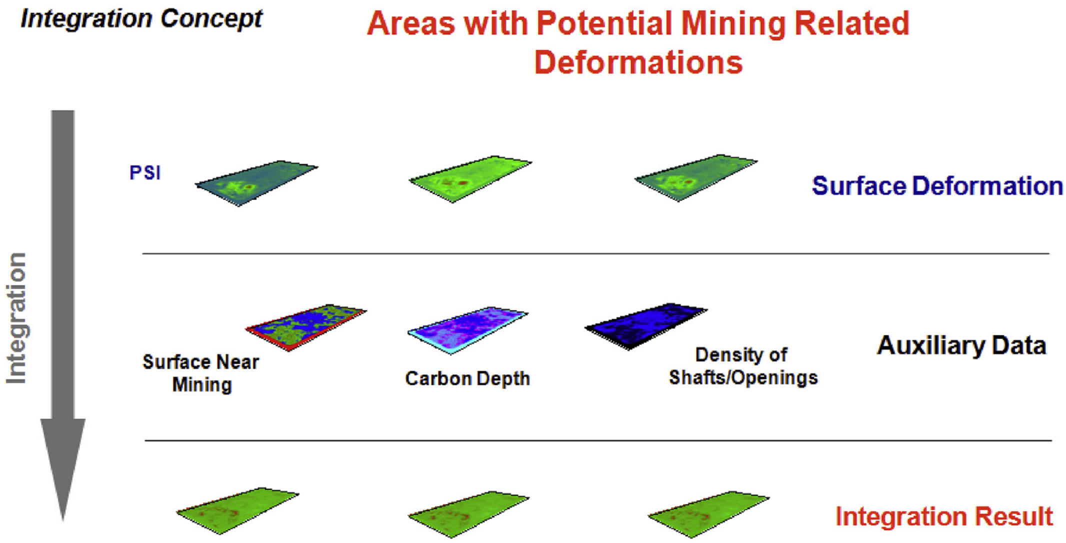

Fig. 5. Cause-and-effect illustration presenting relations between mining induced movements; Source: Zimmermann (2011)

based methods, systematic approaches used by a team of experts, reasoning techniques such as Hazard and Operability Study (HAZOP) methods, supporting techniques such as brainstorming, and Delphi methodologies, etc.

Nevertheless, in an underground coal mine environmental context, risks that may arise are widely known and described in the scientific literature (Didier, et al., 2008) (e.g., water management, air pollution issues, subsidence and other ground movements, residue deposits, soil pollution, abandoned facilities and cumulative environmental impacts):

- Water management issues concerning water balance, water flow schemes and all related effects: drainage volumes together with the quality and quantity of all contaminants of concern for all source terms that may affect water, flow modification, the appearance of humid zones, violent floods, etc (Younger, 2001). (Mayes et al., 2008) (Janson et al., 2009). Additionally, any known or suspected regional interactions with other mines regarding the movement of water between them should be considered (Klinger et al., 2011);
- Air pollution issues: mainly for coal mines, where mine gas can migrate to the surface, inducing significant risks of explosion, suffocation or poisoning. Mine gas can be released from unmined parts of a mine for a relatively long time after the end of mining operations due to a number of mechanisms (Pokryszka and Tauziede, 2000; Tauziede et al., 2002; Krause and Pokryszka, 2013): rising water levels (as water table rise as a consequence of mine flooding will cause a drop in methane desorption and an increase in free gas pressure); feeding the reservoir with gas via its release from coal left in place; and variations in barometric pressure and natural draft. Another aspect that should be considered is the radon and radon progeny present in ventilation air (Skowronek et al., 1998; Wysocka, 2010). Moreover, spontaneous combustion can affect the environment, transporting contaminants directly through the atmosphere or over a broad area within the mine where they may precipitate, thereby entering the hydrological cycle and affecting the water resource (Zhang and Xu, 2010);
- Subsidence often produces significant horizontal and vertical movements along the ground surface that may have significant impacts (Didier et al., 1999; Saeidi et al., 2012; Zimmermann, 2011): physical damage to people, buildings, roads, pavement and networks; economic costs of physical reparations and compensation; economic costs of business and workforce interruption; and social and psychological effects on disaster victims. Subsidence features may only occur in the future, and knowledge of future subsidence risks must be incorporated into identified risks. Special consideration must be placed on water-rock interactions due to ground movements caused from resultant increased levels of hydrostatic pressure and mine flooding. Other water/rock interactions such as salt dissolution (potentially leading to catastrophic subsidence as observed, for example, at the Haoud Berkaoui crater) are outside of the scope of this paper, which focuses on underground coal mines;
- Residue deposits may require rehabilitation to avoid the exposition of fresh minerals for oxidation and potential acid rock drainage. Surface residue deposits can also result in the spontaneous combustion of deposits (Zhang and Wang, 2009) and slope instabilities;
- Soil pollution includes the pollution of soils with materials (mostly chemicals) that are out of place or that are present at concentrations that are higher than normal and that may have adverse effects on humans or other organisms (Sun et al., 2008; Modis and Vatalis, 2014). Soil pollution can lead to water pollution when toxic chemicals leach into groundwater or when contaminated run off reaches streams, lakes or oceans. Soil also naturally contributes to air pollution by releasing volatile compounds into the atmosphere. In addition, chemicals that are not water soluble contaminate plants that grow in polluted soils, and they also tend to accumulate more towards the top of the food chain;
- Abandoned facilities, i.e., mine shafts or other buildings, may collapse or become degraded, may be accessible to people who may fall into them or may even accumulate toxic or flammable gases, thus producing explosions and/or fires if methane is released or accumulated in building cellars (Lecomte and Niharra, 2013). Nevertheless, if they do not contain toxic or hazardous materials or equipment, they are not usually taken into account as an environmental-safety risk factor;
- Finally, cumulative environmental impacts or effects, with the most common being those resulting from the presence of multiple projects (two or more different actors) (Balakrishna Reddy and Blah, 2009; Porto Silva Cavalcanti and La Rovere, 2011; Franks et al., 2013; Eberhard et al., 2013), based not only on the effects of extraction projects concentrated in a region but also on temporal or geographic interactions including different types of industrial activity in the surrounding environment.

4.2. Definition of risk criteria

Risk criteria must be defined for every environmental risk factor to set a benchmark on which risk assessment must be undertaken or acceptable thresholds. Such criteria must be based on regulatory requirements when applicable and should consider stakeholders concerns and risk criteria for human beings and the environment.

The Whitehorse Mining Initiative (Mining Association of Canada (1994)) recommends the following scope: “To ensure that comprehensive reclamation plans that return all mine sites to viable, and, wherever practicable, self-sustaining, ecosystems are developed and are adequately financed, implemented and monitored in all jurisdictions”.

Szwedzicki (2001) states that before developing completion criteria, land use plans must be agreed upon between stakeholders and properly specified while maintaining the natural ecosystem, thus including agriculture, aquaculture, forestry, pastoral use, and industrial and recreational uses with water storage. This is why detailed risk criteria for different environmental risk factors (water, air, residue deposits, soil, abandoned facilities and ground surface stability) should be defined according to land use plans.

Regulatory requirements may vary between different countries and can be non-existent. With a focus on geohazards, Deck et al. (2009) developed a ranking system for subsidence phenomena based on the French urban code, thus defining three types of areas based on the maximum possible subsidence level and recommendations for building projects:

- A maximum subsidence level of less than 1 m: when the surface of a building is less than 400 m^2 and its maximum length is less than 25 m with a maximum of 3 floors (plus the ground floor);
- A maximum subsidence level of less than 2.5 m: when the surface of building is less than 150 m^2 with a maximum length of 15 m and a maximum of one floor (plus ground floor);
- A subsidence level of more than 2.5 m is forbidden.

Nevertheless, the most common criteria used internationally are based on maximum compression and traction tension together with slope limits (see Table 1).

When no legislation can be found in the country where a mine is located, a conservative way to proceed involves adopting the most restrictive legislation found (e.g., the Japanese criterion for concrete buildings (0.5 mm/m) or the German criterion for slopes (between 1 and 2×10^{-3})). Alternatively, average values among neighbouring countries with considerable levels of dispersion between them can be used.

Together with these considerations, it must be noted that subsidence is quite a fast phenomenon, as the main ground movements occur within 200 days after exploitation (Rambaud Pérez et al., 1986). Jeran and Trevits (1995) increase this period to 350 days, and from this point until 800 days (approximately 2 years), only residual subsidence movements take place.

Table 1
Allowed deformation criteria for different coal basins (Rambaud Pérez et al., 1986).

Coal basin	Compression (m)	Traction (m)	Slope	Radius of curvature	Factor of safety	Specific application
UK	1×10^{-3} per 30 m of structure					
France	1 to 2×10^{-3}	0.5×10^{-3}				Pipes
Germany	0.6×10^{-3}	0.6×10^{-3}	1×10^{-3} to 2×10^{-3} for buildings			
Poland	1.5×10^{-3}	1.5×10^{-3}	2.5×10^{-3}			
Donetsk (Ukraine)	2×10^{-3}	2×10^{-3}	4×10^{-3}	20 km	400–550	
Karaganda (Kazakhstan)	4×10^{-3}	4×10^{-3}	6×10^{-3}	3 km	250–300	
Chelyabinsk (Russia)					300–400	
Japan	0.5×10^{-3}	0.5×10^{-3}				Concrete buildings
	1×10^{-3}	1×10^{-3}				Wooden buildings

5. Risk analysis

Risk analyses provide inputs for risk evaluations by identifying which risks must be treated based on appropriate treatment strategies. They also involve the estimation of potential consequences and their associated probabilities, allowing one to measure levels of risk. Methods used may be quantitative, semi-quantitative or qualitative; Laurence (2006) used a risk assessment matrix with a probability range of 10 (certain) to 1 (rare) and with consequence levels ranging from 10 (catastrophic) to 1 (insignificant) over a 10 × 10 matrix, unlike the typical Workplace Risk Assessment and Control (WRAC) method, which allocates the highest likelihood and consequence levels to the smallest numbers in a 5 × 5 matrix.

Currently, for underground coal mines, closure context quantitative methods (numerical simulation) are preferred and are extensively used due to the complexities of analyses conducted.

5.1. *Conceptual models*

To adopt the most effective strategies for obtaining adequate numerical simulation results during the risk management process, it is best to develop conceptual models for various source terms, pathways and receptors; such conceptual models define questions to ask, the necessity to adapt prediction tools and techniques, the structure of sampling programs and assumptions and data values to be used.

Fig. 6 shows a conceptual model for mining related subsidence. The primary cause of movement is material extraction through underground mining operation. The gradual subsidence of the roof into the panel cavity creates movement (subsidence and displacement) in the overlapping rock mass, which continues to the surface. The extent of induced movements depends significantly on characteristics of the mining operation and on the overlying rock mass. Influencing factors, among others, include the mined height of the deposit, the mining technology used, the spatial location and geometry of the panel, the properties of the rock mass and the temporal mining management approaches used.

The numerical simulation must estimate several parameters to define the most suitable transformation function:

- The maximum subsidence obtained for each panel;
- The super-critic length of each panel considered: the panel length at which the subsidence effect no longer increases;
- The draw angle: the angle of influence for the surface subsidence over the excavation convergence (source function).

The development of conceptual models may not be suitable for all environmental factors considered (i.e., abandoned facilities or cumulative environmental impacts), particularly due to degrees of uncertainty and the nature of these factors together with the amount and type of information needed to satisfy an adequate risk identification.

In these cases, any of the above mentioned methods that are "strongly applicable" according to IEC/ISO 31010 (2009) should be used.

5.2. *Numerical simulation*

After defining the conceptual models, adequate numerical simulation tools must be selected according to general

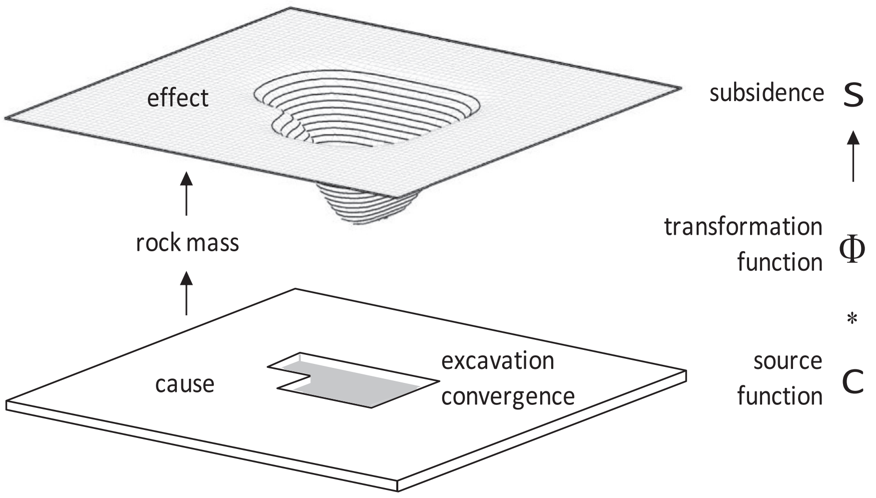

Fig. 6. Integration of PSI ground motion and mining related auxiliary data; DMT Gmc bH & Co., KG.

underground coal mining expertise and track records of utilization and development for the company or for experts that may be involved.

For air pollution numerical models, programmes such as the TOUGH2-a simulator for non-isothermal multiphase flow in fractured porous media (Li et al., 2014) and the VENTGRAPH, which forecasts ventilation processes under very different circumstances (Dziurzynski et al., 2008), are commonly used, although experts from different companies likely use different numerical models.

For subsidence numerical models, available simulation programmes vary considerably. The HUNOSA mining company has developed its own software program called the HUNDEF program. Fig. 7 presents the results for the Pumarabule mine obtained through the HUNDEF software program. The calculated subsidence level considers only those settings that may be caused by galleries that will remain unflooded as well as movements linked to a possible shaft lining deterioration due to degradation.

Due to high degrees of uncertainty associated with the simulation of geomechanical, geophysical and geochemical phenomena, the first stage of numerical simulation should involve the calibration of models in defining the most adequate strategies for achieving an acceptable degree of process accuracy from less information. For this reason, “case studies” for the same region or for similar environments should be used to optimize models so that they can reproduce available measures.

The calibration process must also define all data and relevant information needed to conduct the numerical simulation. Thus, a sampling program must be developed before the numerical model is used to carry out the final simulation, thus allowing one to obtain estimated risk levels.

Benecke and Zimmermann (2011) used a similar approach to quantifying surface movements. The following GIS map shows the probability of surface movements related to abandoned mining (Fig. 8) and offers valuable information on hazard mitigation.

6. Risk evaluation

The next step involves evaluating risk by comparing estimated levels of risk with risk criteria defined during the risk identification phase. All identified environmental risks should be divided into two different categories (potential risks and insignificant risks) to exclude minor risks from the analysis while focusing on the most important risks. Insignificant risks must be documented to include this information in the Final Closure Assessment Report.

The land use plan of the Pumarabule mine area will allow one to compare the estimated subsidence with the maximum possible subsidence according to existing constructions together with specific recommendations for new building projects. Fig. 9 presents the land use plan for the area surrounding the Pumarabule mine shaft, an area that is typically subject to new urban planning regulations after the closing stage.

On the other hand, potential risks should be classified as risks consequences that must be addressed and as risks that are acceptable without further mitigation; these latter issues must be documented in the Final Closure Assessment Report.

7. Management measures

In this final step, the risk management strategy that is considered the most appropriate and that could guarantee a hazard level in compliance with the surface occupation is defined.

When using predictive techniques, any predictions that are made should be verified using an appropriate monitoring program to validate the assessment technique used. This is why a key part of

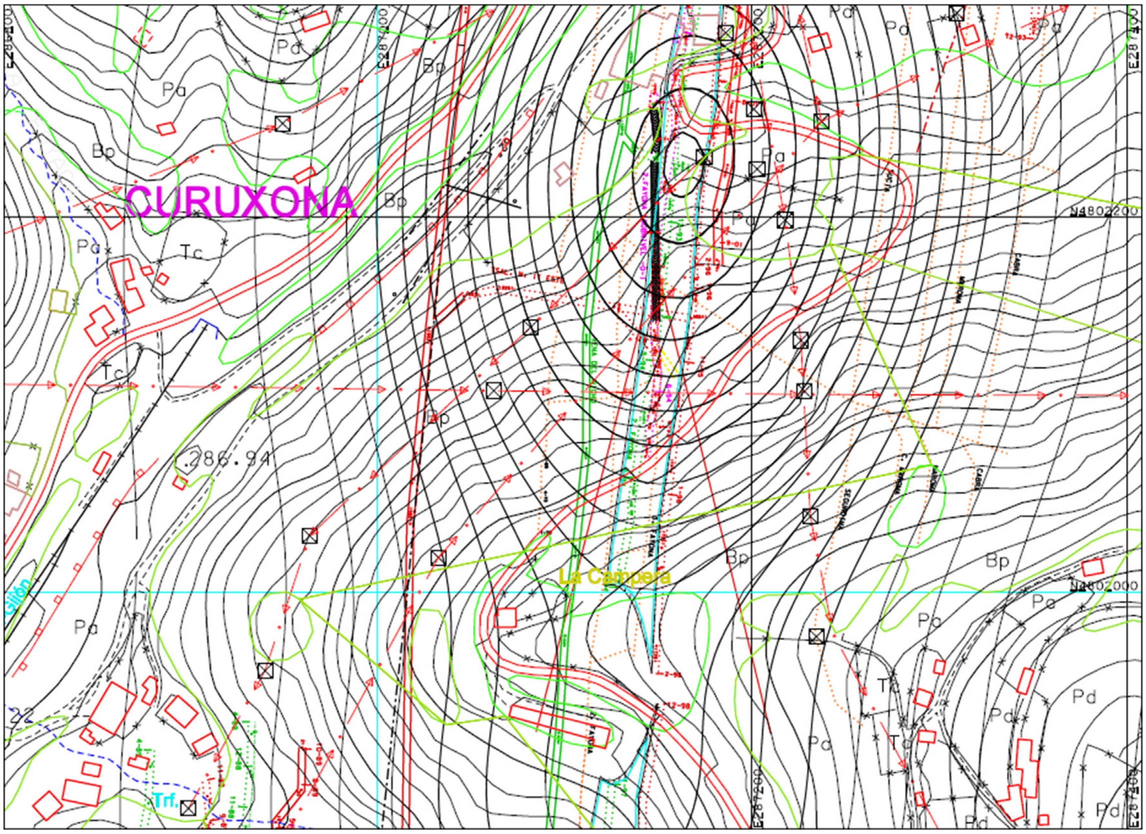

Fig. 7. Pumarabule subsidence simulation developed using the HUNDEF software program; Hulleras del Norte, S.A. (HUNOSA).

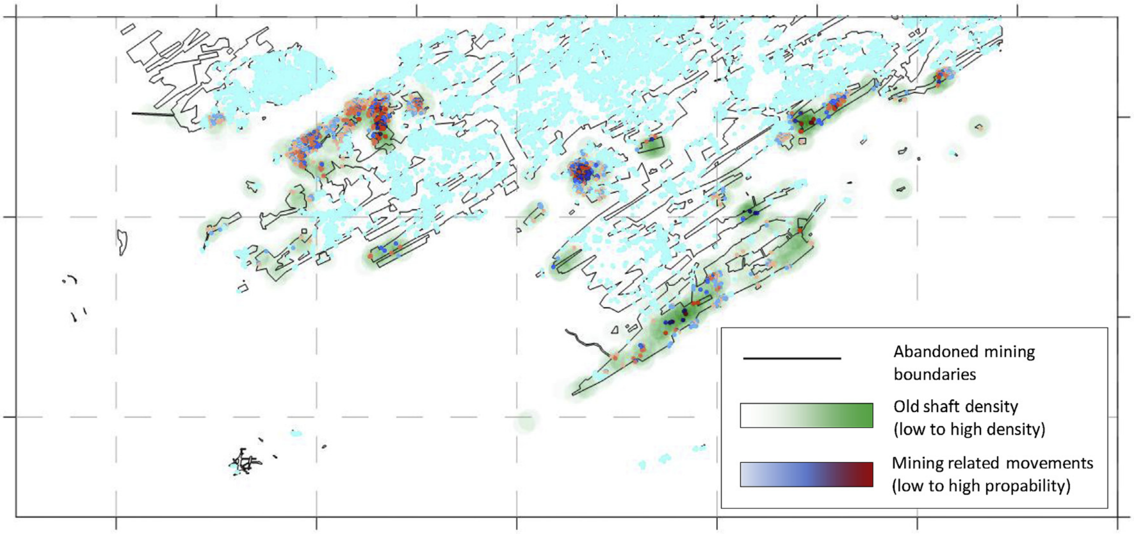

Fig. 8. GIS ground movement risk map; DMT GmbH & Co., KG.

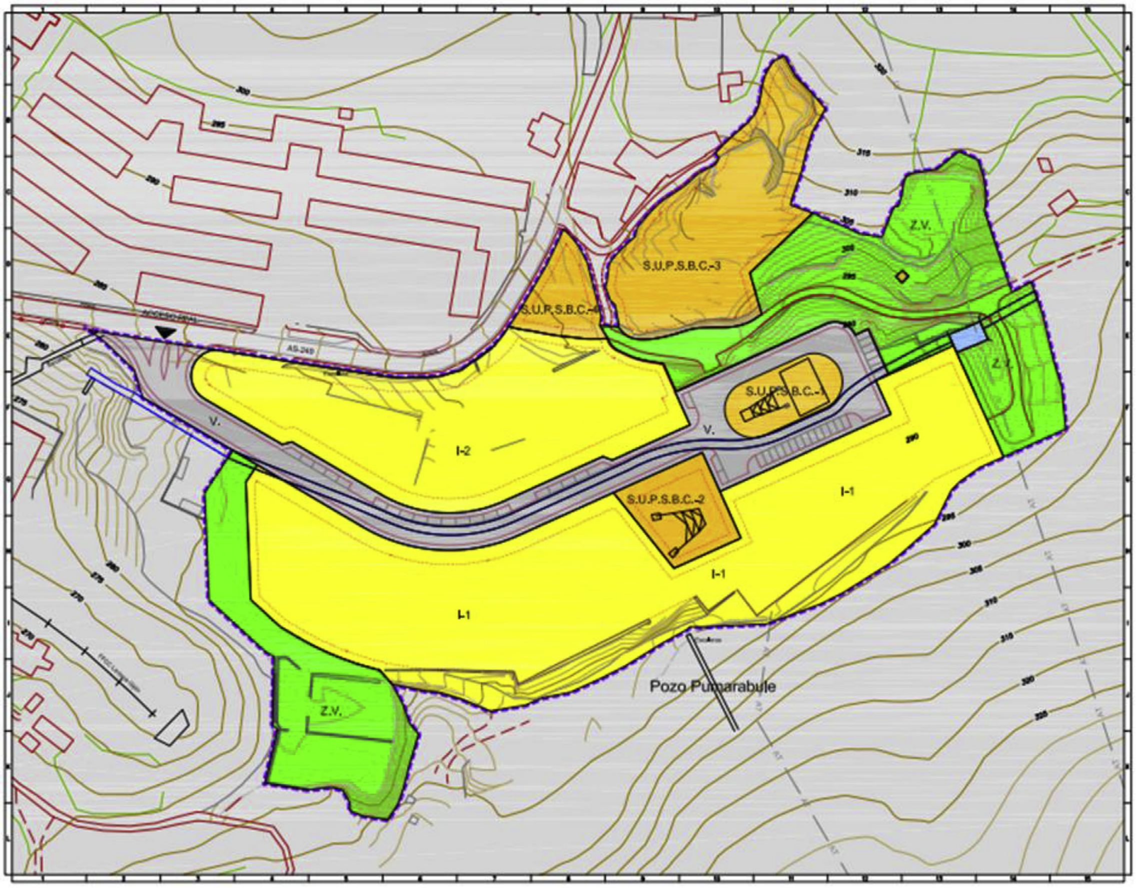

Fig. 9. Land use plan for the area surrounding the Pumarabule mine shaft; Hulleras del Norte, S.A. (HUNOSA).

this task involves the definition of a monitoring programme for each risk to be treated to verify impact assessment and compliance. The Government of Alberta (Canada) requires all mine closure plans to target maintenance-free performance levels after transitional monitoring (Sawatsky, 2012), but this may not be feasible for every mine closure plan.

7.1. Risk treatment alternatives

When identifying feasible risk treatment alternatives, both simple and complex solutions should be considered (e.g., the possibility of using the underground mine volume as a dam: in the winter, water can be stored for pumping in the summer to maintain the flow rate of a river; a mining void can also be used to minimize risks of flooding caused by intense rains). As an example, after heavy rains hit the Queensland Coal Mines in January and February of 2008, the Queensland Environmental Protection Agency granted special discharge conditions as mines were forced to discharge floodwaters into the Fitzroy River catchment. The 2008 wet season proved that emptying flooded mines prove as challenging as having them filled (Queensland Environmental Protection Agency, 2009). Such alternatives may thus constitute sources of impacts, and so special care and analysis should be considered before adopting them.

For the case study, alternatives were selected according to results delivered through the MISSTER project (Lecomte and Niharra, 2013), which defined the best constructive solutions for preventing the failure of shaft lining while maintaining the head frame: (1) checking via inspection the state of lining degradation and reinforcing the lining in cases of degradation, (2) using backfilling methods, (3) reinforcing surrounding land by injection, (4) self-supporting plugs, and (5) anchored plugs.

The results of the numerical models must be used to define and develop monitoring programs to verify impact assessment and compliance with a focus on assessing whether the residual impacts of the mine have reached acceptable levels and that no further ongoing work is required. The key point is to critically review the model and to issue a statement of assurance on the accuracy of predictions made. Fig. 10 presents an example of a laser scan of different facilities affected by an underground coal mine developed to control subsidence predictions made using a specific software program.

Risk treatment alternatives and their associated monitoring programmes must also involve cost-benefit analyses based on common economic models to evaluate the costs and benefits of each specific measure. The economic evaluation of costs and benefits will consider all costs and benefits, from those that may occur in the short run to those that may occur over a longer period of time as in the case of monitoring programmes.

A cost-benefit analysis should be developed together with a sensitivity and uncertainty analysis on its variables. Sensitivity analysis involves the study of how model input uncertainty can be apportioned to different sources of uncertainty in model inputs. It should be followed by an uncertainty analysis, which focuses on quantifying uncertainty in model outputs. A Monte Carlo simulation is typically used when conducting an uncertainty analysis on key variables. This simulation approach involves a computerized mathematical technique that allows one to account for risks involved in quantitative analysis and decision-making. Monte Carlo simulations furnish decision-makers with a range of possible outcomes and with the probability that they will occur for any course of action.

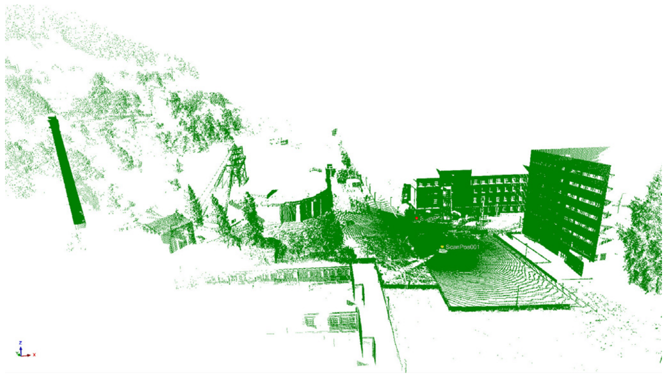

Fig. 10. Laser scan of the area surrounding an underground coal mine; Geomatics Research Group, University of Oviedo.

Among the alternatives selected, the former (checking by inspection the state of lining degradation and reinforcing it in cases of degradation) was the most feasible for cost-benefit analysis; though because it requires continuous maintenance, it was discarded. Backfilling costs and benefits are typically very similar to injection/inclusion techniques, but as the shaft is already partially submerged, costs and technical complexities are much more significant. The anchored plug was thus selected due to the specific geological formation that advises against the use of a self-supporting plug.

7.2. *Risk management strategy*

Risk management strategy selection is not as simple as selecting between different feasible risk treatment alternatives through cost-benefit analysis. Apart from any specific consideration that may apply, an estimation of treatment failure probabilities and their uncertainty bounds through probabilistic risk assessment (PRA) must be undertaken to detect areas presenting the greatest risk of failure. The front end of the PRA process involves identifying incident initiators; this is usually conducted through the construction of a hierarchical structure with known incident initiators or failure modes of the treatment alternatives examined. This is followed by a strategic timeline with data on any treatment run times (start and stop times) that are adjusted to changing treatment profiles. Timing data are used to calculate failure probabilities.

The PRA will help answer questions such as the following:

- What is the best estimate of risk management strategy failure probability?
- Which treatment alternative contributes the most risk to the management strategy?
- If we select an alternative treatment to eliminate a particular failure mode, what would be the benefit of decreased strategy risk?
- If we could select an alternative treatment to reduce the probability of failure due to a particular failure mode by some percentage, what would be the benefit of decreased strategy risk?

The most frequently encountered complexity criteria that were taken into account for the Pumarabule mine PRA subsidence process were related to mine gas emissions risks. To conclude the analysis, a specific procedure was determined to diminish risk levels: the installation of a decompression vent. On the other hand, due to the higher positioning of the Pumarabule mine in relation to the Mosquitera mine, there was no need to consider special measures for risks related to water (e.g., alternative pumping discharge points).

7.3. *Closure assessment report*

Finally, a detailed Closure Assessment Report should be completed. The report will clearly document all work undertaken and will clearly document all decisions and agreements that were reached. Quantitative closure objectives (including performance indicators) in terms of all significant risks will be listed with proposed management measures; residual and latent effects after successful management measure implementation; and time frames and scheduling for the implementation of management measures and maintenance for verifying compliance with these objectives when necessary. A detailed closure cost assessment and financial provision statement should also be included.

8. Results and discussion

Coupling environmental risk management strategies of underground coal mine closures with international standards ISO 31000 (2012) and IEC/ISO 31010 (2009) is not easy to achieve due to the general purposes of these standards.

As an operational methodology that can be used as a reference is currently lacking, the management of environmental risks during and after underground coal mine closure is, in many cases, reduced to a minimum or is conducted without specific and contrasted guidance. Fig. 11 presents a framework that could be applied for future underground coal mine closures independent of major

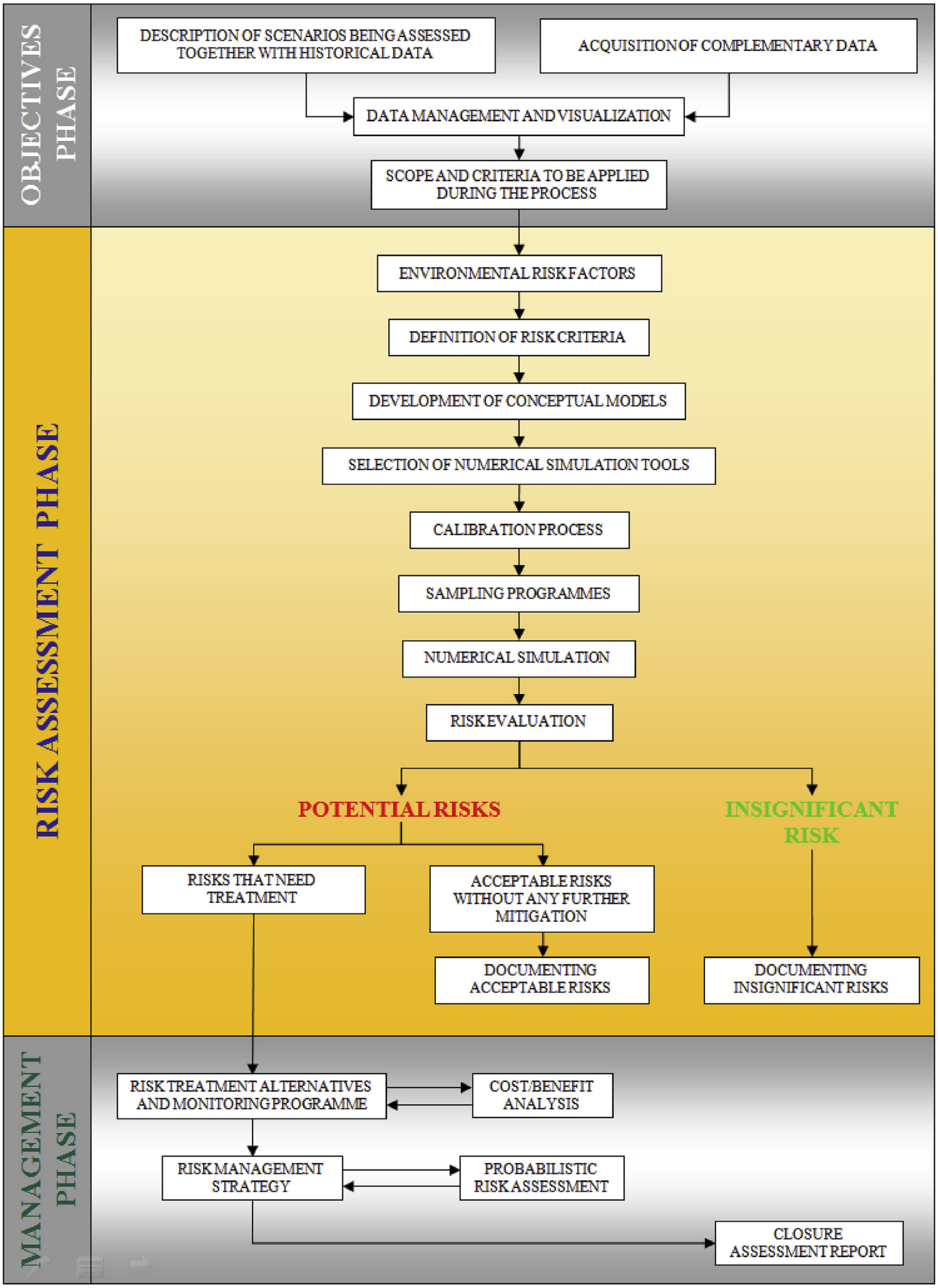

Fig. 11. Methodology proposal for environmental risk management in underground coal mine closure.

environmental problems faced that is perfectly coupled with ISO 31000 (2012) and ISO/IEC 31010 (2009).

Lessons obtained from the case study allowed for a satisfactory validation of the proposed methodology. The main challenges identified through this process were mainly related to obtaining an adequately full description of the given mine and thus to adequately creating Geographic Information Systems. Much of the historical data used were lost or were only available in paper form. In turn, the numerical simulation presented several problems due to a lack of access to certain information. Some gaps were filled thanks to the expertise of those who conducted the simulation, information gathered through experiences with similar mine closures, and in some cases, literature based inputs.

Finally, we must note that this methodological proposal can also be applied to any alternative mine closure context (open-pit mines, underground metal mines, etc.) according to different environmental risk factors that should be considered and various numerical tools that may be applied in some cases.

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