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A Rule-based Expert System for Selection of Rehabilitation Strategies for Abandoned Mines in South Africa

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Abstract

South Africa has 6100 documented abandoned mines. The government is responsible for the management and rehabilitation of these mines to address their environmental problems, physical hazards, and socio-economic issues. In general, rehabilitating abandoned mines involves making a series of critical decisions about the strategies to be implemented in rehabilitating the major features of these mines. This paper presents an expert system developed to aid in selecting appropriate strategies for rehabilitating abandoned mines in South Africa. This system is known as the Expert System for Selection of Strategies for Rehabilitation of Abandoned Mines (ES-SRSA). The ES-Builder (Version 3.0, McGoo software) was used to design the knowledge and rule-based components of the expert system. The rules of the expert systems were developed based on the documented knowledge of the problems of abandoned mines in South Africa and the information gathered by the researcher through visits to selected abandoned mine sites in the country. The ES-SRSA provides 45 recommendations of suitable strategies for dealing with the different problems of features such as underground entries, mine waste, surface mine excavations, silos and orebins, and other features like dilapidated buildings/infrastructure. Most of the rules of this expert system encourage the repurposing and reuse of these mine features to improve the social and economic status of the host communities. The use of this expert system has the potential of contributing to the reduction of the risks of implementation of ineffective strategies for the rehabilitation of abandoned mines in a country like South Africa.

1. Introduction

An expert system (ES) is one of the applications of artificial intelligence (AI) that mimics human experts in specific fields [1]. Expert systems are computer programs developed to solve problems, make decisions, and provide consultations normally given by experts [2]. These systems can also serve as a repository of corporate knowledge that keeps the experiences of engineers after their retirement or resignation [3]. Among others, the goal of designing expert systems is to reduce the risks in decision-making, ensure successive learning, and stimulate creativity [4]. According to Kappes *et al.* [5], expert systems can reduce the time spent learning certain tasks and increase the time of implementation or competence performance. Unlike human beings, expert systems do not forget, and they do not jump to conclusions (they work systematically to the best conclusion) [6]. They can also increase throughput while reducing personal costs and provide consistent answers or recommendations in similar situations [7]. Some of their obvious limitations are that they lack creativity and common sense, and they are dependent on symbolic input, hence they lack sensory experience [8]. Although expert systems have been in use since the 1940s [9], their application in the mining and mineral industry (especially mine closure and rehabilitation) has not gained the necessary traction. Because of this, very few expert systems have been developed to help

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decision-making in the mining industry and related sectors. Some of the expert systems that are reported in the literature to have been developed for different aspects of abandoned mines and their rehabilitation are described in Table 1. These expert expert systems mainly help to identify the hazards of abandoned mines and prioritization of abandoned mines for rehabilitation. This paper presents the first rule-based expert system developed to help decision-making in selecting appropriate strategies for rehabilitating abandoned mines. In general, the representation of knowledge in the form of rules (e.g. IF-THEN format of the rules) in the expert system makes the rules of the expert system to be modular with a significant amount of domain knowledge. It also allows for easy expression of knowledge by experts [10]. The other advantage of rule-based expert systems is that they have cognitive processes like those of human beings, especially in system identification [11].

Table 1. Expert systems developed for different uses in the management and rehabilitation of abandoned mines.

No.	Application area	Uses of system	Special name	Author
1	Ranking of the hazards of abandoned mines.	A tool for prioritization of abandoned mines for rehabilitation was incorporated into the ES.	AMHAZ	[12]
2.	Ranking of abandoned mines	The method of ranking the risks of abandoned mine entries was incorporated in an ES.	ES-RAME	[13]
3.	Planning of reclamation of ARD-contaminated sites	Assist in the planning of remediation of acid rock drainage (ARD) contaminated sites.	ARDx	[14]
4.	Management of the hazards of abandoned mines	For locating the hazards of abandoned mine sites	AMGIS	[15]

In this work, an expert system for the selection of rehabilitation strategies (referred to as ES-SRSA) for abandoned mines was developed within the web-based shell called the ES-builder 3.0 (McGoo software). This expert system shell is famous for allowing the development of expert systems that are accessible as a web page [16]. The use of internet-based technologies or shells to develop expert systems has simplified the process and contributed to many expert systems being available and accessible through the internet [17]. In this case, web-based shells such as ES-builder, CLIPS, JESS, and PyKE have contributed immensely to the continuously increasing number of expert systems that are available on the internet [18]. The presentation of the ES-SRSA in this article is organized into three important sections. The first section gives the background on the problems of abandoned mines and their rehabilitation in South Africa with the purpose of defining the context or problem domain addressed by the ES-SRSA. The next section details the methodology of developing an expert system in the ES-builder shell. It highlights the general architecture of the expert system shell and the rules that underpin the development of a functional decision tree and knowledge base of the expert system. The last sections discuss the characteristics of the ES-SRSA and its potential benefits.

2. Rehabilitation of Abandoned Mines in South Africa – Domain Analysis

South Africa has about 6100 documented abandoned mines that need to be properly closed or rehabilitated. It also has several mines under "care and maintenance". All these mines present different forms and magnitudes of physical hazards and environmental problems. They are also associated with some socio-economic concerns. Currently, the rehabilitation of abandoned mines in South Africa is exclusively the responsibility of the government. This is because the government has a responsibility of protecting its people and the environment from different types of hazards. According to the Constitution of the Republic of South Africa (Section 24), everyone in South Africa has guaranteed rights to an environment that is not harmful to their health or well-being and to have the environment protected for the benefit of present and future generations. This is as well in line with the concept of sustainable development which promotes a socio-economic system that ensures that human needs and long-term improvement of quality of life are achieved while taking into consideration the environmental constraints [19], [20]. Effective closing and rehabilitation of mine sites (including abandoned and prematurely closed mines) contributes to the realization of several sustainable development goals (SDGs) [21-23]. Because of this, the program of rehabilitating abandoned mines in South Africa is an important undertaking that goes far beyond just the government fulfilling its constitutional obligation.

As part of this program of rehabilitation of abandoned mines, the government of South Africa has since 2009 adopted a national strategy for managing derelict and ownerless mines [24]. This strategy aims to ensure that the country follows a systematic approach to addressing the challenges of abandoned mines. The breakdown of the work that has been far conducted to deal with the high-risk abandoned mines in South Africa is shown in Figure 1. With such a strategy, the government of South Africa through its institutions (i.e. Department of Mineral Resources and Energy, Council for Geosciences, Mintek, and National Treasury) has been able to increase the rate of rehabilitation of abandoned mines from 1.67 (before 2009) to 2.25 (between 2009 and 2021) [25]. With the current rate, it is expected that the rehabilitation of the 229 high-risk asbestos mines in South Africa last for 69 years.

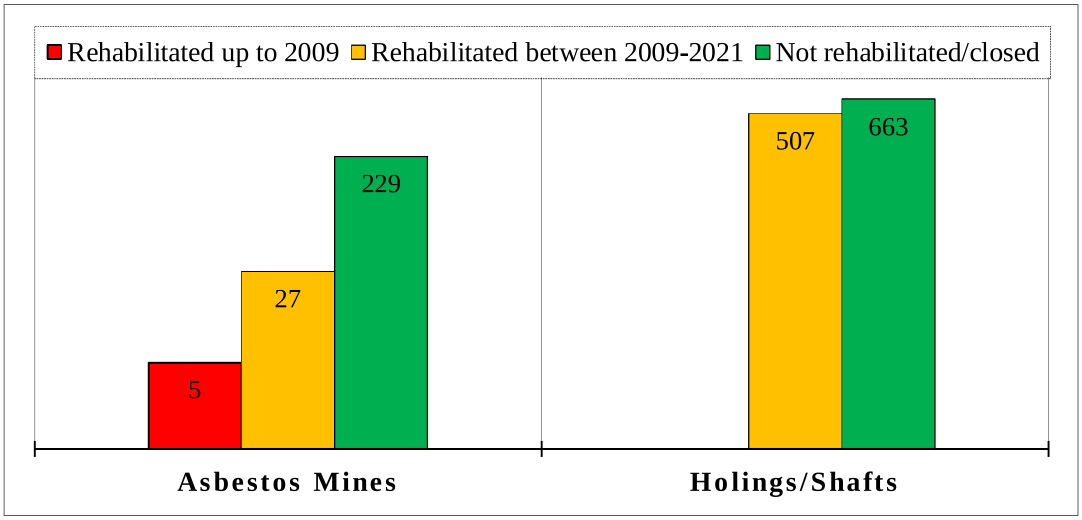

Figure 1. Progress with the rehabilitation of abandoned mines in South Africa [25].

In general, the work of mine closure is concerned with making a series of important decisions for the success of the closure and the post-mining land uses. Good decision-making in mine closure is important because the rehabilitation of mined land is mostly done when the economic stage of the mine has passed, thus with limited resources. This situation is even worse in the case of abandoned mines (especially, in developing countries like South Africa). This is because the resources that the government is expected to use to close thousands of abandoned mines in their countries are also needed to deal with the social and economic challenges confronting the citizens. Therefore, several critical questions need to be answered in the project of rehabilitation of abandoned mines. Some of them are:

- Which mine(s) should be prioritized for rehabilitation?
- What should be the aim and/or goals of the rehabilitation of these mines?
- What cost-effective strategies should be used to rehabilitate abandoned mine sites for sustainable post-mining land uses?
- What suitable post-mining or post-rehabilitation land uses should be considered for the different abandoned mine sites?

Cautious answers to these questions can be provided when a good decision-making process is followed. Such a process needs to consider the interdependence of the factors determining the success of closing the mine sites (especially for the sustainability of the communities). To help this process, an expert system for selecting appropriate strategies for the rehabilitation of abandoned mines in South Africa was developed. This paper discusses the characteristics of this system and how the program of rehabilitation of abandoned mines in South Africa can benefit from it. Such an ES was not developed to dictate the rehabilitation strategies but to suggest the important considerations for the final selection of the rehabilitation strategy. It only gives examples of some of the appropriate strategies for dealing with the specific problems of the major features of abandoned mines.

3. Methodology

The development of the ES-SRSA began with developing a good understanding of the nature of the problems of abandoned mines and the challenges with their rehabilitation in South Africa. This knowledge was acquired through an intensive review of the relevant literature and carrying out a site visit to selected abandoned mines in the Limpopo, Mpumalanga, and Gauteng provinces of South Africa. The specific information gathered about the abandoned mines included their environmental and physical hazards and their associated socio-economic concerns. This knowledge helped to develop the general objectives or goals of the rehabilitation of the major features of abandoned mines shown in Table 2. Based on the established knowledge of all the issues of abandoned mines in South Africa, the knowledge and rule-based components of the expert system were developed in the ES-builder shell (Version 3.0). A summary of the general architecture of the developed ES is shown in Figure 2.

Table 2. A set of objectives for rehabilitation of the features of abandoned mines.

Feature	Type	General objectives of rehabilitation
Mine entries	Vertical shaft	Prevention of ground movement, use of simple strategies, use of strategies that require little maintenance, protect species inhabiting the shaft, and prevent risks of physical injuries
	Inclined shaft	Prevention of ground movement, protecting species inhabiting the shaft, preventing people and animals from entering the shafts, use easy to install strategies and prevention of a discharge of mine water
	Adit	Protect species inhabiting the shaft, prevention of a discharge of mine water, prevent people and animals from entering an adit
Mine waste	Tailings	Improving the physical stability of the dump, reducing the concentration of toxic metals from tailings, improving the physio-chemical properties of tailings, removal of the dump
	Waste rock	Removal of the dump
	Spoil	Removal of the dump
Surface excavation		Pit-lake development, creating an acceptable landform (including backfilling), prevention of access of the excavation, and reducing the slopes of the pit
Other features	Silos and ore bins	Removal from the landscape
	Mine roads	Removal and rehabilitation of the land
	Concrete water reservoirs and mounting stands	Demolition and removal
	Mine houses	Demolition and removal, and protection and reconditioning

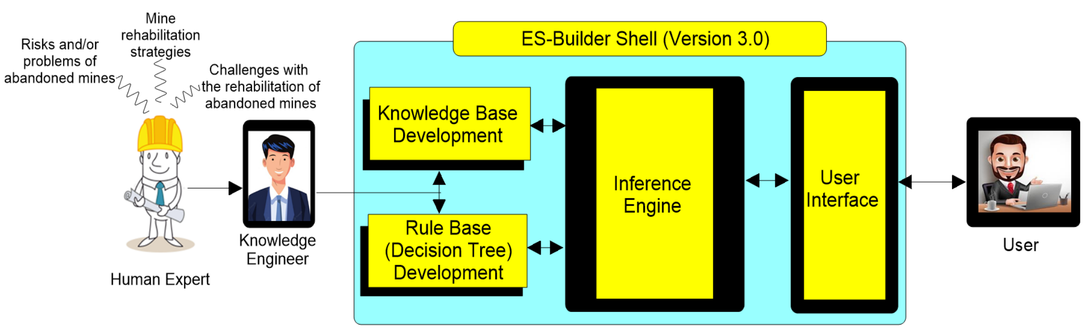

Figure 2. General architecture of an expert system.

3.1. Building the knowledge base and modeling the decision tree in ES-builder

The process of developing the knowledge base and decision tree of the expert system started by accessing the shell (ES-builder shell) online. This shell uses a web interface that is easy to access and can be used by anyone who is familiar with the internet [2], [16]. It was accessed by registering on the web page of the ES-builder shell. This allowed the developer of the expert system to create a user account. After the confirmation of the user registration, it was possible to log into the shell and access the project details page where the "Title" of the expert system was defined, and its "universe of discourse" (which is the range covered by the expert system) was described.

The ES-builder shell is equipped with a platform for modeling a decision tree used for the creation of a logic structure of the expert system [13], [16]. This tree is basically a graphical illustration of the knowledge and rules of the expert system [2]. In the the ES-builder shell, it is developed within the decision tree view window. The tree is developed by entering the attributes, values, and conclusions of the expert system into the decision tree model of the shell. The structure of the rules was in the form of the condition(s) [IF] and the consequence(s) [THEN]. These rules are such that when the IF statement(s) of the expert system is satisfied, the THEN part starts taking place [16].

Care was taken to ensure that the decision tree of the expert system is created with nodes branching to other nodes until the conclusion is reached. The other important rules that were followed in the development of the decision tree are depicted in Table 3. The simple certainty factor (Cf) was applied to the rules, and this factor is reflected on each conclusion page and in every rule and knowledge base of the expert system. The main purpose of the Cf is to estimate the confidence of the conclusion reached by the expert system. For example, the +Cf value indicates the expert's belief in the conclusion reached by the expert system while a -1 Cf value indicates the expert's disbelief [26], [27].

Table 3. General rules for developing decision tree in the ES-builder shell [16].

Point	Rule
1.	The first node of the decision tree is the Universe of Discourse (UofD)
2.	The second node of the tree should be an Attribute that is displayed with an "A" icon
3.	Each attribute to be tested in the ES should at least have two branching nodes
4.	The value nodes are mostly the only type of branch nodes that are accepted by the attribute node
5.	The value node always represents the most correct response to an attribute for a conclusion
6.	The value nodes have two possible types of branch node, therefore, when further attribute needs to be tested, a branch node of a value will be another attribute node
7.	When a conclusion has been made, the branch node of the value will be a conclusion
8.	The conclusion node must be a leaf node such that no branches are accepted from the conclusion node
9.	Apart from the UofD (*i.e.* first node), about 3 data items can be added.
10.	Each attribute, value, and conclusion node may consist of a detailed definition, a paragraph of help notes, and an image to be displayed in the ES.

4. Results

4.1. Description of ES for rehabilitation of abandoned mines

The selection and implementation of strategies for the rehabilitation of abandoned mines depend on many factors (*i.e.* both internal and external). Some of the important factors, in this case, relate to the availability of material, skills, community expectations, and anticipations for post-rehabilitation land uses. In view of this, the production rules of the expert system for the selection of rehabilitation strategies for abandoned mines were developed to work towards making recommendations of strategies to fulfil specific aims or objectives of the rehabilitation project. The rule-chaining approach adopted for this expert system is forward chaining. The sample of such production rules for the ES-SRSA and the corresponding decision tree are shown in Figures 3a and b, respectively.

In general, the production rules of the ES-SRSA for the selection of strategies for the rehabilitation of abandoned mines were designed to lead to a total of 45 conclusions or recommendations (see Figure 4). These conclusions advise on appropriate strategies for dealing with the issues of abandoned mine entries (holings/shafts), mine waste (*i.e.* waste rocks, tailings, and spoils), silos/orebins (including other similar structures), surface excavations, and features such as dilapidated buildings and other infrastructure found in the abandoned mine sites. The most important element of the conclusion page of this expert system is the recommendation that the system gives in the form of a conclusion note. A sample of such notes is shown in Figure 5. The purpose of the conclusion notes of the ES-SRSA is to give recommendations, with some examples of the strategies that could be considered and implemented to achieve the rehabilitation objectives as per the conclusion statement given by the ES-SRSA. It is once again important to emphasize that this expert system was not developed to be exhaustive of all the possible solutions but to provide a piece of clear advice or ideas on the type of strategies that should be considered in the rehabilitation of abandoned mines in South Africa. An illustration of the information presented on the conclusion page of the ES-SRSA is in Figure 5. Such information is the the "conclusion" (found on the top part of the conclusion page) given based on the rules that are shown at the bottom of the page. Some clues about the recommended rehabilitation work are provided by the appropriate picture shown on every conclusion page.

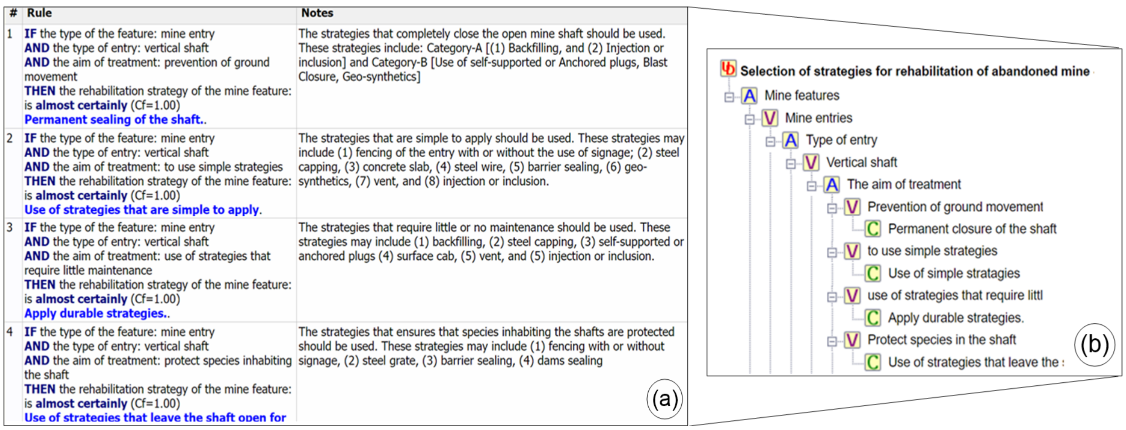

Figure 3. An illustration of the sample of the (a) production rules and (b) decision tree of the ES-SRSA.

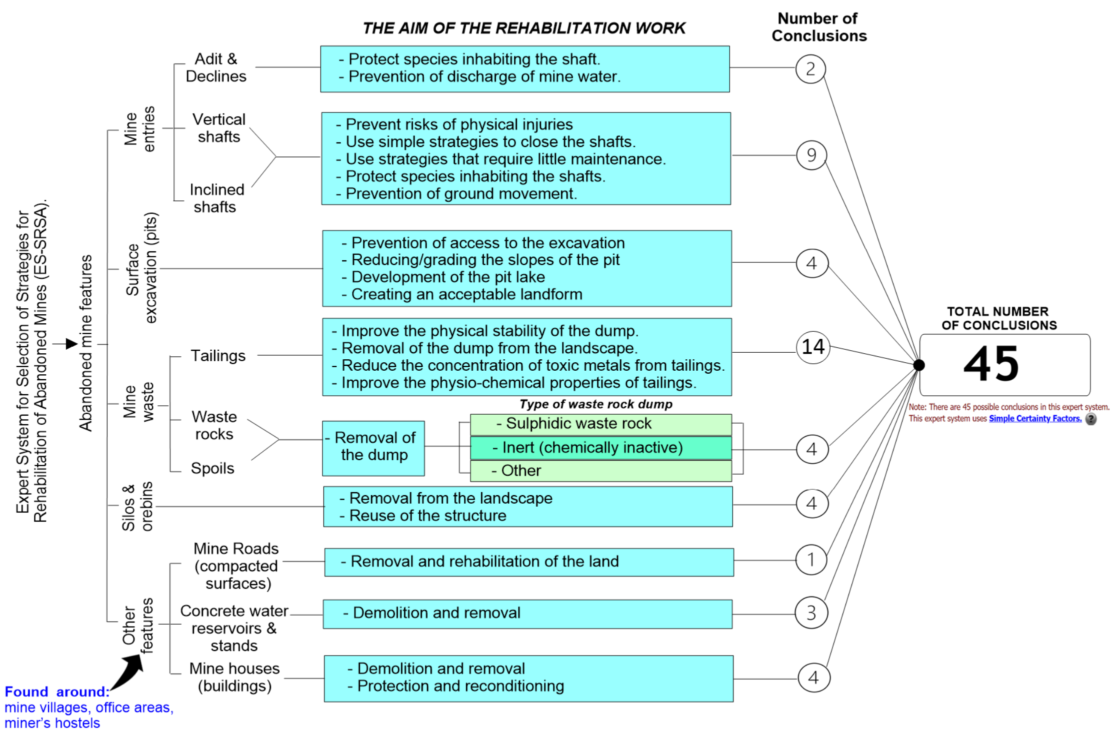

Figure 4. A summarised flow of the rules of the ES-SRSA.

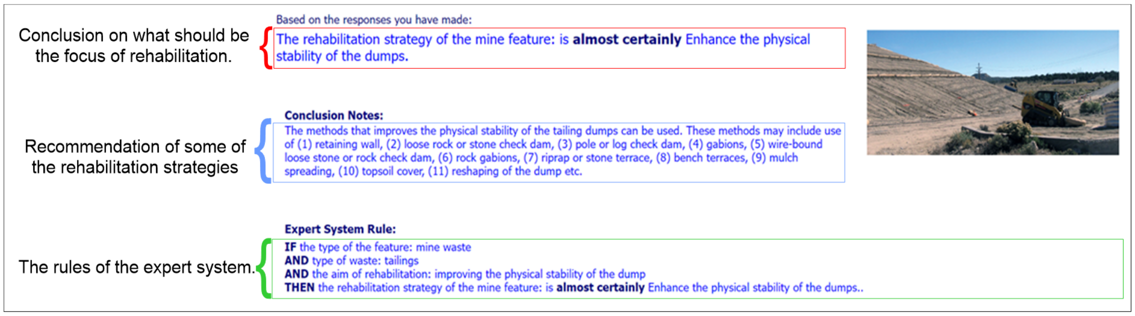

Figure 5. An illustration of the typical conclusion page of the developed ES-SRSA.

5. Discussion

Among the many problems of dealing with the problems of abandoned mines is that their rehabilitation is always done with limited resources (mostly financial and human resources). The problem of lack of relevant mine closure and rehabilitation skills, also required in the implementation of the rehabilitation of abandoned mines is a serious concern suspected to be contributing to the improper closure of mines (including abandoned mines) in South Africa [28]. For example, some of the mines that were reported rehabilitated in South Africa were found to be not properly rehabilitated to address all their environmental risks [25]. The use of inappropriate rehabilitation strategies can, among other contributing factors, be associated with improper rehabilitation of abandoned mines to remove their environmental hazards. With the use of expert systems to support decision-making in abandoned mines rehabilitation projects, some of these problems can be prevented. Some expert systems that assist in different aspects of abandoned mines and their rehabilitation were reported by researchers like Duszak *et al.* [12], Lee *et al.* [15], and Mhlongo *et al.* [13]. These systems are AMHAZ and ES-RAME developed to assist in the ranking of abandoned mines for rehabilitation and the AMGIS developed for the management of the dangers of abandoned coal mines in South Korea. In addition to these expert systems, the expert system known as ARDx [14] also has a great potential for successful use in the rehabilitation of abandoned mine lands contaminated by acid mine drainage (AMD) or acid rock drainage (ARD).

The ES-SRSA reported in this article was designed to aid in the selection of rehabilitation strategies for abandoned mines. Just like any other expert system, it is not a panacea to all the problems of rehabilitation of abandoned mines. It only assists in finding appropriate rehabilitation strategies for these mines. About 60% (28 out of 45 conclusions) of the conclusions of this expert system recommend addressing the problems of abandoned mines by repurposing their features through adaptive reuse and/or reuse potential (see Figures 6a and b). In this case, “reuse potential” refer to the measure of the ability of material from a structure or building (e.g. bricks) to retain its functionality at the end of its primary life. On the other hand, “adaptive reuse” is when part or the whole structure or building is upgraded to meet the requirement of a new alternative use [29]. The rules of the ES-SRSA, in this case, recommend rehabilitation approaches that support adaptive reuse (13%) and reuse potential (47%).

The advice or recommendations of the expert system for ES-SRSA promotes the approach of rehabilitation that prioritizes reuse, recycling, and repurposing actions. This is contrary to the traditional rehabilitation approach for abandoned mines that put more emphasis on addressing the environmental and physical hazards of these mines without looking deeply at the opportunities that these mines present. Although the costs of repurposing abandoned mines are not certainly known [30], most researchers agree that this approach to closing the mine sites offers several benefits that have the potential of helping the communities sustain good social and economic status after the mines have been closed. For example, many mine sites (including abandoned mine sites) in the world have been successfully reused or repurposed for tourism and recreational purposes, wildlife habitat, agricultural and fisheries use, energy/electricity generation, and other businesses that help boost the economic status of the host communities [31], [32].

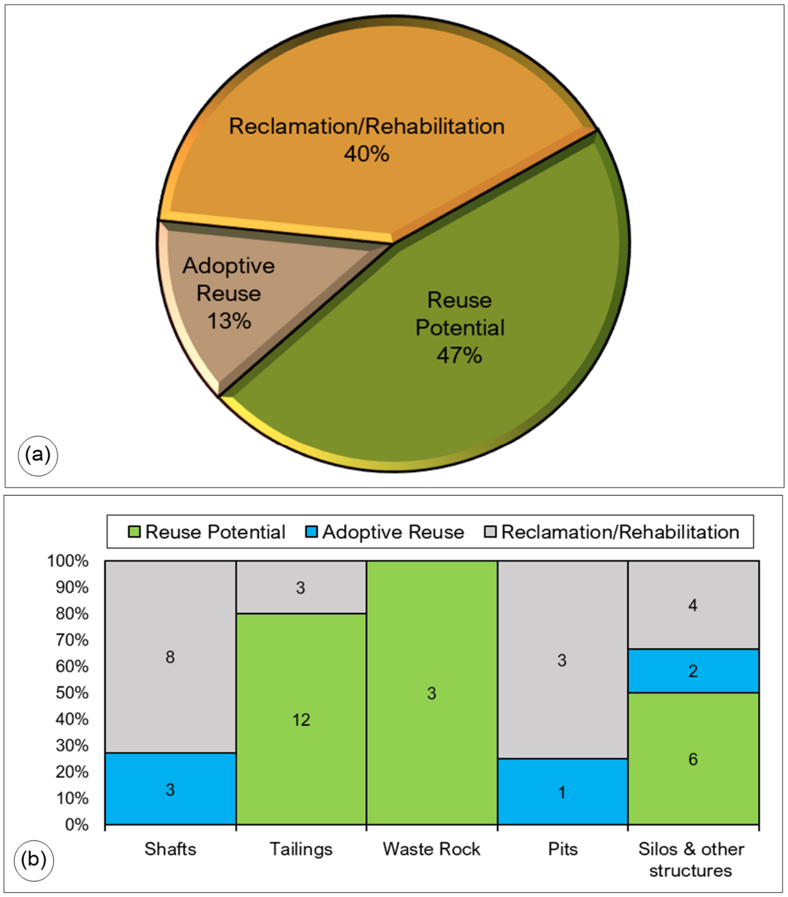

Figure 6. Distribution of the final conclusions of the ES-SRSA.

The ES-SRSA was developed to help decision-making, not to replace human experts. In view of this, it can be considered a supplementary tool that helps in the selection of appropriate rehabilitation strategies for abandoned mines. The significance of such an expert system is justified by the fact that in many counties (including South Africa) there is a shortage of experienced experts in mine closure and rehabilitation [33], [34]. Some of the important benefits of the ES-SRSA are that it can be used to:

- Support or improve decision-making on the selection of strategies for the rehabilitation of abandoned mines,
- Help non-experts and less experienced mine closure specialists to make sound decisions about the appropriate rehabilitation strategies for abandoned mines, and
- The ES-SRSA is available on the Internet[1], which makes it easily accessible to users.

6. Conclusions

This paper presented a web-based expert system developed using an ES-builder shell to help with the selection of suitable strategies for the rehabilitation of abandoned mines. Such an expert system is known as ES-SRSA. Many of its rules recommend reuse, in the form of adaptive reuse and and reuse potential of the major abandoned mine features like shafts, tailings and waste rocks, surface mine pits, and other structures (including silos and dilapidated buildings). The reuse of abandoned mines has the potential of contributing to the economic development of the host communities. The use of this expert system is expected to improve the accuracy of selecting appropriate rehabilitation strategies for abandoned mines, thus, reducing the problem of ineffective rehabilitation of these mines. Moreover, it should be noted that although the ES-SRSA was developed based on the situation of abandoned

1 http://www.mcgoo.com.au/esbuilder/viewer/viewES.php?es=c5597a3b2dded56971ccbc6459ee444d

mines in South Africa, it can be used anywhere in the world as guided by the aims and objectives of the abandoned mines rehabilitation program.

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Conflict of Interest

The authors declare that they are aware of no conflict of interest.

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یک سیستم خبره مبتنی بر قانون برای انتخاب استراتژی‌های احیا برای معادن متروکه در آفریقای جنوبی

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چکیده:

آفریقای جنوبی دارای 6100 معدن متروکه است. دولت مسئول مدیریت و احیای این معادن برای رسیدگی به مشکلات زیست محیطی، مخاطرات فیزیکی و مسائل اجتماعی-اقتصادی آنها است. به طور کلی، احیای معادن متروکه مستلزم اتخاذ یک سری تصمیمات حیاتی در مورد استراتژی‌هایی است که در احیای ویژگی‌های اصلی این معادن باید اجرا شود. این مقاله یک سیستم خبره را ارائه می‌کند که برای کمک به انتخاب استراتژی‌های مناسب برای بازسازی معادن متروکه در آفریقای جنوبی ایجاد شده است. این سیستم به سیستم خبره برای انتخاب راهبردهای احیا معادن متروکه (ES-SRSA) معروف است. ES-Builder (نسخه 3,0، نرم افزار McGoo) برای طراحی دانش و اجزای مبتنی بر قوانین سیستم خبره استفاده شد. قوانین سیستم‌های خبره بر اساس دانش مستند از مشکلات معادن متروکه در آفریقای جنوبی و اطلاعات جمع آوری شده توسط محقق از طریق بازدید از سایت‌های منتخب معادن متروکه در کشور تدوین شده است. ES-SRSA 45 توصیه از استراتژی‌های مناسب را برای مقابله با مشکلات مختلف ویژگی‌هایی مانند ورودی‌های زیرزمینی، زباله‌های معدن، حفاری‌های سطحی معادن، سیلوها و سنگ‌ساخت‌ها و سایر ویژگی‌ها مانند ساختمان‌ها/زیرساخت‌های فرسوده ارائه می‌کند. اکثر قوانین این سیستم خبره استفاده مجدد و استفاده مجدد از این ویژگی های معدن را برای بهبود وضعیت اجتماعی و اقتصادی جوامع میزبان تشویق می‌کند. استفاده از این سیستم خبره این پتانسیل را دارد که به کاهش خطرات ناشی از اجرای استراتژی‌های ناکارآمد برای احیای معادن متروکه در کشوری مانند آفریقای جنوبی کمک کند.

کلمات کلیدی: سیستم خبره، معادن متروکه، راهبردهای احیا، ES-builder.