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# COMPREHENSIVE METHOD FOR ESTIMATING THE TIME AND EXPENDITURES REQUIRED FOR MINE LIQUIDATION PROCESSES OF BUSINESS PROCESSES

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**Abstract:**
The European Green Deal (EU Green Deal) has set the direction for the EU's energy transition towards climate neutrality by 2050. In Poland, this means moving away from the extraction and use of coal. The Social Contract for the Mining Industry signed in 2021 states the necessity of last mine closure by 2049. Mine closure is a complex, lengthy and costly process. A complex scientific solution may concern the use of rational operations and minimization of mine closure costs. This article presents a system for the elementary assessment of the potential time and cost of coal mine liquidation. Estimating coal mine closure costs in the early design phase is an key aspect of supporting the company dealing with mine closure. The aim of the research was to improve the tool for assessing mine liquidation price. The extended assessment solution proposed in the article is formed on base of statistics of past mining institution liquidation processes. This method can, with minor modifications, be used for each restructuring and revitalizing task for mining industries in the process of liquidation. At the core of the developed method is a preliminary data analysis, which should be confirmed by a complex and multi-criteria estimation of the costs of the planned mine liquidation.

***Key words:*** *cost management, restructuring of mining companies, liquidation of a mine, decision-making, multi-criteria analysis*

## INTRODUCTION

In order to reach climate neutrality, European Union countries should make ready to stop using fossil fuels [1, 2, 3]. One of the ways to restructure the mining industry is to liquidate profitless mining plants. Measures to restructure, revitalize or liquidate the mining sector in Poland are stretched over several decades and are the outcome of European Union strategy [4, 5, 6]. The closure of the mine is the final, natural, and unavoidable phase of mining activities [7, 8, 9, 10]. Nevertheless, the literature scarcely addresses issues concerning mine closure and subsequent post-closure activities [11, 12, 13, 14]. The moment active mining operations have ended, abandoned mine infrastructure can hinder the ability to develop mining assets [15, 16, 17, 18,]. Minimizing the capital costs associated with decommissioned coal mines is a challenge for the mining industry has faced since the industry's restructuring processes began at the turn of the century [19, 20, 21]. The prudent allocation of funds for the efficient management of post-mining areas has yet to be thoroughly studied in scientific research [22, 23, 24]. Carrying out mine liquidation is highly complex and expensive due to the extensive amount of work involved [25, 26, 27]. A key factor hindering improvements in liquidation efficiency is the absence of instruments and tools for cost management support [21, 22, 28, 29]. There are few available studies in this area and they cover only selected issues [19, 30, 31, 32]. The research aimed to enhance the current tool for evaluating mine liquidation costs by adding new features and increasing the accuracy of cost estimation. The method presented in the publication estimates liquidation costs on the basis of an analysis of the volume of selected parameters of the mine being

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decommissioned or the amount of selected partial costs, the total cost or all these functions together [26].

## LITERATURE REVIEW

In a fast-paced and competitive economic landscape, a company's success depends on modern management and the implementation of methods that enhance business performance and efficiency [4, 14]. The situation is similar in mining activities. The mining of fossils always leads to adverse environmental changes. These issues arise both during the active extraction period and continue for many years after it concludes [11, 18]. The closure of mines is regulated in Chapter 5 of the Geological and Mining Law of 9 June 2011.

Spółka Restrukturyzacji Kopalń S.A. (Mines Restructuring Company – SRK S.A.) is a mining company (Journal of Laws of 2018, item 1374, as amended) that, among other things, clears post-mining areas from redundant, unmanageable infrastructure. It also supervises and manages the assets left behind after mining plants under liquidation [2, 13, 34]. The management of the assets of mining plants placed in liquidation requires significant support from the state budget [3, 33, 35]. Since 2015, the total cost of liquidating the 19 mines under SRK S.A. reached approximately PLN 6 billion by the end of 2023. On average, the cost of decommissioning each branch is around PLN 300 to 350 million. The challenge of reducing the capital intensity of closed coal mines impacts both the mining communities and the state budget.

The expenses required for the liquidation of a specific mining plant vary significantly because each case is unique, yet some patterns can still be observed [6, 36, 37]. Recently, the concept of process management has become a leading and evolving approach in economic theory and practice for company management, including in mining enterprises [27, 28]. Process management at SRK S.A. also requires further research and development. Comprehensive research to enhance the economic efficiency of mine liquidation has not yet been conducted, with existing literature only addressing general issues [2, 6]. One factor hindering improvements in liquidation efficiency is the lack of instruments and tools to support cost management. Most developed solutions focus on selected aspects related to mining process efficiency or preparatory works. [13, 33]. This research will aim to develop procedures for implementing the management process. The lack of available literature makes the research process difficult.

The purpose of the research was to develop a comprehensive, updated, revised and more accurate method for preliminary assessment of the time and expenditures required to implement mine liquidation. It relied on a limited set of criteria describing the characteristics of mines undergoing liquidation [26, 40] and the amount of individual component costs. The presented publication proposes a tool to support cost management and identifies areas and research problems requiring further analysis. The method can support the team of professionals designing the liquidation of a mine or part of it [4, 12, 40]. When crafting the approach, a degree of functional resemblance among the analyzed mining facilities was taken into account. [42, 43, 44]. Such an assumption in the preliminary assessment should not affect the usefulness of the method. The information obtained will make it possible, already at the very preliminary design stage, to determine the expected time frame of implementation and the estimated financial scope of the planned project [11, 36, 41]. The methodology, instrument, and findings outlined will serve as the groundwork for future studies aimed at enhancing the effectiveness of procedures conducted in any organization engaged in the restructuring, revitalization, and closure of mines [26, 30].

## RESEARCH METHODS

The study enhanced the precision, consolidation, and expansion of the functional range of previously developed tools for the preliminary assessment of time and required expenses for executing the proposed mine closure task [26, 40, 42]. The research methodology was executed based on statistical analysis of mine closure tasks completed or underway by SRK S.A. between 2015 and 2023. Data pertaining to completed mine closures from 2015 to 2022 were extracted from periodic reports of branch activities submitted to the Company's Management Board. Information for 2023 was derived from monthly progress reports for the first ten months of the year (subject to slight adjustments for the annual report).

The aim of the methodology was to approximate mine closure costs utilizing knowledge of various parameters characterizing the closed mine site and/or the value of selected component process expenses of closure. The initial phase involved reviewing literature thematically linked to post-mining site and facility restructuring. Findings indicated that during the initial stages of designing a new mine closure task, it was feasible to roughly estimate implementation duration and expenses for individual component processes based on rudimentary information [26, 40, 42]. Consequently, a statistical approach for estimating closure time and cost by major tasks was proposed.

Following the proposal of a preliminary version of the comprehensive, updated, and expanded methodology, the subsequent step was to verify the tool's accuracy. This involved comparing estimated costs from the methodology with actual closure process expenses. The design phase concluded upon achieving acceptable estimation precision. Additionally, an expert opinion survey was conducted among SRK S.A.'s engineering and technical personnel, who possess experience in managing closure and post-mining asset processes, to further validate the methodology. Face-to-face interviews with experts confirmed the validity of estimation results and provided insights into reasons for significant deviations from anticipated values. The research identified new areas and research challenges for future exploration.

## RESULTS AND DISCUSSION

### Approach for preliminary estimation of mine closure duration and expenses features of mine closure procedures

In formulating the assumptions for enhancing the existing tool with new functionalities, the authors scrutinized the programs and closure plans of 19 mines spanning from 2015 to 2023. This examined group comprised 15 mines already closed and 4 mines or their distinct sections undergoing closure (www.srk.com.pl). The analyzed pool of closed mines exhibits considerable diversity. Closure typically spans an average of 5 years (ranging from 2 to 8 years). Closure expenses vary widely, ranging from approximately 20 to 990 million PLN. This divergence is attributed to the extensive and diverse array of challenging, at times hazardous, and capital-intensive tasks required during the process. The duration and expenses of each closure process typically hinge on factors such as the number, size, and nature of facilities being closed. Closure duration is influenced by the logical sequence of facility closure, the duration of tender processes, and demolition techniques employed.

At SRK S.A., mine closure processes are categorized into 10 sub-processes guided by principles of process management [40, 42, 45]. Each process outlined in Figure 1 encompasses its unique set of operations and tasks. Mine closure typically follows two approaches. In cases where neighboring mines need protection, the entire mine may be closed, or it may be closed except for the pumping station [37, 42].

When closing a mine except for the pumping station, all underground infrastructure is dismantled except for essential shafts and excavations repurposed as a pumping station. Conversely, when there's no need to safeguard adjacent mines, the entire underground infrastructure (pits and shafts) is closed, leaving only surface infrastructure facilities that can be developed [37, 42].

### Method for preliminary estimation of time and cost of mine liquidation

In the calculation, when selected parameters of the liquidated mine and/or the known expenditures of the selected component processes are provided, the method returns the estimated total liquidation cost, the costs of the remaining component processes and the correlating potential time of implementation [46, 47]. The method assigns the mine to one of the accepted groups, based on the entered values of the original estimation parameters or the value of the known costs of the component processes [26, 48]. Then, it estimates the predicted period and cost of liquidation.

In order to enhance the coherence of component liquidation cost structures, the suggestion was made to categorize liquidated mines into 5 groups. To establish these reference groups, an examination of the variation structure of component process costs was conducted utilizing the coefficient of variation. [36, 37, 38]. The mines were divided into Very Large mines (VLM), Large mines (LM), Medium Mines (MM), Small Mines (SM) and a group of Very Small Mines (VSM) [36, 37, 38].

As per the suggested method, computational algorithms have been formulated using Microsoft Excel. Within the software interface of the method, descriptive fields are represented by areas with a white background. Input or decision-making fields (fields A, B, C, D, and E in Figure 2) are distinguished by cells highlighted in light brown. Result fields, where the method furnishes estimated liquidation time and cost outcomes, are highlighted in light blue. The layout of the tool's interface is illustrated in Figure 2.

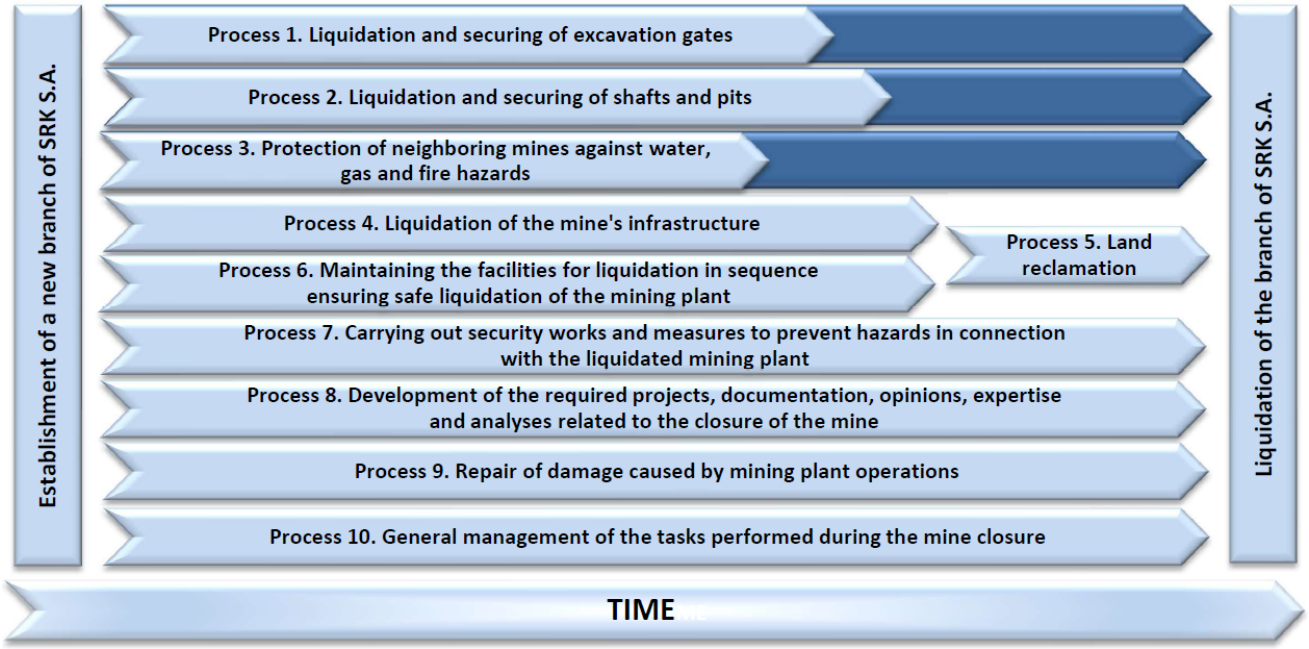


***Fig. 1 Timeline of the component processes of mine liquidation***
*Source: SRK S.A. data.*

| Enter data | Evaluation parameters | | Expected cost of liquidation [mln PLN] | Check if you accept | Expected time of liquidation [years] |
|---|---|---|---|---|---|
| A | Total lenght of excavations | [m] | | No | |
| | Volume of all mine shafts | [m3] | | No | |
| | Number of liquidated facilities | [items] | | No | D |
| | Single-criteria average | | | No | |
| | **Multi-criteria** | | | No | |
| | Enter the maximum expenditure | | B | | |
| | Suggested mine size | | VSM - very small mine | MM | E |
| C | Process 1 (liquidation of excavations) | | 0 | | |
| | Process 2 (liquidation of shafts and pits) | | 0 | | VLM - very large mine |
| | Process 3 (securing of neighbouring mines) | | 0 | | LM - large mine |
| | Process 4 (liquidation of surface facilities) | | 0 | | MM - medium mine |
| | Process 5 (land reclamation) | | 0 | | SM - small mine |
| | Process 6 (maintenance of surface facilities) | | 0 | | VSM - very small mine |
| | Process 7 (securing of liquidated mine) | | 0 | | |
| | Process 8 (projects, expertise etc.) | | 0 | | |
| | Process 9 (mining damage) | | 0 | | |
| | Process 10 (general management) | | 0 | | |
| | Sum | | **0** | | |

***Fig. 2 Interface design of the tool for predicting the costs associated with executing the closure processes of a mining site***

Using this method, it is possible to carry out a forecast of the amount of costs and time of liquidation by:

- entering of the values of selected parameters that characterize the liquidated mining plant (field – A in Figure 2),
- entering the total cost of closure (field B in Figure 2),
- entering the amount of the costs of 1 up to 9 component processes of mine liquidation (field C in Figure 2),
- detailing the estimation by simultaneously applying the above 2 options (fields A + C or fields B + C in Figure 2).

**Determination of the cost and time of liquidation based on selected parameters of the liquidated mine**

Based on previous research, it was determined that parameters which are most correlated with the cost and time of mine liquidation [26] are the characteristics described in Table 1.

***Table 1***

***Adopted parameters for the method of estimating the time and cost of mine liquidation***

| Partial evaluation parameter | Parameter weight |
|---|---|
| Total length of underground excavations | 0,316 |
| Volume of all mine shafts | 0,421 |
| Number of facilities to be liquidated | 0,263 |

*Source: [26].*

These parameters were assigned corresponding weights affecting the final assessment (Table 1). They ought to be gathered when determining the decision to close the mine [26]. The selected evaluation parameters partially reflect 3 of the 10 component processes of the mine liquidation task (processes 1, 2 and 4), and at the same time all processes are related exclusively to the physical liquidation of the mine (Fig. 3). The group of evaluation parameters did not include, for example, references to employment or areas to be reclaimed because their impact on the amount of costs and time of mine liquidation could not be mathematically determined [2, 3, 30, 31].

After entering the data in Field A in Figure 2, the tool presents the results determined under single criteria by each of the component evaluation parameters, and below it yields the average value for the single criteria results.

| Enter data | Evaluation parameters | | Expected cost of liquidation [mln PLN] | Check if you accept | Expected time of liquidation [years] |
|---|---|---|---|---|---|
| 53009 | Total lenght of excavations | [m] | 802 | No | 4,8 |
| 19627 | Volume of all mine shafts | [m3] | 1147 | No | 6,8 |
| 199 | Number of liquidated facilities | [items] | 1141 | No | 6,8 |
| | Single-criteria average | | 1030 | No | 6,1 |
| | **Multi-criteria** | | **836** | Yes | **7,3** |
| | Enter the maximum expenditure | | | | |
| | Suggested mine size | | VLM - very large mine | MM | |
| | Process 1 (liquidation of excavations) | | 4 | | |
| | Process 2 (liquidation of shafts and pits) | | 34 | | VLM - very large mine |
| | Process 3 (securing of neighbouring mines) | | 1 | | LM - large mine |
| | Process 4 (liquidation of surface facilities) | | 32 | | MM - medium mine |
| | Process 5 (land reclamation) | | 18 | | SM - small mine |
| | Process 6 (maintenance of surface facilities) | | 150 | | VSM - very small mine |
| | Process 7 (securing of liquidated mine) | | 235 | | |
| | Process 8 (projects, expertise etc.) | | 8 | | |
| | Process 9 (mining damage) | | 168 | | |
| | Process 10 (general management) | | 185 | | |
| | Sum | | **836** | | |

***Fig. 3 Estimation of mine liquidation time and the amount of costs of liquidation processes on the basis of selected parameters of the liquidated mine***

Below, the technique combines all three component parameters, employing a quotient transformation per Equation 1, to allocate the examined set of component parameters to the relevant mine reference group. Once within the reference group, the method then predicts the anticipated liquidation time and the designated value of liquidation expenses [43, 48].

$$WK_j = \sum_{i=1}^{3} w_i \frac{h_{ij}}{h_{i\,max}}, \quad (1)$$

where:

$WK_j$ - multi-criteria value of component evaluation parameters for mine "*j*" ,

$w_i$ - the weight of the component evaluation parameter "*i*",

*i* - the number of the component evaluation parameter,

*j* - the number of the analyzed mine,

$h_{i\,max}$ - the largest value of the component evaluation parameter "*i*",

$h_{ij}$ - the value of the analyzed component evaluation parameter "*i*" for mine "*j*".

**Determination of cost and time of liquidation based on the given maximum cost of mine liquidation**

An alternative way of conducting the forecast shown in Figure 4 is to calculate the costs of individual processes by using the total cost of liquidation (Field B in Figure 2) as a reference point. By analyzing the expenditures, the method predicts the most probable duration of the liquidation processes and the size of the mine, based on the entered total cost. As before, the estimation is generated only after the user enters the accepted size of the mine to be liquidated (Field E in Figure 2).

| Enter data | Evaluation parameters | | Expected cost of liquidation [mln PLN] | Check if you accept | Expected time of liquidation [years] |
|---|---|---|---|---|---|
| | Total lenght of excavations | [m] | | No | |
| | Volume of all mine shafts | [m3] | | No | |
| | Number of liquidated facilities | [items] | | No | |
| | Single-criteria average | | | No | |
| | **Multi-criteria** | | | No | |
| | Enter the maximum expenditure | | **840** | | **7,2** |
| | Suggested mine size | | VLM - very large mine | VLM | |
| | Process 1 (liquidation of excavations) | | 13 | | |
| | Process 2 (liquidation of shafts and pits) | | 29 | | VLM - very large mine |
| | Process 3 (securing of neighbouring mines) | | 106 | | LM - large mine |
| | Process 4 (liquidation of surface facilities) | | 46 | | MM - medium mine |
| | Process 5 (land reclamation) | | 19 | | SM - small mine |
| | Process 6 (maintenance of surface facilities) | | 121 | | VSM - very small mine |
| | Process 7 (securing of liquidated mine) | | 317 | | |
| | Process 8 (projects, expertise etc.) | | 8 | | |
| | Process 9 (mining damage) | | 59 | | |
| | Process 10 (general management) | | 120 | | |
| | Sum | | **840** | | |

***Fig. 4 Estimation of mine liquidation time and the amount of component costs of liquidation processes based on the total cost of mine liquidation***

In Figure 4, for example, 840 million was entered as the total cost and a group of very large mines was chosen. On this basis, the method estimated the potential amount of component costs of liquidation processes.

**Determination of liquidation costs and time based on selected component processes of mine liquidation**

In the tool variant shown in Figure 5, the user (in Field C in Figure 2) enters from one to nine estimated component costs of the liquidation processes for calculation.

| Enter data | Evaluation parameters | Expected cost of liquidation [mln PLN] | Check if you accept | Expected time of liquidation [years] |
|---|---|---|---|---|
| | Total lenght of excavations [m] | | No | |
| | Volume of all mine shafts [m3] | | No | |
| | Number of liquidated facilities [items] | | No | |
| | Single-criteria average | | No | |
| | **Multi-criteria** | | No | |
| | Enter the maximum expenditure | | | |
| | Suggested mine size | VLM - very large mine | VLM | |
| | Process 1 (liquidation of excavations) | 12 | | |
| | Process 2 (liquidation of shafts and pits) | 26 | | VLM - very large mine |
| 33 | Process 3 (securing of neighbouring mines) | 33 | | LM - large mine |
| | Process 4 (liquidation of surface facilities) | 41 | | MM - medium mine |
| 6 | Process 5 (land reclamation) | 6 | | SM - small mine |
| | Process 6 (maintenance of surface facilities) | 107 | | VSM - very small mine |
| 355 | Process 7 (securing of liquidated mine) | 355 | | |
| | Process 8 (projects, expertise etc.) | 7 | | |
| | Process 9 (mining damage) | 53 | | |
| 146 | Process 10 (general management) | 146 | | |
| | Sum | **785** | | |

***Fig. 5 Estimation of mine liquidation time and the amount of costs of liquidation processes based on the amount of costs of selected component processes of mine liquidation***

The proposed method utilizes the input values to statistically determine the most probable classification of the analyzed mine into one of the reference groups. Upon entering the initial value, a likely reference group is identified through single-criteria analysis based on the component liquidation cost. As additional component values of liquidation costs are added, membership to a reference group is established via multi-criteria analysis [43, 49]. This enhances the precision of assigning liquidation tasks to the appropriate group. The user's selection of the correct reference group aids in accurately estimating costs. Due to variations in the scope of activities, each reference group has a slightly different cost structure. If the user disagrees with the estimation result for a particular reference group, they can opt to apply the correct liquidation scope determined by another reference group [38]. The user-entered component cost value is mirrored in the result field as the base value. Considering the input values, the method statistically approximates the size of the remaining component liquidation costs beyond those already entered. The final row indicates the total mine liquidation cost, comprising the sum of entered costs and the averaged estimated values of the remaining component costs [38, 50, 51]. Including the value of each successive component process heightens the accuracy of estimating the remaining component costs and the total cost. Users can input between 1 to 9 known component process costs out of a possible 10. Although it's technically feasible to input ten component costs, such an instance doesn't yield a cost forecast. For instance, in Figure 4 (in Field C in Figure 2), previously estimated values of component processes 3, 5, 7, and 10 were entered. After determining that the studied mine belongs to the category of very large mines, the method proposed potential amounts of the remaining component costs and the probable total cost of mine liquidation. Forecasting the mine's liquidation time entails copying the estimated liquidation cost from the last row to Field B in Figure 2.

**Improving the accuracy of the conducted forecast of mine liquidation costs.**

Knowing the selected component costs of the designed liquidation task, it is possible to increase the accuracy of the forecast obtained on the basis of the selected features of the mine being liquidated or the total cost of liquidation (Field C in Figure 2). The method determines the remaining component costs to be consistent with either the total cost of liquidation entered by the user (Field B in Figure 2) or the forecast obtained based on the distance of mine excavations, the size of shafts, and the amount of objects to be liquidated (Field A in Figure 2). In Figure 6, for example, the basic features of the mine to be liquidated (Field A in Figure 2) were entered, accepting the multi-criteria evaluation of these parameters (in field D in Figure 2) and giving the known values of the costs of processes 3, 5, 7, and 10 (field C in Figure 2).

| Enter data | Evaluation parameters | Expected cost of liquidation [mln PLN] | Check if you accept | Expected time of liquidation [years] |
|---|---|---|---|---|
| 53009 | Total lenght of excavations [m] | 802 | No | 4,8 |
| 19627 | Volume of all mine shafts [m3] | 1147 | No | 6,8 |
| 199 | Number of liquidated facilities [items] | 1141 | No | 6,8 |
| | Single-criteria average | 1030 | No | 6,1 |
| | **Multi-criteria** | **836** | Yes | **7,3** |
| | Enter the maximum expenditure | | | |
| | Suggested mine size | VLM - very large mine | VLM | |
| | Process 1 (liquidation of excavations) | 14 | | |
| | Process 2 (liquidation of shafts and pits) | 31 | | VLM - very large mine |
| 33 | Process 3 (securing of neighbouring mines) | 33 | | LM - large mine |
| | Process 4 (liquidation of surface facilities) | 49 | | MM - medium mine |
| 6 | Process 5 (land reclamation) | 6 | | SM - small mine |
| | Process 6 (maintenance of surface facilities) | 130 | | VSM - very small mine |
| 355 | Process 7 (securing of liquidated mine) | 355 | | |
| | Process 8 (projects, expertise etc.) | 9 | | |
| | Process 9 (mining damage) | 64 | | |
| 146 | Process 10 (general management) | 146 | | |
| | Sum | **836** | | |

***Fig. 6 Enhancing the precision of estimating the duration and expenses associated with liquidation procedures through the comprehensive assessment of chosen parameters of the closed mine and the expenditure levels of selected component processes.***

The estimation was obtained assuming that the mine belongs to the very large mines (field E in Figure 2).

**DISCUSSION AND VERIFICATION OF THE PRESSENTED METHOD**

The verification of the accuracy of the designed algorithms of the method was carried out in two ways. In both cases, the forecast estimated on the basis of data taken from 19 liquidation processes carried out in reality was compared with the actual task completion time and actually incurred liquidation costs. In some cases, the estimation of liquidation time according to the algorithms of the proposed method yielded very good results. This occurred with:

- estimation based on the distance of excavations, the size of shafts and the amount of liquidated facilities, when the forecast was made for a combined multi-criteria analysis of these parameters;
- estimation based on the total cost of liquidation;
- estimation based on the value of the components costs of liquidation, when the processes that always occur during liquidation were analyzed.

In these cases, the estimated liquidation time coincided with actual implementation and did not exceed 1 year. Slightly inferior results were given by single-criteria estimations based on the length of excavations, the volume of shafts or the number of liquidated facilities or based on optional components of liquidation processes. Increasing the number of data analyzed increased the validity of the estimation.

In 2 cases of estimating the time of mine liquidation, the forecast determined a significantly shorter time for their liquidation. After analyzing the documents and obtaining expert opinions, it was determined that this occurred for mines where the liquidation time was artificially extended for reasons of protecting nearby active mines. The accuracy of the method's estimation obtained was considered sufficient for the initial stages of potential design work for mine liquidation.

The validation of liquidation expenses followed a similar procedure. Through forecasting based on the analysis of specific attributes of the closed mine, it was determined that factors such as excavation length, shaft volume, and surface facility count should be considered via a multi-criteria evaluation. These parameters, constituting components of liquidation processes 1, 2, and 4, collectively account for approximately 11% of the funds allocated to mine closure. The remaining 89% of the closure cost is influenced by the effective execution of processes 1, 2, and 4 [36, 37, 38, 40]. Across all mines and mine groups except for medium-sized mines (MM), the median deviation of the estimated value from the actual value did not exceed 25% (Table 2). The largest discrepancies were observed in the category of medium-sized mines (MM), where the median deviation reached approximately 50%.

***Table 2***

***Median forecast of total liquidation costs determined according to various aspects in relation to their actual value by mine size***

| The aspect of mine liquidation | | ALL | VLM | LM | MM | SM | VSM |
|---|---|---|---|---|---|---|---|
| Total length of excavations | [m] | 100% | 104% | 76% | 153% | 71% | 100% |
| Volume of all mine shafts | [$m^3$] | 110% | 136% | 92% | 170% | 100% | 100% |
| Number of liquidated facilities | [items] | 100% | 136% | 121% | 144% | 92% | 100% |
| Single-criteria average | | 119% | 123% | 108% | 137% | 87% | 100% |
| **Multi-criteria** | | 100% | 100% | 99% | 123% | 91% | 100% |
| VLM - very large mine, LM - large mine, MM - medium mine, SM - small mine, VSM - very small mine | | | | | | | |
| | | | | | From 75% to 125% | | |

Upon comparing the liquidation costs derived from the closure practice of all 19 analyzed mines with the cost estimates generated by the proposed method, three instances emerged where the outcomes diverged from reality. Documentation analysis (including liquidation plans and programs), statistical assessment, and expert interviews (with individuals overseeing liquidation processes) revealed that these three cases stood out from the rest. Experts attributed this deviation to the unique extent of the implemented liquidation activities. As for the inconsistencies observed in other mining facilities, they stemmed from the atypical progression of the liquidation component process itself.

The subsequent step in validating the cost estimates involved comparing estimates derived from the values of liquidation process component costs. The method yielded the most accurate estimations for the total liquidation cost and the costs associated with executing processes 2, 4, 5, and 8, particularly for medium (MM), large (LM), and very large (VLM) mine groups. As an illustration, Table 3 showcases the results of total liquidation cost estimates. In most instances, median deviations from comparative values did not exceed 25%. Such consistency was observed across the entire group of mines undergoing liquidation (ALL). Slightly less favorable outcomes were noted within the reference groups. Perfect alignment was achieved solely within the very small mines (VSM) group. This outcome can be attributed to the fact that this group comprises only one example of completed liquidation, serving as the benchmark.

***Table 3***

***Median forecast of total liquidation costs determined according to various component processes in relation to their actual value grouped by mine size***

| Component process of liquidation | ALL | VLM | LM | MM | SM | VSM |
|---|---|---|---|---|---|---|
| Process 1 (liquidation of excavations) | 124% | 89% | 143% | 107% | 132% | 100% |
| Process 2 (liquidation of shafts and pits) | 119% | 121% | 164% | 40% | 107% | 100% |
| Process 3 (securing of neighboring mines) | 85% | 86% | 79% | 80% | 98% | 100% |
| Process 4 (liquidation of surface facilities) | 86% | 64% | 93% | 98% | 85% | 100% |
| Process 5 (land reclamation) | 89% | 166% | 85% | 82% | 98% | 100% |
| Process 6 (maintenance of surface facilities) | 80% | 127% | 73% | 77% | 108% | 100% |
| Process 7 (securing of liquidated mine) | 111% | 87% | 126% | 107% | 101% | 100% |
| Process 8 (projects, expertise, etc.) | 114% | 122% | 100% | 135% | 114% | 100% |
| Process 9 (mining damage) | 103% | 111% | 85% | 150% | 84% | 100% |
| Process 10 (general management) | 95% | 87% | 97% | 99% | 109% | 100% |
| VLM - very large mine, LM - large mine, MM - medium mine, SM - small mine, VSM - very small mine | | | | | | |
| | | | | | From 75% to 125% | |

Positive cost estimation outcomes were linked to component processes that were consistently present across all analyzed cases, with the most accurate results observed for processes constituting the largest proportion of the total cost (processes 6, 7, and 10). These processes exert a significant influence on the total cost,

accounting for roughly 70% of it. By accurately estimating the total cost and the cost of these major component processes, the estimated results closely align with actual figures. Conversely, estimating based on processes that may or may not occur during mine liquidation (optional processes 3, 5, and 9) yielded the largest disparities from reality, with some cases unable to produce a forecast. This occurred, for instance, when the entered value of a process's liquidation cost was zero. While the percentage differences between the estimated and actual costs of processes 1, 2, 3, 4, 5, 8, and 9 may seem substantial, their collective impact on the total cost is minor, comprising only about 20%. Consequently, the discrepancies expressed in PLN are not as significant, and according to experts, such minor deviations, when the major components are accurately estimated, ensure the overall coverage of expenses for the entire mine liquidation process. After excluding these cases from the method's verification, experts deemed the estimation results of components and total liquidation cost based on a single cost value of the component process satisfactory.

The unpublished segment of the study reveals that with each additional data point in the form of component process cost, the accuracy of estimation improved. Optimal results were achieved for estimates based on component cost groups constituting the majority of the total cost and consistently carried out in all liquidation cases. Conversely, as anticipated, the poorest liquidation cost estimation results were obtained for component groups of processes conducted only optionally during liquidation. Considering these limitations, experts deemed the accuracy achieved to be sufficient for this phase of potential design work [38, 39].

The third stage of verification analyzed the example of the liquidation of a very large mine. The costs estimated and assumed in the preliminary stage of the liquidation work of this mine were used as a reference for the forecasts of the unit costs of liquidation. Due to the change in the scope of liquidation, the final cost structure changed and the liquidation of the mine was implemented in a different model. According to experts, the estimation of costs for this mine at the analyzed moment, was carried out correctly, and it is this example that can be used as a comparative example for the estimations generated by the proposed method. Table 4 compares the forecasts of liquidation component costs obtained by single-criteria and multi-criteria estimation based on the distance of excavations, the size of shafts and the amount of surface facilities with the comparative values. In all forecasts, there was a significant overestimation of the costs of processes 3 and 5. This was consistent with the model where, due to the small scope of liquidation, extremely low expenditures were allocated to these processes. The best results were obtained for the multi-criteria evaluation where the difference in total cost was only PLN 4 million lower than the base value (less than 1% of the base cost). Very similar estimation results were obtained for the forecast based on total liquidation cost, which confirms the accuracy of the method's algorithms.

***Table 4***

***Comparison of the estimated amount of liquidation costs determined by the evaluation criteria with the real costs of liquidation of the mine***

| Forecast for | length of excavations | volume of shafts | number of facilities | single-criteria average | multi-criteria | max. expenditure |
|---|---|---|---|---|---|---|
| | % | % | % | % | % | % |
| Process 1 | 86% | 123% | 122% | 110% | 90% | 90% |
| Process 2 | 113% | 162% | 161% | 146% | 118% | 119% |
| Process 3 | 307% | 439% | 437% | 395% | 320% | 322% |
| Process 4 | 60% | 86% | 86% | 78% | 63% | 63% |
| Process 5 | 289% | 413% | 411% | 371% | 301% | 302% |
| Process 6 | 128% | 182% | 182% | 164% | 133% | 134% |
| Process 7 | 85% | 122% | 121% | 110% | 89% | 89% |
| Process 8 | 65% | 92% | 92% | 83% | 67% | 68% |
| Process 9 | 67% | 96% | 95% | 86% | 70% | 70% |
| Process 10 | 79% | 112% | 112% | 101% | 82% | 82% |
| Total | 96% | 136% | 136% | 123% | 100% | 100% |
| | | to 60% | from 80% to 120% | | | above 200% |

Similar to the second stage, the percentage deviation from the baseline value was computed. Table 5 illustrates the deviation of estimated liquidation costs from the base value, calculated after the hypothetical mine under analysis was successively categorized into all reference groups. The forecast exhibited the highest accuracy for very large mines (VLM), primarily due to the alignment of the mine's actual size with the reference group specified by the user. Conversely, the poorest estimation results were observed for small mines (SM). This stemmed from the introduction of excessively high values for the component costs of the liquidation process, leading the method to generate results akin to those of larger reference groups. In this scenario, the deviations of the estimation from the base value did not surpass 40%. However, significant discrepancies were noted for processes 3 and 5, characterized by extremely low values in the model mine.

***Table 5***

***Comparison of the estimated amount of liquidation costs determined for different mine sizes with the real costs of the mine liquidation***

| Forecast for | VLM - very large mine | LM - large mine | MM - medium mine | SM - small mine |
|---|---|---|---|---|
| Process 1 | 90% | 79% | 29% | 57% |
| Process 2 | 118% | 167% | 140% | 299% |
| Process 3 | 320% | 147% | 3% | 0% |
| Process 4 | 63% | 55% | 44% | 72% |
| Process 5 | 301% | 484% | 284% | 0% |
| Process 6 | 133% | 179% | 165% | 362% |
| Process 7 | 89% | 90% | 66% | 37% |
| Process 8 | 67% | 51% | 69% | 82% |
| Process 9 | 70% | 59% | 198% | 42% |
| Process 10 | 82% | 86% | 127% | 133% |
| Total | 100% | 100% | 100% | 100% |
| | to 60% | from 80% to 120% | | above 200% |

The possibility of obtaining a more accurate cost estimation was checked by a combined analysis of several component process costs of liquidation and an additional limit on the maximum cost of liquidation. Table 6 presents an estimation based on two selected large component costs (process 7 and 10) as an example.

***Table 6***
***Comparison of cost estimation determined for several different aspects of mine liquidation with the real costs of mine liquidation***

| Forecast for | Process 7 and 10 | Process 3, 5, 7 and 10 | Process 3, 5, 7, 10 and max expenditure |
|---|---|---|---|
| Process 1 (liquidation of excavations) | 99% | 80% | 97% |
| Process 2 (liquidation of shafts and pits) | 131% | 105% | 128% |
| Process 3 (securing of neighboring mines) | 354% | 100% | 100% |
| Process 4 (liquidation of surface facilities) | 70% | 56% | 78% |
| Process 5 (land reclamation) | 333% | 100% | 100% |
| Process 6 (maintenance of surface facilities) | 127% | 119% | 124% |
| Process 7 (securing of liquidated mine) | 100% | 100% | 100% |
| Process 8 (projects, expertise etc.) | 74% | 60% | 73% |
| Process 9 (mining damage) | 77% | 62% | 76% |
| Process 10 (general management) | 100% | 100% | 100% |
| Total | 112% | 94% | 100% |
| | to 60% | from 80% to 120% | above 200% |

As expected, with the exception of a very inaccurate forecast of the costs of processes 3 and 5, a deviation from real costs of no more than 31% was obtained. The inaccurate cost forecast for processes 3 and 5, as noted earlier, was also in line with expectations. Entering values of these most deviant costs into the forecast significantly improved the correctness of the estimate of the remaining element costs and the entire cost of liquidation. This version of the forecast, however, indicated a large underestimation of process 4 and 8. Despite the significant difference expressed in percentages, the real difference expressed in money is no longer so significant. These costs are only 6% of the total cost of mine liquidation and accurately estimating them would only improve the total cost forecast by about 2%. Other unpublished cost estimations generated were in line with the examples presented. This leads to the conclusion that the accuracy of the forecast made for the large component costs carried out in each liquidation case can be improved by entering the values of the costs of processes carried out optionally.

An additional significant improvement in the consistency of the forecast with the benchmark object was achieved by determining the total cost of liquidation. The maximum deviation of the forecast of the amount of component costs from the benchmark values decreased to 28%.

The cost estimates produced for a sample mine closure were presented for assessment to individuals overseeing SRK S.A. branches. During face-to-face interviews, surveyed experts (individuals possessing practical experience in managing closure processes) confirmed that the estimation results aligned with past practices. The experts also validated the accuracy of the method's algorithms and associated software.

## CONCLUSIONS

Mining companies currently lack comprehensive and consistent solutions for estimating the costs of planned mine closure processes, despite various components of this concept being available. One way to bridge this gap is through the proposed procedure. This method, based on statistical cost evaluation, enables an analysis independent of the scale of the closure task. Accurate forecasts can be obtained when data are correctly input according to the provided tool options. Each additional data element enhances the accuracy of the estimation.

The presented method, comprehensive, updated, and expanded, for the preliminary assessment of time and cost of mine closure, can serve as a comparative tool for estimating time and cost in the prospective design of closure for subsequent mines or their parts. Leveraging the experience of Spółka Restrukturyzacji Kopalń S.A. accumulated over 20 years, this method can be applied without modifications by any company conducting mine closure. Its algorithm relies on obtaining only a few fundamental parameters of a closed mine plant, unrelated to the structure of closure processes developed by SRK S.A. However, modification would be necessary if generating a forecast based on the amount of selected component costs of closure processes or the total maximum cost of closure.

It has been established that, for the validity of the estimation, reliance on the costs of optionally conducted processes should be avoided. Their analysis may sometimes result in an indeterminate situation, making estimation impossible. Relying on processes carried out in each case of mine closure typically yields satisfactory forecast results.

The method excels in estimating the major components of closure costs and the total cost of closure. Accurate estimation of these major components, even with significant variations in other smaller components, ensures adequate expenditure to ensure the correctness of the overall mine closure process.

An unresolved issue is the estimation of closure costs considering abnormalities in the main closure processes. In such cases, only the unstructured knowledge of practitioners can be applied.

While the proposed method requires further research, its current form can serve as a valuable supplementary tool

in engineering and preliminary design work for the restructuring of post-mining assets.

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