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The concept of forecasting the reclamation cost in rock mining

Introduction

The reclamation of post-mining areas is a critical stage in the development of a mining project. It involves a socially responsible and economically expensive process of restoring useful environmental conditions to a site transformed during deposit extraction works. This process is regulated by legal, environmental and economic factors which influence the investor's decisions at the stages of planning a mining operation, organizing production in the extraction phase and choosing a method and form of mine closure. These factors must be considered already at the stage of preliminary analyses and plans, as they are the basis for the investor to estimate the profitability of a mining operation and the related economic risk. The economic risk faced by the investor in this case also becomes an environmental and social risk, as a company may fail to fulfill its environmental commitments due to economic

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reasons (bankruptcy) (Malewski 2012; Kaźmierczak et al. 2015). In such cases, a lack of sufficient funds secured for land reclamation purposes constitutes a liability for the local community and budget.

Calculating the cost of investment projects is a practice widely employed in the construction industry, as investors want to estimate their costs and risks already when tendering for a contract. These evaluations are based on the analyses of particular technical designs and the price lists of construction works. In the mining industry, however, the situation is more complex, as the reclamation phase, which may be considered a construction project, does not yet have a separate technical design at the initial stage of mine planning – it is only described in a declarative, so-called *reclamation direction*. This declaration is a very general commitment of the investor to restore the post-mining area to its useful condition in accordance with the provisions of the *Local Spatial Development Plan* (further: LSDP). These, in turn, are very general spatial planning guidelines, which allow the investor a lot of freedom to declare a reclamation direction, and thus also the scope and cost of the reclamation project. The costs of the reclamation project should already be estimated at the stage of investment planning, i.e. as part of the so-called feasibility study, as they may significantly influence the profitability of the investment project. Moreover, in the case in which the project is carried out, such estimations allow sufficient funds to be secured for the reclamation works.

Estimating reclamation costs in relation to a chosen direction/target is difficult, because each case has previously been analyzed as a unique project, which escapes generalization. This article is an attempt to address the problem formally, by applying fuzzy-set logic to the rock mining industry.

1. The concept of forecasting the reclamation cost

The first obstacle to be overcome is to define the concept and scope of a reclamation direction. This problem has been widely discussed (among others in: Malewski 1998, 1999, 2012; Kasztelewicz and Zajączkowski 2010; Ostreęga and Uberman 2010; Kaźmierczak 2016; Kaźmierczak et al. 2017). Ultimately, the proposed reclamation cost forecasting concept was based on the classification of reclamation directions offered by Strzałkowski and Kaźmierczak (2014b) and by Kaźmierczak et al. (2017), who identify 6 general and 23 particular reclamation directions (Table 1), as well as on the scope of reclamation works in both the general and the particular phases, as described by Strzałkowski and Kaźmierczak (2014a, 2014c, 2019), Kaźmierczak and Strzałkowski (2015, 2016).

This proposal is based on a detailed review of the type and scope of reclamation works, as well as on the calculations of physical and financial expenditures related to the reclamation of a post-mining area in its basic (technical) and particular (biological) aspects. For this purpose, a significant number of examples (found both in industry and in literature) were examined: Chwastek 1972; Graszta and Morawski 1972; Cymerman 1988; Ślebodziński 1988; Dwucet et al. 1992; Glapa and Jonek 1998, 1999; Maciak 1999; Ciepeliowski 1999; Bobrek

Table 1. Classification of reclamation directions (Strzałkowski and Kaźmierczak 2014b; Kaźmierczak et al. 2017)

Tabela 1. Systematyka kierunków rekultywacji

General reclamation direction	Particular reclamation directions
Agricultural	Cropping; breeding
Forest	Forestry; protection; recreation
Aquatic	Water management; recreation
Natural	Nature reserve; landscape park; protected landscape area; species protection; nature monuments; inanimate nature documentation site; ecological areas; landscape-nature protected complex; Natura 2000 areas; natural succession; green areas
Economic	Housing; industry; services
Cultural	Scientific; artistic

and Paulo 2005; Król 2005; Paulo 2008; Kasztelewicz 2010; Rosik-Dulewska 2010; Uberman and Uberman 2010; Jamróz 2012; Strzałkowski and Kaźmierczak 2014a, 2014c, 2019; Kaźmierczak and Strzałkowski 2015, 2016; Kaźmierczak et al. 2017. The analysis of the empirical material indicates that post-rock-mining land reclamation projects may be aggregated around the so-called reclamation directions which include a finite and similar set of typical reclamation operations that vary in terms of the amount and cost of physical expenditures. At the same time, the set of projects is also finite and, as shown in Fig. 1, the projects overlap to a greater or smaller extent with respect to the type of reclamation works. From a formal perspective, such a problem can conveniently be interpreted with the use of fuzzy logic, as each land reclamation project is an individual project, although it still includes a number of operations that are characteristic of alternative projects.

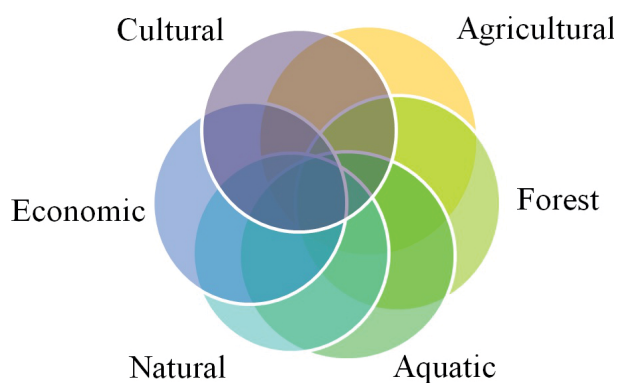


Fig. 1. Reclamation projects as sets of characteristic reclamation operations

Rys. 1. Projekty rekultywacji jako zbiory charakterystycznych operacji rekultywacyjnych

In relation to the assumed classification of reclamation directions, the analysis of the operations typically performed in such projects leads to an observation that these operations may be aggregated into structures consisting of the following types of works: performing preliminary works, shaping of the terrain relief, restoring soil, regulating hydrogeological conditions, constructing roads, protecting excavations, performing agricultural works, introducing legume plants, introducing target vegetation and maintaining plants. The above types of works are customary, and their scope may be very broad and escape a precise definition. At the same time, their cost fluctuations allow estimations with some degree of probability. An example can be found in Fig. 2, in which the (theoretical sample) the unit cost in successive projects differs with respect to the type of land use as part of the same reclamation direction. The variability and limited predictability causes individual land reclamation solutions to be subject to analysis only in terms of fuzzy logic (Dworniczak 2003; Szybisty 2009; Nowak-Brzezińska 2019).

Therefore, the proposed method is based on an assumption that a finite set of reclamation directions exists, which can be assigned an identical (with respect to the structure) set of reclamation operations. Moreover, their “mixing” in proper proportions allows for the combination of several reclamation directions (following several reclamation directions simultaneously).

Formally, this can be noted as follows: let us have $\{P\}$ basic reclamation directions, where particular implementations shall be referred to as projects P_1, P_2, \dots, P_j . Each of these projects has a finite set X of technical (reclamation) operations having number m , i.e.

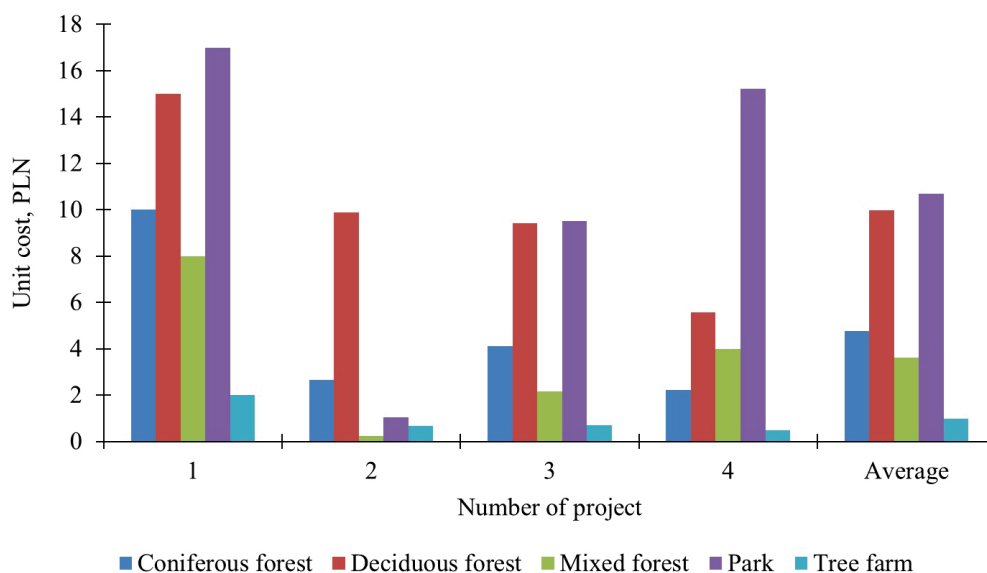


Fig. 2. Example of probable costs related to implementing the forest reclamation direction in various projects (own study)

Rys. 2. Przykład prawdopodobnych kosztów realizacji kierunku leśnego w różnych projektach

$\{\mu_j(x_i)\}_{j=1,2,\dots,n;i=1,2,\dots,m}$. Values $\mu_j(x_i)$ represent probabilities or membership functions of the i -type technical (reclamation) operation to the j -project P_j and their value is between $[0,1]$, i.e.

$$\mu(x) = \begin{cases} 0, & x \leq 0 \\ 1, & x \geq 1 \end{cases}$$

Events x_i are elements of projects P_j and occur in each of the projects (sets), albeit at various intensity, which indicates that they may simultaneously belong to several projects, although with various probability levels $\mu_j(x_i)$, as illustrated in Fig. 2. Estimation of the value of the membership function is possible through statistical analysis or may be produced by an algorithm which performs a series of the following operations:

$$IF(x, P_k) \supset \{R \cap P\} \text{ THEN } \mu(x) \neq 0 \text{ ELSE } \mu(x) = 0$$

- $\Rightarrow R$ – a set of the implemented mining technologies and of post-mining objects typical of such technologies (compact rock, clastic rock),
- P – a set of alternative reclamation projects for such objects,
- $\mu(x) = f(R_j, P_k, C_z)$ – is the value of the membership value resulting from the type of the objects characteristic of a particular technology (type of rock and excavation), and the type and probable amount of work required to achieve reclamation as conditioned by objectives C .

In this case, let us assume that values $\mu(x)$ are estimated statistically, based on the analysis of a number of actual projects and the amount of physical expenditures carried out in order to achieve the reclamation objectives defined in projects in accordance with land use and with the form of spatial development. By standardizing the absolute values of these expenditures with respect to the particular project, $\mu(x)$ is obtained, representing the share of individual operations.

“Mixed” direction is a project in which parts of the reclaimed area are given various functions, e.g. forest-agricultural, in given proportions w_j . In such a case, according to the principle of calculations on fuzzy sets, an image is obtained as in Fig 3, without the intersection of the two sets. Formally, this will be a set of membership functions $\mu^*(x)$ as the maximum value of a pair of numbers which belong to the combined sets, i.e.

$$\mu^*(x_i) = \max\{\mu_A(x_i) \cdot w_A; \mu_B(x_i) \cdot w_B\}_{i=1,2,\dots,n}$$

For all i , the sum $\Sigma\mu^*(x_i)$ is different than one. These should be standardized to the value of $\mu^*(x_i)/\Sigma\mu^*(x_i)$, as shown in the example in Table 2. Fig. 5, on the other hand, shows the effect of mixing (agricultural and forest) directions based on the assumptions of the presented method (as in Table 2) and on the determined cost structure (as in Table 3).



Fig. 3. The principle of creating the “mixed” direction on the basis of fuzzy sets

Rys. 3. Zasada tworzenia kierunku „mieszanego” na zasadach zbiorów rozmytych

2. Estimation of membership functions for basic reclamation directions

Analyses of a number of land reclamation projects, types of works (x) involved and their costs allowed estimating the share of expenditures $\mu(x)$ in projects corresponding to the reclamation directions included in Table 2. This reasoning is based on a strong assumption that the structure of sets $\{\mu(x)\}$ is constant, and that $\mu(x_i)$ are expected values, while the price list of construction works is subject to the significant influence of market factors. This fact means that $\mu(x)$ represent the expected values of the investigated population of actual projects (mean values), i.e. unlike labor costs commonly accepted in the market, they are based on “statistically stable” values. Figure 4 shows a distribution of $\mu(x)$ values in clastic rock mines according to the data included in Table 2.

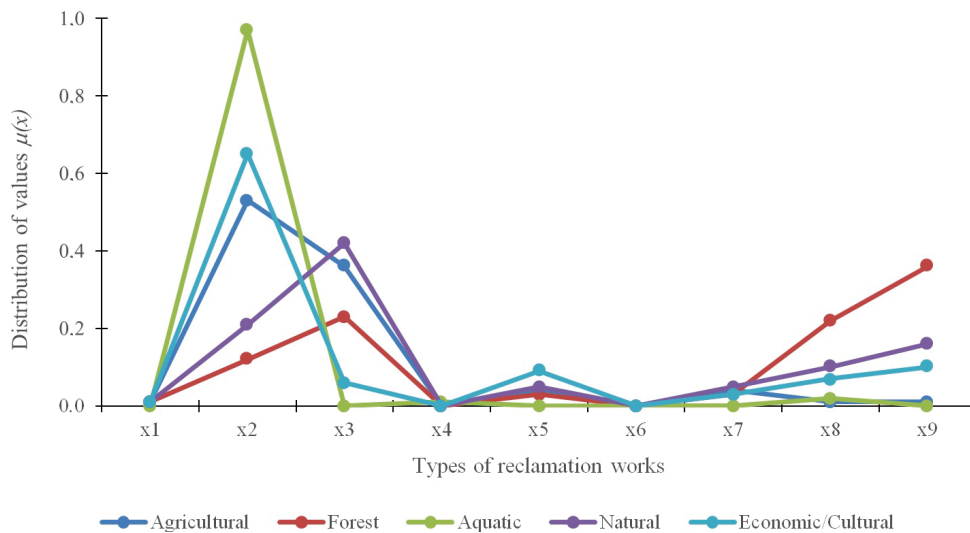
Fig. 4. Example of the distribution of values $\mu(x)$ for clastic and clay rocks according to data from Table 2Rys. 4. Przykład rozkładu wartości $\mu(x)$ dla skał okruchowych i ilastych według danych z tabeli 2

Table 2. Distribution of the value of membership functions of the reclamation direction (Strzałkowski 2016)

Tabela 2. Rozkład wartości funkcji przynależności wg kierunków rekultywacji

Mineral type	Reclamation direction	Membership functions (shares) of reclamation works $\mu(x)$								
		Preliminary works	Terrain relief shaping	Soil restoration	Regulating hydrogeological conditions	Road construction	Protecting excavations	Agricultural works and introducing legume plants	Introducing target vegetation	Maintenance of plantings
	K/x_i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
Clastic rocks/clays	Agricultural	0.01	0.53	0.36	0	0.04	0	0.04	0.01	0.01
	Forest	0.01	0.12	0.23	0	0.03	0	0.03	0.22	0.36
	Aquatic	0	0.97	0	0.01	0	0	0	0.02	0
	Natural landscape	0.10	0	0	0	0.90	0	0	0	0
	Water management	0.01	0.65	0.06	0	0.09	0	0.03	0.07	0.10
	Cultural	0.01	0.65	0.06	0	0.09	0	0.03	0.07	0.10
Compact rock	Agricultural	0.01	0.13	0.29	0	0.12	0.38	0.05	0.01	0.01
	Forest	0.01	0.05	0.13	0	0.06	0.17	0.02	0.21	0.35
	Aquatic	0	0	0	0.08	0	0.92	0	0	0
	Natural landscape	0.01	0	0	0	0.23	0.76	0	0	0
	Water management	0.01	0.08	0.07	0	0.15	0.46	0.03	0.07	0.12
	Cultural	0.01	0.08	0.07	0	0.15	0.46	0.03	0.07	0.12

3. Price list of the reclamation works

A further step is to determine the unit cost list for reclamation works. In this case, the optimal measure was decided to be the cost $c(x)$ of performing individual types of works in relation to the surface area of the reclaimed land. This estimation may be based either on a specially prepared evaluation of labor- and cost-intensity or on the analysis of other information sources. In Strzałkowski (2016), the current price lists and historical data regarding reclamation projects served to identify the unit costs of the works (in 2016) presented in

Table 3. The value of money over time requires recalculating the cost of reclamation works to the current price level. This can be done on the basis of price indices of consumer goods and services.

The result of the work cost forecast for a project P will consist of a vector product:

$$K = |\mu(x_i)| \cdot |c(x_i)|$$

- ↳ $|\mu(x_i)|$ – the assignment function of relative expenditures in the analyzed reclamation project/direction,
 $|c(x_i)|$ – unit cost of work x_i in this project.

Table 3. Price of reclamation works by type of mining, PLN/m² (Strzałkowski 2016)

Tabela 3. Cennik robót rekultywacyjnych wg rodzaju kopalnictwa, PLN/m²

Reclamation operations	Symbol	$c(x)$ – rock mining	
		clastic rocks or clays	compact rocks
Preliminary works	x_1	1.06	1.06
Terrain relief shaping	x_2	40.07	0.62
Soil restoration	x_3	12.23	12.23
Regulating hydrogeological conditions	x_4	0.38	0.38
Road construction	x_5	4.07	4.07
Protecting excavations	x_6	0.0	3.96
Agricultural works and introducing legume plants	x_7	2.26	2.26
Introducing target vegetation	x_8	5.89	5.89
Maintenance of plantings	x_9	8.06	8.06

4. Example of multi-directional (mixed) reclamation

Figure 5 shows an example, for a clastic rock mine, of the distribution of costs related to reclamation works in the forest, agricultural and forest-agricultural direction, with the latter in proportions from 0.3 to 0.7. In accordance with the data from Tables 2 and 3, the calculated unit cost of reclamation for the listed directions is: agricultural – 26.04 PLN/m², forest – 12.02 PLN/m², forest-agricultural – 14.73 PLN/m². Therefore, for a post-mining area with a surface of 20 ha, the cost of the project in the agricultural, forest and forest-agricultural directions is respectively: PLN 5,208,640, 2,403,840 and 2,946,759.

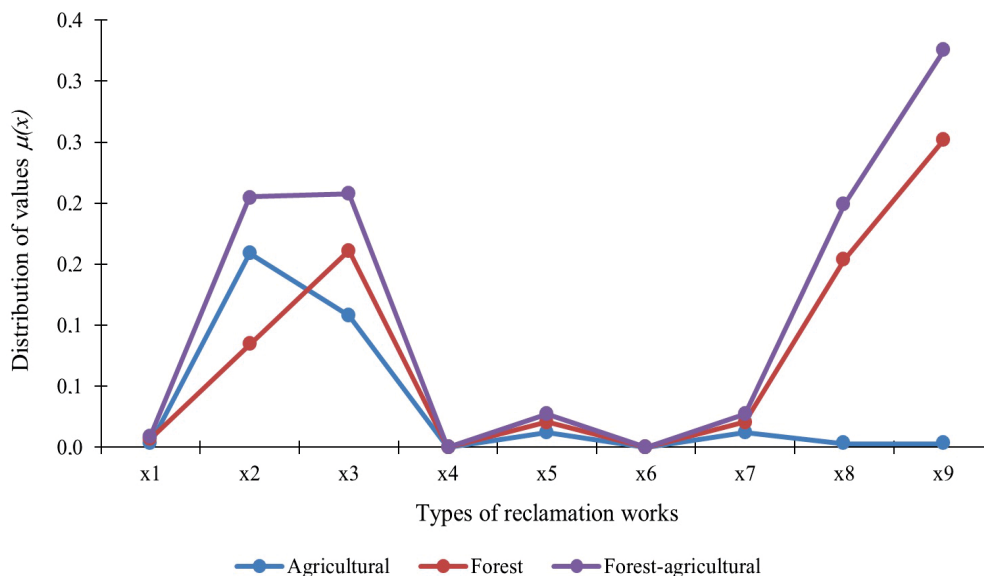


Fig. 5. Example of the distribution of values $\mu(x)$ according to the data from Table 2 of the agricultural and forest directions and the combination of these directions in the 0.3:0.7 ratio, in elastic rock mines

Rys. 5. Przykład rozkładu wartości $\mu(x)$ według danych z tabeli 2 kierunków podstawowych rolnego i leśnego oraz połączenia tych kierunków w jeden w proporcji 0,3:0,7 w kopalniach skał okruchowych

Conclusions

Modeling of land reclamation in post-mining areas is a very difficult task, as it needs to address its multi-dimensional nature and the variety of forms employed in practice.

The literature studies and the analyses of historical data on reclamation projects performed as part of this research demonstrate that land reclamation projects in rock mining can be aggregated around reclamation directions. These directions include a limited and similar set of typical reclamation operations which are different only in the number and cost of physical and financial expenditures.

From the perspective of reclamation objectives in post-rock-mining areas, 6 so-called basic reclamation directions were identified: agricultural, forest, aquatic, economic, natural and cultural. Each direction (reclamation project) was assumed to be limited to 9 typical types of operations (works), which are performed in the area with varying intensity. Therefore, a reclamation project may be simultaneously represented as a unidirectional project or a multi-directional (mixed) project.

The formal model for such an analysis involves fuzzy-set algebra, in which the individual elements of the sets (operations/works) have values between 0 and 1, here referred to as

membership functions. This article presents the estimated values of membership functions which are classified by clastic and compact rock types of mining. Mixed projects are a synthesis of basic directions, whose membership functions are obtained in accordance with the principles of the algebra of sets. The absolute values (work cost) are estimated on the basis of independent price lists used in geoen지니어ing.

The presented concept is an attempt at a formal approach to this issue, and – as demonstrated in the above analyses – may be especially useful at the feasibility study stage of a mining project or at the stage of acquiring licenses to mine so-called common minerals. This may be improved when further knowledge is gained from new reclamation projects or from scientific publications.

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THE CONCEPT OF FORECASTING THE RECLAMATION COST IN ROCK MINING

Keywords

reclamation, reclamation costs, rock mining

Abstract

This article presents a concept method which aids the forecasting of the reclamation cost in post-rock mining areas. The method may also prove useful in estimating the investment profitability of a mining operation at its planning stage as well as managing a potential Reserve Fund to cover future activities, such as land reclamation. The development of the method consisted in defining a set of basic/typical land reclamation directions and the typical structure of reclamation operations/works, which are based on “statistically stable” values. The estimations included the distribution of the probable cost of these works with respect to the reclamation direction and were calculated on the basis of the analyzed current price lists and historical land reclamation projects. The article proposes a method for estimating the cost structure of multi-directional projects by combining the basic directions. The changeability and predictability of various land reclamation solutions was analyzed in terms of fuzzy logic. A price list was developed, which included unit costs for separate types of reclamation works, independent of their type and scale. The assumed optimal measure involved comparing the cost of individual types of operations to the surface of the reclamation area. As an example, the method was also applied to hypothetical data from a clastic rock mine with a surface of 20 ha, and for the forest, agricultural and forest-agricultural reclamation directions. The forest-agricultural reclamation directions was presented in the proportions of 0.3:0.7.

KONCEPCJA PROGNOZOWANIA KOSZTÓW REKULTYWACJI W GÓRNICTWIE SKALNYM**Słowa kluczowe**

rekultywacja, koszty rekultywacji, górnictwo skalne

Streszczenie

W niniejszym artykule przedstawiono koncepcję metody szacowania kosztów rekultywacji terenów po eksploatacji surowców skalnych, która może być użyteczna do określania opłacalności inwestycji górniczej na etapie planowania, a także szacowania ewentualnych funduszy rezerwowych na realizację zdarzeń przyszłych, którym jest rekultywacja. W tym celu zdefiniowano zbiór podstawowych i typowych kierunków rekultywacji i ustalono typową dla nich strukturę operacji/robót rekultywacyjnych, które opierają się na „statystycznie stabilnych” wartościach. Na tej podstawie oszacowano rozkłady prawdopodobnego kosztu realizacji tych robót zależnie od kierunku rekultywacji na podstawie analiz aktualnych cenników i archiwalnych projektów rekultywacyjnych. Zaproponowano sposób szacowania struktury kosztów projektów wielokierunkowych przez mieszanie kierunków podstawowych. Zmienność i przewidywalność różnych rozwiązań rekultywacyjnych analizowana była w terminach logiki rozmytej. W dalszej części opracowano cennik jednostkowych kosztów realizacji poszczególnych robót niezależny od rodzaju i ich wielkości. Przyjęto, że najlepszą miarą będzie koszt poszczególnych rodzajów prac odniesionych do powierzchni rekultywowanego terenu. Podano sposób użycia metody na przykładzie hipotetycznych danych dla kopalni skał okruchowych o powierzchni 20 ha oraz dla leśnego, rolnego i rolno-leśnego kierunku rekultywacji. Z tym, że kierunek rekultywacji rolno-leśny został przedstawiony w proporcjach odpowiednio 0,3:0,7.

