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EVALUATION OF NON-SEPARATION OPERATIONS OF MINERAL ENGINEERING

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The vast majority of technological operations in mineral engineering involves separation operations in which two or more products are obtained differing in the value of a particular property that constitutes the separation characteristic. They include all enrichment, classification and dewatering operations. The determination and evaluation of the technological efficiency of such processes is the subject-matter of numerous theoretical, and particularly methodical studies, as well as control procedures that are commonly applied in industry and experimental investigations. Apart from these operations there are others that (as a rule) aim at the change of the material form without the separation of elements having common properties. Such operations include first of all comminution and inversely agglomeration (as well as briquetting and pelletizing), but also division into smaller portions (or parts) – its specific kind is sampling. These operations have crucial, though variable in importance, significance for the processing while the evaluation issue of their efficiency is practically non-existent in professional literature and in wider practical applications. The aim of this paper is to present the idea of determining the technological efficiency of such operations. Alternative principles of defining the efficiency and methods for obtaining quantitative results as well as their selection for the assumed control targets and the required evaluation accuracy are presented.

Key words: *technological operations of mineral engineering, non-separation operations, and technological efficiency*

SEPARATION AND NON-SEPARATION OPERATIONS

In the entire, large and very differentiated, set of types of technological operations of mineral engineering, one can separate two groups which differ significantly with respect to the general characteristics of their results. The review of the discussed operations indicates that a vast majority of them are used for obtaining several products, mutually differentiated, from the initial material, i.e. the feed, which is either

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raw mineral or, quite often, a secondary material (intermediate product or waste products of other processing processes) of several products of mutually differentiated properties. These are such operations as:

- enrichment the aim of which is to reach the differentiation of the content of the feed component which is considered to be useful. In such an operation at least two separate products are obtained. These usually are: the concentrate of high content of the useful component and the waste of possibility low content of it;
- grain classification the products of which differ by grain distribution and are as a rule separate (all feed grains of a certain size, most often determined in ranges, should be only in one product);
- dewatering[1] which contributes to the fact that one of the products of the feed, which is a two-phase mixture of water and solid parts, contains mainly solid parts whereas the other one mainly water (here is also water clearing the product of which is cleaned water and not dewatered solid material as in classical dewatering).

Such operations are classified as **separation operations**. They constitute the basic technological set of mineral engineering, particularly mineral processing, and in the majority of practical tasks, in the specially constructed technological systems, they are the “main” operations, determining the final result of the technological task.

The second group of operation, much smaller, is used to modify the feed material properties, generally[2] without separating it into several products. In technological processes they usually are preparatory operations, only in some cases as main operations, although they are certainly necessary in such systems and cannot be neglected in any case. Here there are only operations which change the form of the material:

- comminution – the aim of which is to decrease the grain sizes, in practice it is the elementary part of the task of changing the grain composition of the feed material, i.e. decreasing the grain size distribution; sometimes this task is accompanied by the implementation of requirements concerning grains shapes, practically reaching a significant content of grains of assumed shapes in the product,
- lumping – of the tasks opposite to crushing, assuming the increase of the material grain size distribution by means of consolidation of fine grains into larger permanent aggregates, it includes pelletizing, briquetting (together with “compacting”) and agglomeration (sintering); in majority of cases, despite agglomeration, the products of certain grain shapes are obtained, especially in case of briquetting which fulfills the role of the main operation, giving a completed commercial product. Other operations are usually used to make intermediate products to be further processed (e.g. agglomeration or lumping of

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[1] Analogical assumptions occur in mixtures of the solid and gaseous phases (gas suspensions, aerosols), for their separation dust removal is applied

[2] this concerns the division operations

fine-grained iron-ore concentrates to be used as blast-furnace charge) or to be refined (e.g. making crude lumps from clays, transformed later into lightweight aggregates),

- division – separation of the feed into parts, occurring mainly as a preparatory operation in sampling and sample preparation as well as in the division of the material stream is large plants into several parallel streams, processed in separate machine lines of mutually similar operation characteristics, the lack of differentiation of qualitative characteristics of the obtained products is the basic qualitative requirement,
- averaging – homogenization of qualitative properties of the material in the entire range in which it is included (this may be the range determined statically, only by means of geometrical features, or dynamically – when the characteristics of material stream movements are considered on the geometrically track – closed or open).

These operations belong to the group of **non-separation processes**.[3]

Formal differentiation of separation and non-separation processes result from the characteristics of their product though the number of products is an additional criterion for most non-separation products: <u>only one product occurs exclusively</u> in case of non-separation products.

The criteria which qualify the technological operations into separation or non-separation groups can be presented as follows.

Let an operation be given in the result of which N products of qualitative characteristics sets $\{K_j\}$ – $j = 1, 2, ..., N$ are obtained from the feed material of the $\{K_0\}$ qualitative characteristics set. In such a product k exists ($1 \le k \le N$) when $\{K_k\} \neq \{K_{j\neq k}\}$ at least for one $j \neq k$, the operation is a **separation** one[4];
In the opposite case the operation is non-separation, then, additionally, if $N > 1$, then $\{K_k\} = \{K_0\}$ for every j (division operation)[5].

TECHNOLOGICAL EFFICIENCY OF OPERATIONS

Every technological process must have its goal. The determination of its technological efficiency is used to evaluate how much of this goal has been reached. For the basic group of mineral engineering processes it was assumed to determine the efficiency as a numerically balanced relation of really obtained process results to the results assumed, forecast or theoretically possible. The latter variant is generally assumed in general methods of efficiency calculations. The general definition of efficiency is as follows:

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[3] it may appear amazing to include the division into non-separation processes but it results from the quoted condition of not differentiating the obtained products among themselves

[4] then most often $\{K_j\} \neq \{K_0\}$ at least for some values

[5] all these names concern elementary operations, many operations, especially the non-separation ones, occur simultaneously with others, when it is not taken into account at identification, mistakes may appear,

$$S = \frac{W_r}{W_0} \quad (1)$$

where:
W_r – the obtained result,
W_0 – the expected result (or more rarely, theoretically possible[6]).

Equation (1) is a general definition of efficiency. In technological applications only such cases are considered in which W_r and W_0 assume the strictly determined numerical values. In practice, multiplying the fraction in expression (1) by 100, the efficiency value, calculated in this way, is assumed to be a percentage evaluation of success in aiming at reaching the value W_0.

The position of separation operations, privileged in mineral engineering, (cf. Chapter 1) caused that so far the notion of technological efficiency (in abbreviation "efficiency") had been practically considered exclusively in relation to these operations. Various detailed requirements, concerning both shaping the process reevaluation, caused the origin of very many methods and useful means of such an evaluation. The literature contains literally hundreds of various proposals of formulas to calculate the efficiency of these operations in various variants of conditions and detailed requirements in relation to the performed evaluations (Verchovskij 1949, Barskij, Plaksin 1967; Barskij, Rubinštejn 1970; Sztaba 1983-2001, Stępiński 1961, Sztaba 2000a, 2000b, 2001, 2002 and the others). Depending on the basic evaluation criterion, these methods were formally ordered into a few basic groups:

- technological,
- statistical,
- economic,

but also:

- power engineering,
- thermodynamic,

and separating the approaches:

- statical and
- kinetic.

No such considerations have been made in relation to non-separation operations. This work is the first public presentation of an attempt to determine the method of evaluation of the efficiency of such operations. Only a part of them was presented during the lectures held by the author (Sztaba 1983-2001).

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[6] considerations of assuming one or another level of reference – of a precise definition of the W_0 value – are not included in this paper

THE CONCEPTS OF EVALUATION OF EFFICIENCY OF A NON-SEPARATION OPERATION IN CRUSHING

Comminution (crushing and grinding) is a non-separation operation that occurs practically in all technological systems. Its general aim is, as it was said before, to decrease the grain sizes of the feed.

Additional detailed requirements can concern (in the order of increasing the requirements and the rate of complication).

- decreasing[7] the maximum grain size d_m[8] to the fixed value,
- transforming a certain part of the feed (exactly or limitingly: “at least” / “utmost”) (of the yield γ) to the class of assumed grain size distribution – $d_1 \div d_2$ ($d_1 < d_2$),
- obtaining the comminution product of an assumed value of the average grain size[9] (D),
- obtaining the product of the fixed grain composition described by the grain composition function, for example the $\Phi(d)$ increasing function,
- obtaining the product of the fixed specific area (P),
- obtaining the product of the fixed grain shape, expressed by the dimensionless shape coefficient, for example the spherical coefficient (k_g)[10] (Sztaba 1983-2001).

Figure 1 represents the example of a draft of grain composition curves of comminution products:

- with t index – the planned (“theoretical”) product,
- with r index – the real product, obtained as a result of the performed operation, which clearly go in different direction (strongly exaggerated on purpose).

Such curves, as it is known, fully characterize the grain composition of the grained material and allow us to read the data necessary for investigating this composition and for calculating the derivate values, such as specific area (in approximation depending on grain shapes) and others, depending on the grain size distribution (Sztaba 1983-2001).

The values read from the curves in Fig.1 will be used to present simple formulas for calculating the formerly given variants of determining the comminution efficiency.

It should be noted that comparing the values characterizing grain compositions has been the basic of description of comminution results by means of “comminution rates” for a long time (Budryk, Stępiński 1954) and these values are also obtained from the grain composition curves, in this case describing the grain size distribution of the feed

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[7] all grain sizes are linear (mm), specific area m^{-1} (m^2/m^3)

[8] this value can be also determined as the grain size below which not 100 % material occurs but less, for example 80 % (then we speak about the eighty-percent grain – d_{80}) or, similarly, in general $d_{\%}$, (so-and-so) percent grain

[9] determined according to the method chosen from numerous possibilities (Sztaba 1983-2001)

[10] requirements concerning the grain shapes of the comminution product can be additionally developed and detailed similarly as those concerning the grain size distribution.

and operation product. Therefore the majority of formulas used to calculate the effectiveness are of the form similar to the formula for comminution rates. The simplicity of these approaches and forms of formulas allows us to see these analogies without an additional commentary.

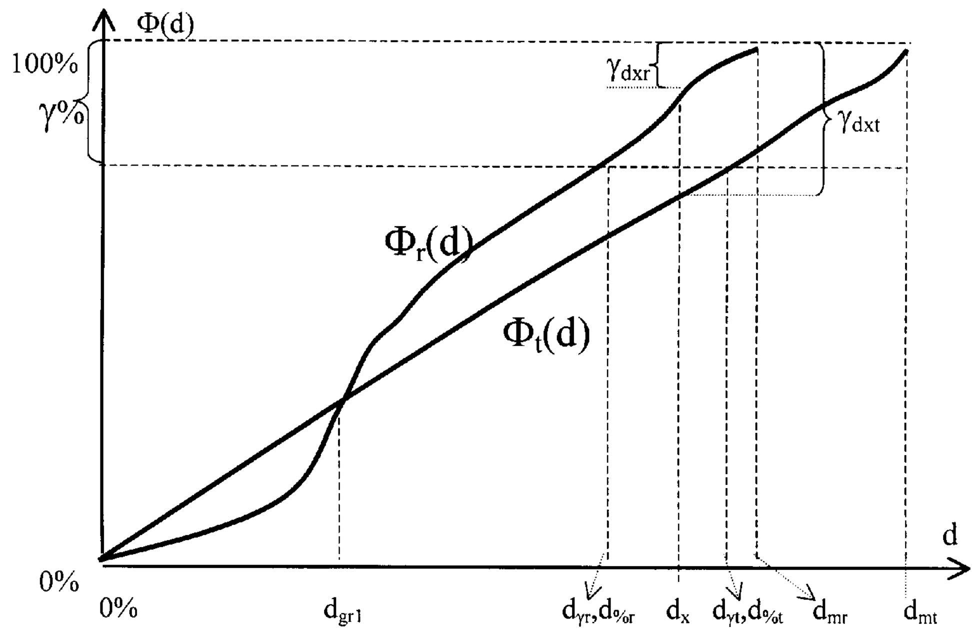

Fig. 1.

a) in case of requiring the fixed value of maximum grain or percent gran:

$$S_m = \frac{d_{mr}}{d_{mt}} \cdot (100\%) \tag{2.1}$$

$$S_\% = \frac{d_{\%r}}{d_{\%t}} \cdot (100\%) \tag{2.2}$$

Whereas it is also possible to use class limits of a selected yield γ ($d_{\gamma r}$ and $d_{\gamma t}$), they overlap with $d_{\%r}$ and $d_{\%t}$ on the graph.

b) in case of requiring the fixed content in the product of grains of the determined grain class, here, as an example, the classes of grain size distribution > d_x ($d_x < d \le d_m$)[11]

[11] Assuming the markings < and ≤ results from the way of defining the grain class limits, cf. for instance (Sztaba 1961, 1983-2001)

$$S_{\gamma} = \frac{\gamma_{d_x r}}{\gamma_{d_x t}} \cdot (100\%) \tag{3}$$

c) in case of requiring the fixed value of specific area of the comminution product (most often in case of grinding):

$$S_P = \frac{P_r}{P_t} \cdot (100\%) \tag{4}$$

d) analogically in the case of the assumed average grain size in the product:

$$S_D = \frac{D_r}{D_t} \cdot (100\%) \tag{5}$$

e) if the requirements concern the full characteristics of the grain size distribution (obtaining a product of the assumed course of the function of grain composition ($\Phi(d)$), the effectiveness, i.e. the rate of compability of the obtained composition with the assumed one, can be estimated, for example, according to the average distance of the grain composition curves in question (its value will be expressed in the units of the Y-axis scale – the $\Phi(d)$ axis:

$$S_{\Phi} = \frac{1}{d_{mt}} \cdot \int_0^{d_{mt}} \left|\Phi_r(z) - \Phi_t(z)\right| \cdot dz \tag{6.1}$$

if the analogical forms the Φ (d) function are known , or

$$S_{\Phi} = \frac{1}{d_{mt}} \cdot \sum_{i=1}^{n} \left|\Phi_r(d_i) - \Phi_t(d_i)\right| \cdot (d_{i2} - d_{i1}) \tag{6.2}$$

if at disposal there are only data of the grain composition in the table or graphic form.

In this case d_1 and d_2 are the boundaries – upper and lower – of the summed classes (grain size ranges) of the representative grain size d_i, whereas n – is the number of the selected ranges of summing while it is their current numeration. It can be observed that the more precise the result will be, the denser are the points d_i selected. High accuracy can be provided[12] by a direct measurement of the surface area contained between the $\Phi_r(d)$ and $\Phi_t(d)$ curves which are determined by the integral in equation (6.1) or the sum in equation (6.2). The measurement, of course, should be executed by fragments determined by the points of intersection of both curves, limiting the fragments of the discussed area , in the graph there is, for instance, one

[12] depending, of course, on the assumed method of measurement and the way of its execution

"boundary" point d_{gr1}, or along the sections of both curves, constituting the envelope of measured surface, and not in the continuous way, along both lines respectively (absolute value of this area is needed).

THE BASES OF DETERMINING THE EFFECTIVENESS OF OTHER NON-SEPARATION OPERATIONS

EFFECTIVENESS OF LUMPING

The aim of lumping is as a rule to obtain a product which is not only caked (and in the case of agglomerations and some applications of pelletizing, also over-reacted to a certain degree), but also included in the fixed grain class. Briquetting in the full-matrix presses (roll and punch ones) corresponds best this requirement, most difficult it is in agglomeration whose raw product, sinter, is subjected to crushing. Assuming that quantitively the operation goes correctly (possible mistakes may occur only in agglomerating), the yield of the required product grain class can be treated as lumping effectiveness:

$$S_{kaw} = \gamma_{prod} \tag{7.1}$$

while the yield of the required class – γ_{prod} – is usually given in percent values. If the production plan predicts making a few classes, for instance provided for different aims (different grain classes of lightweight aggregates, etc., the γ_{prod} value is the sum of planned and obtained[13] production of all such classes. A simple recording of formula (7.1) assumes that the entire bulk (100%) of the material is the W_0 value (formula (1)). This can be only assumed, for instance, in case of briquetting. For other processes it is known in general what are the real boundary quantitative possibilities of obtaining a "good" product from the processed feed ($W_{gran} < 100\%$). In these cases it is plansible to calculate the effectiveness:

$$S_{kaw} = \frac{\gamma_{prod}}{W_{gran}} \cdot (100\%) \tag{7.2}$$

It can be easily noticed that assuming the W_{gran} value has the same logical represcutation as the assumption of the meaning of the expected value instead of the theoretically obtainable value, as it was shown when discussing formula (1) in chapter 2.

[13] this formulation means that it c be counted as a "successful" operation of the formed surpluses of one of classes providing it can be subject to another application, or, for instance, additional

EFFECTIVENESS OF DIVISION AND AVERAGING

For both operations it is assumed that the obtained products will not differ qualitatively from the input product (feed), nor among themselves ($\{K_{0,1,2,...,N}\}$ = const), while:

– in the division operation we obtain physically separated products which must additionally meet other requirements:
  - in case of division into, for example, parallel technological streams, a similar value of yields of these streams ($\gamma_{1,2,...N}$=const=γ_0 (100%/N))[14] is an additional requirement,
  - in case of sampling, the requirement {K} = const can be limited if the samples are collected only to test one or several material features, not sufficing its full characteristics (including technological) requirement concerns then only the material properties taken into consideration in the test; it cannot be limited when taking a general sample whose characteristics of the tested material – general population (Poradnik 1976; Sztaba 1983-2001, 1988),
  - in the averaging operation no physically separated products are obtained; effectiveness is determined under the same assumption as the one at the beginning of this subchapter; jointly for division and averaging, but the material is subareas into which the entire area (tank, dump, means of transport), occupied by the considered material can be divided in assumed to constitute conventional "products". Separating these subareas, and practically the representative testing spots of interesting properties, occurs most often together with the assumption of regular grid of points of sampling, treated as representative for these areas (Sztaba 1983-2001, 2000a and others). Similarly as in sampling, in averaging limited ranges of properties {K} can be assumed, which are considered execution of the operation and determining its effectiveness, depending on the fixed detailed goals of this operation (resulting from market demands, conditioning of respective technological operations, etc.).

In all the cases of subchapter 4.2. the effectiveness is determined according to obtained homogeneity of property sets {K} (at the division, additionally the homogeneity of sets of division product yields). This enables the well-known dispersion dimensions to be applied to estimate this effectiveness, most often:

– average deviation

[14] practically, it is not possible to obtain the yields of product streams of exactly equal values, a certain permissible level of tolerance of deviations should be assumed, for instance analogically to the determination of representativeness of samples (Poradnik 1976, Sztaba 1983-2001)

$$S_s = \frac{\sum_i |x_i - E(x)|}{n} \tag{8}$$

– standard deviation

$$S_d = \sigma = \sqrt{\frac{\sum_i (x_i - E(x))^2}{n-1}} \quad [15] \tag{9}$$

or others,
where:
x – value which is the evaluation basis
E(x) – average value of value x,
meanings of symbols “i” and “n” were assumed as in formula (6.2) with the appropriate change of action objects.

The large practical significance of the averaging operations, sampling sample preparation contributed to the origin of large basis works, methodological works and directly utilisation papers, concerning these operations. The remarks in chapter 4.2 can be treated only as an outline of initial assumptions which are made in these works and a broader discussion of these problems here would not be purposeful. Nevertheless, mentioning their effectiveness as the operations clearly belonging to the non-separation group as it is meant in chapter 1 seemed to be necessary to stress the consistency of the set of general features of such operations despite their differentiated specifications and various practical applications. Due to it we can talk about the grounds of a general system of determining the effectiveness of such operations, adapting the general rule of effectiveness evaluation to their characteristics formulated according to formula (1) and its discussion.

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[15] as it is known, when the value n is sufficiently large, n-1 can be replaced by n in the denominator

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Zdecydowaną większość operacji technologicznych inżynierii mineralnej (w szczególności przeróbki surowców mineralnych) stanowią operacje rozdzielcze, w których otrzymuje się dwa lub więcej produktów, różniących się wartością określonej właściwości, będącej cechą rozdziału. Należą do nich wszystkie operacje wzbogacania, klasyfikacji ziarnowej, odwadniania itp. Określanie i ocena skuteczności (efektywności) technologicznej takich procesów są przedmiotem bardzo licznych zwłaszcza metodycznych opracowań procedur kontrolnych oraz są powszechnie stosowane w przemyśle i doświadczalnictwie. Poza takimi operacjami istnieją jeszcze takie, których zadaniem jest (z reguły) zmiana postaci rzadziej innych właściwości materiału, bez wydzielania z niego określonych części o wyróżnionych właściwościach. Należą do nich: przede wszystkim rozdrabnianie, a także kawałkowanie oraz dzielenie, którego specyficznym rodzajem jest pobieranie próbek. Operacje te mają istotne, aczkolwiek wzajemnie nieporównywalne co do rangi, znaczenie dla procesów przeróbki. Tymczasem problem oceny ich skuteczności właściwie nie istnieje w literaturze przedmiotu, ani w szerszych zastosowaniach praktycznych. Zarys tej problematyki był jedynie treścią fragmentu wykładów z przedmiotu *kontrola procesów technologicznych*, prowadzonych przez autora od kilkudziesięciu lat dla studentów specjalności Przeróbka Kopalin Stałych na Wydziale Górniczym AGH w Krakowie. Celem niniejszego opracowania jest przedstawienie koncepcji określania tytułowej skuteczności technologicznej takich operacji. Przedstawia się różne warianty zasad jej definiowania i metod otrzymywania wyników ilościowych, a także ich doboru do założonych celów kontrolnych.