A Multi-Criteria Procedure for Selecting Mechanical Excavation Methods

Maciej ZAJĄCZKOWSKI[1], Zbigniew KASZTELEWICZ[2], Mateusz SIKORA[3], Tomasz BĘDKOWSKI[4]

[1] AGH University of Science and Technology; email: maciejz@agh.edu.pl
[2] AGH University of Science and Technology; email: kasztel@agh.edu.pl
[3] AGH University of Science and Technology; email: sikoram@agh.edu.pl
[4] WKG Sp. z o.o. Sp. k. w Raciszynie; email: t.bedkowski@wkg.pl

http://doi.org/10.29227/IM-2019-02-36

Submission date: *28-07-2019* | Review date: *02-09-2019*

Abstract

This paper presents the results of a technical and economic analysis of the process of obtaining aggregates by mechanical excavation using hydraulic hammers, vibration rippers, Wirtgen surface miners, and ripper-dozers. The analysis involved a number of machine performance tests carried out at the "Raciszyn" Jurassic limestone deposit. The values determined in the tests included the average performance of individual devices making up the process system, unit fuel consumption and particle size distribution curves. These data served as inputs for the economic analysis of mechanical excavation and aggregate production methods. The method with the smallest unit production cost was determined.

As different mechanical excavation methods affect not only the costs of obtaining aggregates, but also other non-economic values, Bellinger's multi-criteria procedure was used to determine the optimal method.

Bellinger's multi-criteria procedure of selecting the mechanical excavation method may prove to be a useful optimisation tool, although one that requires knowledge of a given industry and its processes. Its advantage lies in relative simplicity and ease of use. This procedure should facilitate the preliminary assessment of selecting the most optimal technology and the assessment of the risk of choosing the least optimal one. The precision and, consequently, the objectivity, of the conducted analysis depends on the number and quality of the adopted criteria, which are largely connected with the knowledge level of the decision maker.

On the basis of the authors' assumptions, the most optimal mechanical excavation method at the "Raciszyn" Jurassic limestone deposit is the Wirtgen surface miner. The main advantage of this procedure is the optimal fragmentation of the excavated material and the low unit cost of aggregate production.

Keywords: mechanical excavation, carbonate rocks, "Raciszyn" deposit, milling, Bellinger's method

Introduction

There is a growing number of situations in which explosives cannot be used for solid rock excavation. This is usually due to environmental restrictions and potential conflicts with the local community. This phenomenon is connected with the expansion of residential housing which reaches areas located in the vicinity of raw material deposits, particularly those which have been already documented but are as yet not operated.

If explosives cannot be used, other methods of solid rock excavation must be taken into account considering the criterion of minimising the unit operating costs. Mechanical excavation methods could be seen as a viable alternative, although they are characterised by higher energy consumption, increasing unit costs by 30–100% [5–6]. Some alternative methods of excavating solid rocks involve the use of ripper-dozers, surface miners, hydraulic hammers, and vibration rippers. Other excavation methods may also be listed, e.g. using a milling head or expanding materials, but they are not widely used in opencast mining due to their very limited output and cannot be considered viable alternatives to the previously mentioned mechanical excavation methods [6].

The conducted performance tests of the process systems using the selected mechanical excavation methods

Due to the limitations resulting from the ban on the use of explosives, performance tests of various mechanical excavation methods were conducted. These tests were carried out at the "Raciszyn" Jurassic limestone deposit located in the southern part of the Łódzkie Province The extracted mineral is characterised by small and medium compactness and compressive strength within the range 50–60 MPa. The average uniaxial compressive strength of the extracted part of the deposit was 57 MPa. The obtained material was characterised by stable and consistent physico-mechanical properties.

To obtain the most effective assessment of the measurement results, the performance tests were carried out under similar geological conditions of the "Raciszyn" Jurassic limestone deposits in a geologically homogeneous area of 3 ha [1].

The results of the conducted in situ tests served as the basis for analysing the impact of the mechanical excavation methods of carbonate rocks on the technical and economic process of aggregate production. Determining annual output as 700 thousand Mg of the finished product was a significant assumption forming the basis for technical and economic analysis. This translated into the output of all production processes of 190 Mg/h. The 0–31.5 mm size of limestone aggregate was treated as the finished product.

The analysis of the technical and economic parameters of aggregate production was based on the comprehensive process system, which is composed of the following operations:

- obtaining the aggregate using mechanical excavation methods involving:

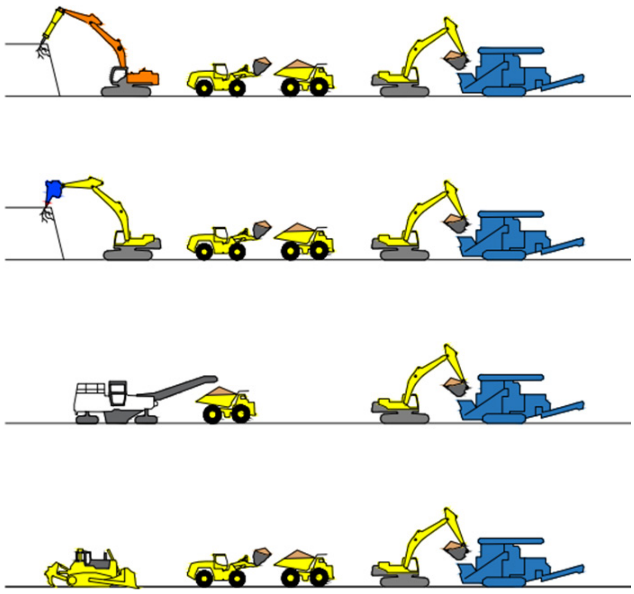

Fig. 1. The analysed process systems involved in the use of mechanical excavation methods
Rys. 1. Układy technologiczne z różnymi sposobami mechanicznego urabiania skał

- hydraulic hammers
- vibration rippers,
- Wirtgen surface miners,
- ripper-dozers

and

- other process operations:
- loading the excavated material using a loader,
- transporting the excavated material using dumpers,
- loading the excavated material onto the crushing machine using a single-bucket excavator,
- the crushing process.

The respective process systems are presented in Fig. 1.

Fuel consumption by each machine was monitored during the performance tests. All machines were diesel-powered.

As unit fuel consumption is a full measure of the energy consumption of the excavation process, the average unit fuel consumption per 1 Mg of excavated material was also compared between the machines. The smallest unit fuel consumption per 1 Mg of excavation material was recorded for the surface miner, which was 0.45 l/Mg. The highest value was obtained for the excavator with a pneumatic hammer, where consumption was as high as 0.66 l/Mg.

This data suggest that the most energy-consuming excavation process is that which uses the excavator with a pneumatic hammer, followed by the ripper-dozer. The least energy-consuming of the studied methods were the surface miner and the excavator equipped with a vibration ripper.

A significant relationship between the costs of operation of the crushing machine and the particle composition of the excavated material from various excavating machines.

For excavated material with a significant fragmentation caused by the Wirtgen surface miner, the average output of the crushing machine was higher, which allowed a reduction in its working time to 240 h/month. Fuel consumption was also lower – 28 l/h. Similar outputs were assumed in the economic model for crushing the excavated material from the Vermeer surface miner.

For the remaining mechanical excavation methods which produce less fragmented material (i.e. from the hydraulic hammer, vibration ripper and ripper-dozer), the output of the crushing machine was lower and more fuel was consumed. As result, the average working time of the crushing machine was 280 h/month, with 31 l/h fuel consumption.

The technical and economic analysis of process systems using the selected mechanical excavation methods

To compare the process systems used and the results generated by them it is necessary to analyse their outputs. The tests demonstrated significant differences in the amount of excavated material in a unit of time. For example, during the tests the Wirtgen surface miner produced the average hourly output of 193 Mg/h, which is three times as much as for the excavator + hydraulic hammer configuration.

The excavation process of the Wirtgen surface miner should also be taken into account in the analysis of the individual process systems. In this case, the excavated material is loaded directly onto dumpers, without using a loader. In the remaining methods, using the loader is necessary. The benefits of this were not taken into account in the technical and economic analysis of the excavation process.

The following parameters were included in the economic analysis:

- the average output of excavating machines obtained in performance tests,
- the average unit fuel consumption of excavating machines obtained in performance tests,
- capital expenditures on the purchase of the respective machines (new),
- the 60-month amortisation period of the machines,
- the costs of maintenance and repairs of the excavating

Tab. 1. A summary of the unit excavation costs by selected mechanical excavation method [2]
Tab. 1. Zestawienie jednostkowych kosztów urabiania w zależności od sposobów mechanicznego urabiania skał

Parameter	Excavator + hammer	Excavator + ripper	Surface miner	Dozer
Unit cost of excavation [PLN/Mg]	**6.00**	**4.61**	**4.37**	**6.13**
% of the lowest cost	137	106	100	140

Tab. 2. A summary of the unit excavation costs depending on the selected methods of mechanical excavation
Tab. 2. Zbiorcze zestawienie całkowitych kosztów pozyskania kruszywa w zależności od wybranych sposobów mechanicznego urabiania skał

Parameter	Excavator + hammer	Excavator + ripper	Surface miner	Dozer
Unit cost of aggregate production [PLN/Mg]	**12.98**	**12.42**	**11.48**	**14.37**
% of the lowest cost	113	108	100	125

Tab. 3. The assessment criteria
Tab. 3. Określenie kryteriów oceny

K1 – unit cost of aggregate production [PLN/Mg]
K2 – acoustic power of excavating machine [dB]
K3 – the minimum working area requirements of the machine [ha]
K4 – the degree of fragmentation of the material being excavated P80 [mm]
K5 – the cost of purchasing excavating machines [PLN thousand]

machines representing 12% of capital expenditures annually,

- the costs of salaries and social insurance of excavating machine operators,
- other operating costs connected with mining supervision, lighting in the pit area, insurance.

In addition, in the case of the Wirtgen surface miner, the cost of supplying water necessary for cutting drum cooling was also taken into account.

Table 1 contains a summary of the unit excavation costs depending on the selected methods of mechanical excavation.

As demonstrated by Table 1, the Wirtgen surface miner has the lowest unit excavation cost, followed by excavator + vibration ripper, in the case of which it is 6% higher. For the excavator + hydraulic hammer and ripper-dozer, the costs are much higher, by 37% and 40%, respectively.

Table 2 presents a summary of the unit excavation costs depending on the selected methods of mechanical excavation.

It can be concluded on the basis of the obtained economic analysis results that the total costs of aggregate production are at similar levels for all mechanical excavation methods except for the ripper-dozer. In this case the cost was PLN 14.37/Mg and it was about PLN 2/Mg higher when compared to the other methods. The main reason for this was the high energy consumption of the excavation process carried out with this machine. The lowest cost was found for the process system using the Wirtgen surface miner. The cost for this machine was PLN 11.48/Mg of the output aggregate. This was possible due to the fact that a loader was not necessary and because the excavated material was highly fragmented by the excavating machine, which resulted in lower crushing costs.

A multi-criteria procedure for selecting mechanical excavation methods

Selecting the most optimal mechanical excavation method is a typical problem in multi-criteria decision making.

Bellinger's procedure involves preparing decision variant scores for all criteria for comparison and then aggregating them. Therefore, the most and the least desired states for each analysed assessment criterion of the available decision variant should be established. It is then determined whether a given assessment criterion boosts or inhibits the decision variant [3, 4, 7].

The purpose of decision analysis was to ensure the most effective use of a selected technology taking into account specific mining, geological and environmental conditions using the example of the "Raciszyn" Jurassic limestone deposit.

The decision variants in the presented procedure were the selected mechanical excavation methods for carbonate rock, i.e. involving:

- hydraulic hammers,
- vibration rippers,
- Wirtgen surface miners,
- ripper-dozer.

The decision-making model was divided into 7 stages. Stage 1 (Table 3) defined 5 assessment criteria which were the most significant for the specific analysis, designated K1 to K5.

Stage 2 (Table 4) defines the values desired and expected by the decision-maker, which reflected the idealised working conditions related to the technical and economic parameters analysed in this paper. The expert method was used to determine the values of weights corresponding to the degree of importance of each of the adopted criteria.

Unit cost of aggregate production and the degree of fragmentation of excavated material were determined to be the most important assessment criteria.

Stage 3 (Table 5) involved the creation of a matrix containing the real values of the criteria achieved in each variant. Information contained in the engineering documentation of excavating machines was used to determine their acoustic power and the minimum working area was defined on the basis of field studies.

Tab. 4. Defining the desired values and determining the degree of importance of each of the adopted criteria
Tab. 4. Określenie wartości pożądanych oraz określenie ważności każdego z kryteriów oceny

Item	K1	K2	K3	K4	K5
desired value	12	80	2	30	1,600
weight value	0.4	0.1	0.15	0.25	0.1

Tab. 5. Real values of assessment criteria by excavation method
Tab. 5. Zestawienie rzeczywistych wartości kryteriów oceny dla każdego sposobu urabiania

Item	K1	K2	K3	K4	K5
excavator + hammer	12.98	129	2	45	1,706
excavator + ripper	12.42	95	2	50	1,689
Wirtgen surface miner	11.48	110	10	25	3,617
dozer	14.37	125	10	35	2,672

Tab. 6. The obtained scores and ranks
Tab. 6. Zestawienie uzyskanych wyników wraz z miejscem rankingowym

Item	Score	Rank
excavator + hammer	0.58	**3**
excavator + ripper	0.30	**2**
Wirtgen surface miner	0.26	**1**
dozer	0.75	**4**

Stage 4 determined the amount of deviation from the desired state. The highest values were found for the machine purchase criterion and the lowest for the degree of fragmentation of the feed material.

Stage 5 normalised deviations from the desired state and stage 6 took into account the weights assumed in stage 2. The interpretation was presented in stage 7 (Table 6). It allowed determining the sum of the scores awarded to the respective variants, taking into account all five criteria. This stage allowed the classification of the mechanical excavation methods.

The lower the score, the closer a given variant is to the desired values. Taking into account the assessment criteria adopted by the authors and the assumed weights, the best excavation method involves the Wirtgen surface miner. It was followed by a single-bucket excavator with a vibration ripper. Using a ripper-dozer was found to be the furthest from the desired values.

Conclusions

Mechanical excavation methods are an alternative for the traditional excavation using drilling and explosives. Despite the much higher energy consumption, which translates into production costs, these methods are often the only available solutions to obtain the mineral. This was the case in the "Raciszyn" Jurassic limestone deposit, where nearby residential buildings made it impossible to use drilling and explosives.

The conducted technical and economic analysis defined the energy consumption and unit cost of aggregate production from the "Raciszyn" Jurassic limestone deposit. It should be noted that the excavated material obtained using various mechanical excavation methods differed in terms of particle distribution. It was observed that the degree of fragmentation had an impact on the costs of the remaining processes such as transport and crushing.

On the basis of the authors' assumptions, the most optimal mechanical excavation method at the "Raciszyn" Jurassic limestone deposit is the Wirtgen surface miner. The main benefits of this method were connected with the favourable fragmentation of the excavated material and the relatively low unit cost of aggregate production. A significant deviation from the desired value for this excavation method could be observed for criterion K3, i.e. working area requirements. This corresponds to the requirements for the operating technology of surface miners, which require long work sites for effective operation.

To summarise the results of the multi-criteria procedure of selecting the mechanical excavation method, the most optimal excavation method for the "Raciszyn" Jurassic limestone deposit was the Wirtgen surface miner.

Literatura – References

1. Będkowski T., Kasztelewicz Z., Sikora M., Raciszyn – unikatowe złoże wapieni [Raciszyn, a unique limestone deposit], Kamieniarz [Stone-Mason] 05/2013
2. Będkowski T., Kasztelewicz Z., Zajączkowski M., Sikora M., Analiza techniczno-ekonomiczna mechanicznego urabiania skał na przykładzie złoża "Raciszyn" [The technical and economic analysis of mechanical excavation using the example of the "Raciszyn" deposit], Inżynieria Mineralna [Mineral Engineering], 2016 R. 17 No. 2
3. Duchaczek A., Optimization of the selection of trucks used in construction projects, Zeszyty Naukowe Politechniki Poznańskiej. Organizacja i Zarządzanie [Research Bulletin of the Poznan University of Technology – Organisation and Management], 2015 vol. 65
4. Górny P., Elementy analizy decyzyjnej [Elements of decision analysis]. National Defense University, Warsaw 2004.
5. Kasztelewicz Z., Zajączkowski M., Sikora M., Przegląd mechanicznych sposobów urabiania skał zwięzłych [A review of mechanical methods of excavating compact rocks], Prace Naukowe Instytutu Górnictwa Nr 136 Politechniki Wrocławskiej [Scientific Papers of the Insitute of Mining, No. 136 of the Wrocław University of Science and Technology], Wrocław 2013
6. Kuznetsov V., Efficiency of excavation of overburden rock at quarries with the use of blast-free technology, Journal of Mining Science, v.32, no 5, 1997
7. Wolny M., Wspomaganie decyzji kierowniczych w przedsiębiorstwie przemysłowym. Wieloatrybutowe wspomaganie organizacji przestrzennej komórek produkcyjnych z zastosowaniem teorii gier [Assisting managerial decisions in an industrial company. Multi-attribute assistance in the spatial organisation of production units using game theory], Wydawnictwo Politechniki Śląskiej, Gliwice 2007.

Wielokryterialna metoda wyboru sposobu mechanicznego urabiania skał

W artykule przedstawiono wyniki analizy techniczno-ekonomicznej procesu produkcji kruszyw z wykorzystaniem mechanicznego urabiania skał za pomocą młota hydraulicznego, zrywaka wibracyjnego, kombajnu frezującego typu Wirtgen oraz spycharki z osprzętem zrywakowym. W tym celu wykonano próby eksploatacyjne tych maszyn na złożu wapieni jurajskich „Raciszyn". Określono średnią wydajność poszczególnych maszyn wchodzących w skład całego układu technologicznego, jednostkowe zużycie paliwa oraz krzywe składu ziarnowego. Dane te stanowiły dane wejściowe do analizy ekonomicznej poszczególnych sposobów mechanicznego urabiania skał oraz produkcji kruszyw. Wskazano sposób charakteryzujący się najmniejszym jednostkowym kosztem produkcji. Ponieważ różne sposoby mechanicznego urabiania skał wpływają nie tylko na koszty produkcji kruszyw ale również na inne pozaekonomiczne wartości, do wyboru optymalnego sposobu wykorzystano wielokryterialną metodą Bellingera.
Wielokryterialna metoda wyboru mechanicznego sposobu urabiania skał z wykorzystaniem metody Bellingera może być użytecznym narzędziem optymalizacyjnym, wymagającym jednak wiedzy z obszaru danej branży i występujących w niej procesów. Zaletą tej metody jest fakt, iż jest ona stosunkowo łatwa i prosta w użyciu. Metoda ta powinna ułatwić wstępną ocenę wyboru najbardziej oczekiwanej technologii oraz jednocześnie ocenę ryzyka zastosowania najmniej pożądanej technologii. Dokładność, a zatem i obiektywność, prowadzonych analiz uzależniona jest od liczby i jakości przyjętych kryteriów, co w dużym stopniu zależy od wiedzy osoby decyzyjnej.
Na bazie przyjętych przez autorów założeń, najbardziej pożądanym sposobem urabiania mechanicznego na złożu wapieni jurajskich „Raciszyn" było wykorzystanie kombajnu frezującego Wirtgen. Główne zalety tego sposobu związane są z korzystnym rozdrobnieniem urobku oraz niskim jednostkowym kosztem produkcji kruszyw.

Słowa kluczowe: mechaniczne urabianie skał, skały węglanowe, złoże „Raciszyn", zrywanie, frezowanie, metoda Bellingera