# WIELKOŚĆ SYSTEMU KOPARKI-WYWROTKI A WZRASTAJĄCA WIELKOŚĆ WYROBISKA STOŻKOWEGO – ANALIZA WSTĘPNA

## SHOVEL-TRUCK SYSTEM SIZE VERSUS PIT DEVELOPMENT – PRELIMINARY ANALYSIS\

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*System koparki-wywrotki jest szeroko stosowanym systemem maszynowym. Wyjątkową uwagę poświęca się jego wykorzystaniu w przemyśle górniczym, a szczególnie w kopalniach stożkowych. System ten stosowany od lat, był obiektem zainteresowania ośrodków naukowych, co skutkowało rozwiązaniem szeregu problemów z nim związanych. Mimo tego, wciąż istnieją zagadnienia, które pozostają bez rozwiązania, bądź nigdy wcześniej nie były poruszane, a mają istotne znaczenie dla funkcjonowania tego typu systemu. I tu można wymienić zagadnienie wielkości systemu koparki-wywrotki w relacji do powiększającego się wyrobiska i odpowiedź na pytanie, kiedy dodatkowe wozy odstawcze powinny być dokupywane i wprowadzone do wyrobiska, aby sprostać wciąż rosnącym wymaganiom eksploatacyjnym i transportowym. Niniejszy artykuł został poświęcony przedstawieniu wstępnych rozważań w tym temacie oraz wynikających z tego wniosków.*

*The shovel-truck system is a widely used machinery system. In this paper special attention is given to its use in the mining industry, especially in open-pit mining. This system has been used for many years, and has focused the attention and attracted the interest of many researchers, therefore over the years many problems have been solved, allowing this kind of system to operate much better. However, there are still some problems that are important for the functioning of this type of system which are unresolved or have never been addressed. One of them is an analysis of a shovel-truck system's size as the pit develops. This article contains a preliminary discussion of this topic and presents conclusions arising from it.*

## Introduction

For years shovel-truck systems have been widely applied all over the world not only in mining. Their application in open pit workings is widespread in spite of the fact that they have some severe characteristic demerits. In 2009 the number of large open pits exceeded 1000 and in all these enterprises such a type of machinery system was applied.

In addition, for many years the exploitation process of shovel-truck systems has been a point of interest of researchers. However, the difficult stochastic properties of the process has meant that the proper modelling, analysis and then system calculation have been accomplished only by different approximation methods (e.g. Barnes, King and Johnson 1979, Barbaro and Rosenshine 1986, Carmichael 1987, Czaplicki 1997). Finally, the D.Sc. dissertation of Czaplicki in 2006 was published showing how to model, analyse and calculate shovel-truck systems taking into consideration almost all of the stochastic phenomena occurring during the process realisation. These considerations were generalised significantly in his monograph of 2009. Many problems connected with operation of this type of machinery system were solved. Nevertheless, there are still some important issues waiting for a successful explanation. One of them is the problem of when additional trucks should be purchased for a system of this kind in order to fulfil the increasing requirements connected with the development of the mineral extraction. Additionally, the problem of repercussions associated with this enlargement of the system is also very interesting.

In the Mining Mechanisation Institute of the Silesian University of Technology, Gliwice, Poland, research has been commenced to get an answer to these questions. It requires both a good theoretical background as well as a good connection with mine practice.

The purpose of this paper is to present some results of preliminary considerations in this regard that have been obtained to date.

## The number of power shovels applied

A description of the early mine development phases, starting from an increased demand for a mineral product through the exploration phase resulting in the detection and description of deposits plus an evaluation regarding their financial attractiveness up to the commencement of production are presented in the Hustrulid and Kuchta monograph of 2006. Further parts of a mine's progress are also explained in a comprehensive way; however, the problem of the machinery required to achieve the potential mine production is treated marginally. This theme was not of interest in their considerations.

For a determination of the development of a machinery system in open pit mining two factors are of utmost importance, namely:

(a) mine planning to determine the amount of rock extracted that has to be removed from the pit in a planned sequence and in a given period of time,

(b) the increasing travel distance for the haulers accomplishing mine development.

Mine plans are prepared prior to a mining operation. Later, a graph showing the movement of the total mass of broken rock and waste/ore ratios is prepared. Looking at such a graph, the planner can see, among the other things, what has to be done to adjust or smooth out the production. Additionally, at least two conditions must still be kept in mind:

–    good ore exposure, and

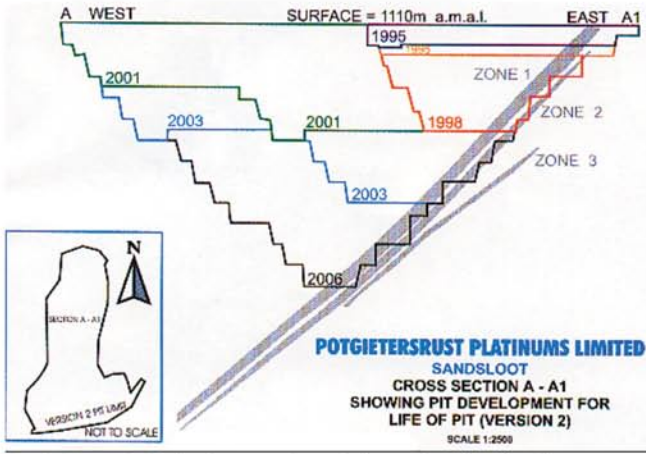–    the operating conditions that have to be assured.

Fig.1. Planned pit development for a platinum mine, South Africa (cf. Czaplicki 2006)

Rys. 1. Planowany rozwój wydobycia kopalni platyny, Południowa Afryka

Fig. 1 illustrates – as an example – a sequence of planned works to provide good ore exposure in order to extract platinum ore in a smooth way.

Going a bit deeper into this consideration the planner must apply an appropriate computer program (there are several on the market nowadays, e.g. Maptek's Vulcan or MineSight). The application of such a program allows for grade and tonnage estimation and gives a visualisation of the deposit as a collection of blocks (Fig.2). It also gives the sequence in which these blocks should be removed for specified field constraints.

Finally, taking into account all conditions that have to be satisfied, mining and geological limits and mine plans that are worked out by the mine planner, a final production schedule is prepared. The most communicative way to present the plan is to show it in a graphical form. An example of a final production programme graph that was taken from Couzens's paper of 1979 is presented in Fig. 3.

The various relationships between the total tonnage of mass movement, ore requirements, waste ratio, and shovel shifts are contained in this Figure.

Usually, pit development comprises three phases:
(a) early stage development,
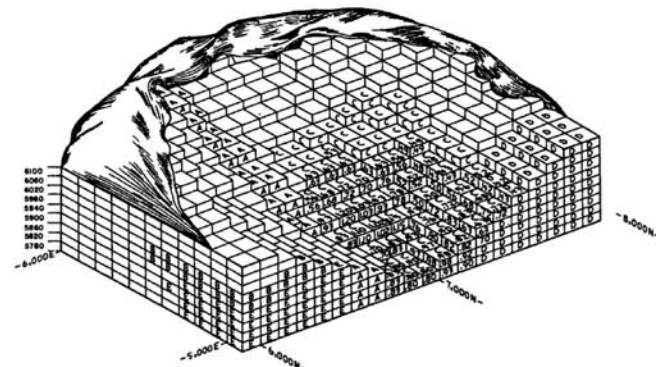(b) regular development,
(c) termination stage development.



Fig. 2. Diagrammatic view of a 3-D block matrix containing an ore body (Crawford and Davey 1979)

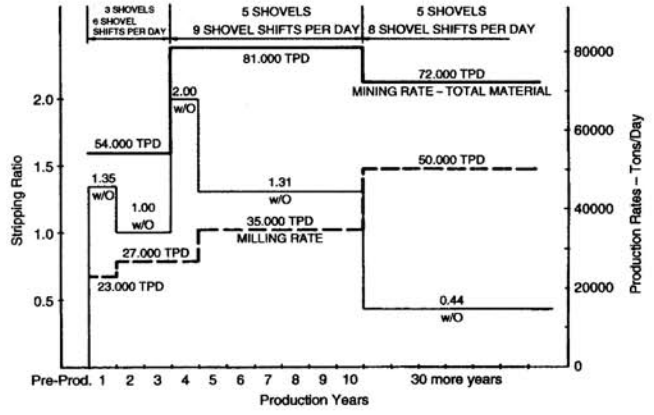Rys. 2. Trójwymiarowy blok macierzowy opisujący złoże (za: Crawford i Davey 1979)



Fig. 3. Example of a final production schedule graph based on a mining plan (Couzens 1979)

Rys. 3. Przykład planowania górniczego i sekwencji wielkości wydobycia (za: Couzens 1979)

Phase (a) is characterised by the increments in the mine production and the number of power shovels being applied grows. The truck fleet increases significantly as well.

Phase (b) typifies a stable level of mine production. The number of loading machines is usually constant; however, the truck fleet enlarges – first of all – because the dimensions of the pit increase.

Phase (c) is the final period of the pit's life. Frequently, mine production declines and the number of power shovels applied decreases. The truck fleet size remains intact, although in some cases it decreases slightly[1].

Reed (1990) gives – as an example – a pit production, i.e. the number of tonnes achieved per year and this is presented graphically in Fig. 4. Phases (a) and (b) are presented here[2].

Production $W$ versus time $t$ can be approximated, for example, by function:

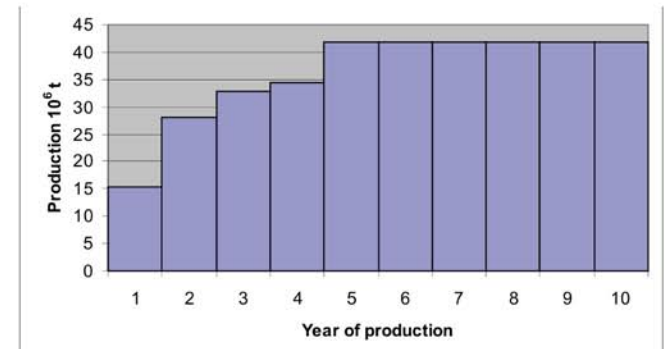$$W(t) = \frac{\alpha t}{t + \beta}, \quad t > 0, \; \alpha > 0, \; \beta > 0$$



Fig. 4. Production $W$ in tonnes $x\ 10^6$ in the subsequent years of pit operation $t$ (Reed 1990)

Rys. 4. Produkcja górnicza $W$ w tonach $x\ 10^6$ planowana w kolejnych latach (za: Reed 1990)

It is necessary to remember that the main goal of a mining operation is to remove ore. In order to accomplish this we have to make a pit in order to expose the ore and suitable ore exposure must be maintained during the whole mining operation. For this reason the planner creates a plan – a description of the successive works that have to be done to make it possible for continuous ore removal from the pit in a proper sequence provided that safety requirements are fulfilled. This plan *de facto* contains

tasks for the drilling system, afterwards for the loading system and later on for the hauling system.

If we look at Figure 3, bearing in mind the machinery involved in the exploitation running in the pit, it is easy to observe that the number of loading power shovels is specified (together with the number of shovel shifts per day), in relation to a period of operation. And that is all if machinery is concerned. The mine planner has an idea of what the stream of material generated by a determined shovel will be and the number of necessary loading machines is then calculated, or to put it frankly, the obtained reading from prepared plans. This fleet of power shovels is income data used to determine the number of trucks needed to haul the streams of broken rock extracted[3].

Nowadays, there is one method of truck fleet size determination being applied widely. It is based on schemes that are a part of mine planning. It has been worked out through gathering experience from mine practice over many years; however, the most recent data is the most important. But frankly speaking this method is only an approximate one. Other methods are also fairly accurate, even those making use of simulation schemes. But now, the size of a truck system can be estimated accurately based on the procedure developed by Czaplicki (2006, 2009).

Returning to machinery consideration we can state that the number n of power shovels that will be operating in the pit for a given period of time is determined by the mine plan prepared for a given pit. This means that this number is a parameter for further analysis from the mathematical point of view. Generally, its value changes as the mine develops.

## Number of trucks needed

The number $h$ of trucks needed to accomplish the transportation task determined by the shovel system is defined (e.g. Caterpillar 1996, Terex Manual 1981, and Czaplicki 2006) from the formula[4]:

$$h = \frac{z_t}{u_t} \tag{1}$$

where:
$z_t$ – the given transportation task in a unit of time
$u_t$ – the hauling capacity of a selected truck in a unit of time.

Denoting as $W_{mxef}$ the maximum effective output of the selected shovel, as $n$ the number of shovels applied, as $Q$ the truck payload and as $T_c$ the truck mean time, the following formula can be recorded:

$$h = \frac{nW_{mxef}}{Q/T_c} = n\frac{Q}{Z'}B_kA_k\frac{T_c}{Q} = nG_k\frac{Z'+T_j}{Z'} = nG_k\left(1+\varpi^{-1}\right) \tag{2}$$

where:
$B_k$ – the accessibility coefficient of the shovel
$A_k$ – the steady-state availability of the shovel
$G_k$ – the shovel loading capacity coefficient
$Z'$ – the adjusted mean time of loading
$T_j$ – the mean time of truck travel (haulage-unload-return)
$\varpi$ – the coefficient of relative intensity of loading given by the pattern:

$$\varpi = \frac{Z'}{T_j} \tag{3}$$

The magnitude $h$ denotes, in fact, the expected number of trucks in a work state. In other words, the number $h$ determines $h$ ideal, totally reliable haulers. However, if their reliability is taken into account the number of *real* trucks needed is given by pattern:

$$V = \frac{h}{A_w} \tag{4}$$

where $A_w$ is the steady-state availability of selected trucks.

Let us look more carefully at pattern (2). We can analyse which of its components will change as the pit develops. But first, let us identify some block elements of the formula.

The product $nA_k$ denotes the number of totally reliable power shovels which is equivalent to the system of shovels applied, whereas the product $nA_kB_k$ denotes the number of totally reliable and always accessible power shovels which is equivalent to the system of shovels operating in the pit. By changing:
- the type of the power shovels applied or
- their number

we change the number of trucks needed for the system in a directly proportional way. Let us notice a certain subtleness.

If a new power shovel is introduced into the pit the number of haulers needed jumps significantly.

If one power shovel is replaced by a different one of different reliability, the number of haulers required changes only slightly.

There is also one important parameter associated with power shovels but not only with them. This is the adjusted mean time of truck loading. 'Adjusted', because one adds the mean time of all small operations made by shovel that do not stop loading but during this time (small operations) loading action is not realised to the mean time of loading (Czaplicki 2009 p. 43). Practically, we increase the mean time of loading by 5%.

If some trucks are added or subtracted from the machinery system operating in the pit, but all haulers are the same, the mean time of loading remains intact. An identical statement can be



Fig. 5. Chuquicamata mine, Cu, Chile
Rys. 5. Kopalnia Chuquicamata, Cu, Chile

Fig. 6. Aitik mine, Cu, Sweden
Rys. 6. Kopalnia Aitik, Cu, Szwecja



Fig. 7. Escondida mine, Cu, Chile
Rys. 7 Kopalnia Escondida, Cu, Chile

formulated in relation to power shovels.

One parameter in formula (2) is noticeably associated with the development of the pit. That is the mean time of truck travel. This increases continuously in a smooth way as the pit enlarges. It is not only connected with the pit depth (Chuquicamata, Chile, Figure 5, is almost 1 km deep) but generally it depends on the spatial characteristics of the working (see also photos 2, 3) and is also dependant on the assumed and realised configuration of haul roads in the pit[5].

Bearing the above in mind and looking at formula (2), a quick conclusion can be drawn that the truck fleet should continuously grow as the pit develops. However, the mean time of truck travel increases smoothly but the number of trucks required is a function of a stepped character increasing in a discrete way as is shown in Fig. 8. Symbol $\nabla(V)$ denotes the natural number obtained from the real number $V$ by rounding it up.

Looking at patterns (2) and (4), the angle $\zeta$ is determined by the relationship:

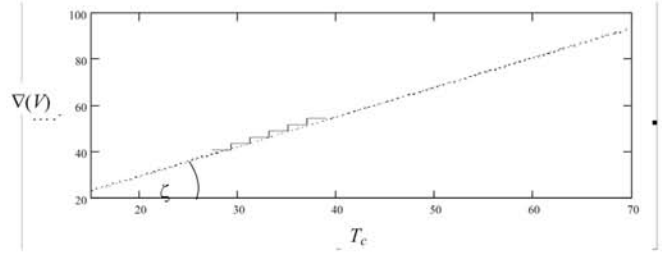$$\frac{nG_k}{Z' A_{s}} = tan\, \zeta \qquad (5)$$



Fig. 8. Function of the number of trucks needed depending on the mean time
of truck work cycle $T_c$
Fig. 8. Function of the number of trucks needed depending on the mean time
of truck work cycle $T_c$

## Repercussions

The variable number of trucks needed for the machinery system operating in a given pit has a significant influence on the exploitation process running in the mine. Let us list the most important ones.

(1) Each system of trucks has a reserve of size, say, $r$. Therefore, it is necessary to select a pair $<m, r>$, where $m$ denotes the number of trucks directed to the pit to accomplish the transportation task. The proper procedure of the selection of such a pair is given in Chapter 8 of Czaplicki's monograph (2009).

(2) Each system of trucks generates – during its operation – a stream of failed trucks. This stream must be taken by the maintenance system consisting of, among other things, repair stands of an appropriate number and equipped with the appropriate equipment. It is of great importance to determine this number in a most rational way. Otherwise, a queue of failed haulers will be waiting for repair and the transportation task will be difficult to achieve. The maintenance bay should be enlarged as the fleet of trucks increases.

(3) Each system of trucks generates the necessity of its maintenance. The maintenance bay must possesses the proper number of maintenance stands required to realise all actions in this regard and have both the exploitation materials (spare parts, lubricants etc) as well as the appropriate equipment to accomplish them (manipulators, jacks, diagnostic apparatuses and so on).

(4) Each system of trucks generates a requirement for fuel even when a trolley assist system is arranged on the main haulage ramp of the pit and haulers are equipped with electric motors. This increasing demand for fuel must be satisfied. This can be done having suitably large tanks, the proper number of fuel taps and an appropriately frequent oil supply .

(5) An increasing number of haulers running in the pit means increments in the maintenance requirements for the mine haul roads .



Fig. 9 and 10. Heavy traffic situation in open pit mining
Rys. 9 i 10. Przykłady zatłoczenia na drogach odstawy

(6) An increasing number of haulers running in the pit means that a lot of tires will be needed; there must be a large area to store new tires and worn ones and a growing demand for utilisation of these worn out ones will be observed.

(7) An increasing number of haulers running in the pit boosts the requirements for a truck dispatcher.

(8) An increasing number of haulers running in the pit means that safety problems connected with many machines moving around become more serious.

(9) Sometimes it happens that if many trucks are in circulation in pit (see for instance Figures 9 and 10), they begin to disturb each other and the mean time of truck travel decreases[6] and mine production drops. Such a situation should be avoided.

**Final remarks**

The discussion presented here is the first step in recognising the regularities and existing relationships in the process of changes in a machinery system operating in a given pit taking into account its continuous development. Further analysis in this regard will mainly be orientated on truck fleet enlargement as well as on enlargement of the backup facility in the shape of repair shop. This analysis is currently being carried out.

**Literature**

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**Footnotes**

[1] Notice, that the average life of open pit actually does not exceed twenty years. Nevertheless, there are some pits whose life may last even a hundred years.

[2] Unfortunately, in Reed's chapter there are two errors. Starting from the fifth year of a hypothetical mine operation, the number of haulers is constant and the mine production is also constant. This does not work. The dimensions of the pit increase during mine operation which means that the truck travel time increases as well. There is no way to maintain stable production if there is a constant number of trucks. Additionally, there is a presumption stating that truck life is eight years but no new trucks are shown in Reed's example after eight years of the pit's operation.

[3] There is an operational limit in the application of power shovels in a pit. This boundary is connected with fact that shovels should operate round-the-clock i.e. they require a lot of haulers. When there are too many trucks in a pit, they disturb each other causing a reduction in output which is obviously inconvenient.

[4] Sometimes one can find different formulas for determining truck fleet size, but these are often ineffective, e.g. the patterns presented in Bagherpour dissertation 2007.

[5] For different haul road arrangements see for example Hustrulid and Kuchta (2006, chapter 4.8).

[6] This problem is a subtle one. The moment when trucks start to disturb each other is difficult to trace. It is possible to state such a regularity by analysing data on the operation of trucks taken from the computer in the dispatch centre and verifying it with drivers. Czaplicki presented a few analytical methods to trace heavy traffic situation in a pit (2011) and one of these methods was discussed more comprehensively by Czaplicki and Kulczycka (2011).