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On the Dynamics of Mining Operations in Open Pit Mines

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ABSTRACT

In this paper, mining dynamics is defined as the relationship between the mining rate and movement of mining operations conducted on the benches of a surface mine. This relationship describes the intensity of the pit development in space, in order to meet ore demand at the mill over time. Meeting the mill ore demand is a key factor in optimizing production scheduling in surface mines. Displacement velocity of mining operations within cutbacks, or independent pit units, is introduced in the context of long-term mine planning. Displacement velocity allows the place and time of transition of the mining operations from one independent pit unit to another to be determined as the condition for meeting the mill ore demand. An application using data from Mt Keith Nickel Operations in Western Australia is used to elaborate on the methods presented.

Keywords: surface mining, long-term mine planning, optimization, transition dynamics, cutback.

1. INTRODUCTION

Surface mines are dynamic environments characterized by a continuous displacement of the working faces of mining operations in time and space. In a mechanical context, dynamics deals with forces and their relationship to motion. Similarly, mining dynamics may be defined as the relationship between the mining rate and the movement of mining operations being conducted on the working benches in the open pit. This relationship describes the intensity of the development of an open pit mine in the horizontal and vertical directions. The dynamics and intensity of mining operations are thereby characterized by their horizontal and vertical components of displacement velocity.

The dynamics of the mining operations are determined by several factors. One of them is the geometry of the partitioning of the orebody within the ultimate pit limits

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into cutbacks or, more generally, independent pit units (IPUs). Mining operations within one or more IPUs form the overall working zone of the mine, which covers the working benches in the open pit mine. Other factors affecting the dynamics of the mining operations include the capacity of the production equipment, including drills, shovels and trucks, and the organization and management of production.

The assessment of mining dynamics deals with the prediction of the place and time of the transition of mining operations from one IPU to another, so that the demand for ore at the mill is met. Prediction of the parameters of transition from IPU to IPU can contribute to the optimization of long-term production scheduling as well as to the understanding of average production characteristics in a given design. As part of the optimization in a mine design, assessment of the dynamics of mining operations is constrained by a geometric compatibility of the formation of the overall working zone of the open pit mine. Geometric compatibility means that the level of the working bench of each succeeding IPU must be higher or equal to the level of the working bench of the preceding IPU.

The concept of dynamics of mining operations for surface mining, given the ore demand at the mill and the introduction of the displacement velocity of mining operations as a contributor to mine planning, was introduced by Arsentiev [1,2]. This paper extends this development to the context of modern mine planning [3] and presents initial experiments in the use of displacement velocity for characterizing and evaluating the production performance of IPUs in a given mine design and mill demand. The definitions of displacement velocities are presented in Section 2. Section 3 describes the method linking velocities to the time of transition of mining operations from IPU to IPU, based on mill requirements. Section 4 shows a case study in which Mt Keith Nickel Operations, WMC Resources, Western Australia, is a first example of application of the methods. Conclusions are presented in Section 5.

2. DEFINING THE DISPLACEMENT VELOCITY OF MINING OPERATIONS

This section defines displacement velocity and related concepts pertinent to the assessment of the dynamics of mining operations in an open pit mine. The definitions are based on the following assumptions.

1. An open pit mine is represented by a group of cutbacks or independent pit units (IPUs).
2. Mining operations within each IPU are conducted bench after bench, from top to bottom.
3. Characterization of the dynamics of mining operations is suitable for long-term planning, and is thus limited to average assessments.

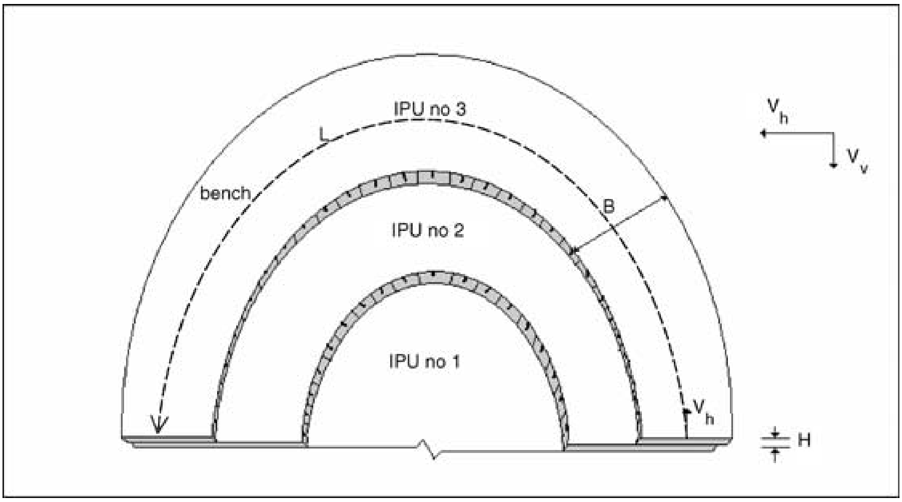

Fig. 1. Schematic representation of an open pit mine with three IPUs showing the geometric characteristics of a working bench; please refer to the text for details.

4. The mine layout is nearly *central-elliptical*, corresponding to the commonly used Whittle approach [3, 4, 5] based on pit shells that can be used to form IPUs.

The dynamics of mining an IPU are characterized by the displacement velocity of the mining operations. This velocity has two components: horizontal (V_h) and vertical (V_v). The horizontal velocity is related to a bench of an IPU and determines the rate of change in displacement of the mining operations as a result of excavating a bench. This is illustrated in Figure 1, which shows an open pit mine with three IPUs. The geometric characteristics of the working bench, for example IPU no. 3, are the bench height H, bench width B, and bench length L. The working bench of an IPU is defined here as a geometrical body of rock mass, whose size is determined by two consecutive locations of the horizontal plane used to distinguish benches, and which has to be mined. In the context of the Whittle Four-X methodology [6,7], the bench height is a constant while the bench width is a variable because the shape of the bench is determined as an incremental extension of the pit outlines. The latter outlines are a function of the metal price variation, thus the bench width can be seen as a parameter related to economics.

The horizontal velocity of the displacement of mining operations can be assessed in terms of an average and instantaneous velocity. The average velocity is defined as

$$V_h = \frac{L}{T} \tag{1}$$

where L is the displacement of the face of the working bench and T the time of the face displacement. T can be further expressed as

$$T = \frac{Q_{rm}}{Q_{sh}} \tag{2}$$

where Q_{sh} is the annual production of the working shovel (bank cubic metres per year [bcm/a]) and Q_{rm} is the volume of the bench (bcm) such that

$$Q_{rm} = \sum_{j=1}^{n_b} q_j \tag{3}$$

with q_j being the volume of j-th block of the bench (bcm) and n_b being the number of blocks in the bench.

Another form of Equation 1 can be derived by substituting T from Equation 2, which leads to

$$V_h = \frac{LQ_{sh}}{Q_{rm}} \tag{4}$$

Equation 4 assesses the annual horizontal velocity of the mining operations in the case that only one shovel is used for the excavation of the working bench. This means that the bench length coincides with the length of the shovel front. In the case that a bench is excavated simultaneously by more than one shovel, Equation 4 is generalized to

$$V_h = \frac{L \sum_{k=1}^{n_{sh}} Q_{sh_k}}{Q_{rm}} \tag{5}$$

where Q_{sh_k} is the annual production of k-th shovel (bcm/a) and n_{sh} the number of working shovels.

The instantaneous horizontal velocity of the mining operations displacement is defined as

$$V_h = \frac{dL}{dt} = f'(t) \tag{6}$$

Equation 6 shows the horizontal velocity as a derivative of the position function *f(t)* of the bench face at time instant *t*. The instantaneous horizontal velocity deals with the determination of the details of the location of the bench face and its displacement. Instantaneous horizontal velocity is a characteristic of interest to short-term planning, and its practical importance in the context of current mine planning remains to be further explored.

The average vertical velocity of the mining operations is defined as a relationship between the vertical displacement of the mining operations, bench height H, and the time of displacement T

$$V_v = \frac{H}{T} \tag{7}$$

T has the same meaning and can be expressed in the terms of Equation 2, that is the annual production of the working shovel(s) and the volume of the bench being mined.

In practice, vertical velocity of the mining operations within an IPU is assessed from the height of the bench to be mined. Assessment with Equation 7 provides information about the dynamics of mining the corresponding IPU. It reflects the intensity of mining, which in turn reflects, to a large extent, the quality of the ore being mined. The vertical velocity can be used to verify the geometric compatibility of the formation of the overall working zone of the open pit, particularly when two or more IPUs are included simultaneously in the mining operations. Vertical velocity can be linked to the ability to meet mill requirements and is further discussed in the following section.

There is a relationship between the vertical and horizontal components of the velocity of mining operations based on Equations 1 and 7

$$V_v = \frac{H}{L} V_h \tag{8}$$

As expected, equation 8 shows that the vertical and horizontal components of the velocity of the mining operations are proportional. Increase in the horizontal component leads to increase in the vertical component. The proportionality between the two components is controlled by the bench height and length relationship. The relationship of displacement velocity to the mining IPU and to mill requirements are explored next.

3. TRANSITION DYNAMICS FOR IPUS AND MEETING MILL DEMAND

The dynamics of transition of mining operations from one IPU to another is constrained by two key considerations. The first is geometric compatibility of the formation of the overall working zone of the open pit. The second is ore supply and waste management from the pit so that ore demand at the mill is always met. Open pit optimization formulations which consider ore and waste as the products of a mine, produced under a variety of technical and economic constraints, and managed under given mill demand, are developed by Rzhenevisky [8] and Arsentiev [1], and are presented by Tan and Ramani [9].

The geometric compatibility of the formation of the overall working zone of the mine is schematically shown in Figure 1. The working zone of IPU no. 1 is represented by its top bench (starter pit), which requires the excavation of drop cuts. In the same figure, the upper bench of IPU no. 2 represents its initial working zone. For geometric compatibility of the overall working zone, the working zone of IPU no. 2 must follow or coincide with the working zone of IPU no.1, so that it does not overtake the working zone of IPU no. 1 at, for example, a potential simultaneous exploitation of both IPUs.

The transition of mining operations from one IPU to another must be planned so that, over the life of the mine, mill ore demand is met. This is a key constraint in optimizing long-term production schedules. Planning transitions requires the choice of time and location in the pit for the transition of mining operations from one IPU to another. In Figure 1, the place and time of transition can be represented by a bench of the starter pit whose excavation begins simultaneously with excavation of the upper bench of IPU no. 2.

The time of transition is the time of inclusion of an IPU in the exploitation of the open pit mine. Following an optimization and mine planning framework introduced from Russian mining [7, 8], Figure 2 shows the cumulative plots of tonnes or rock

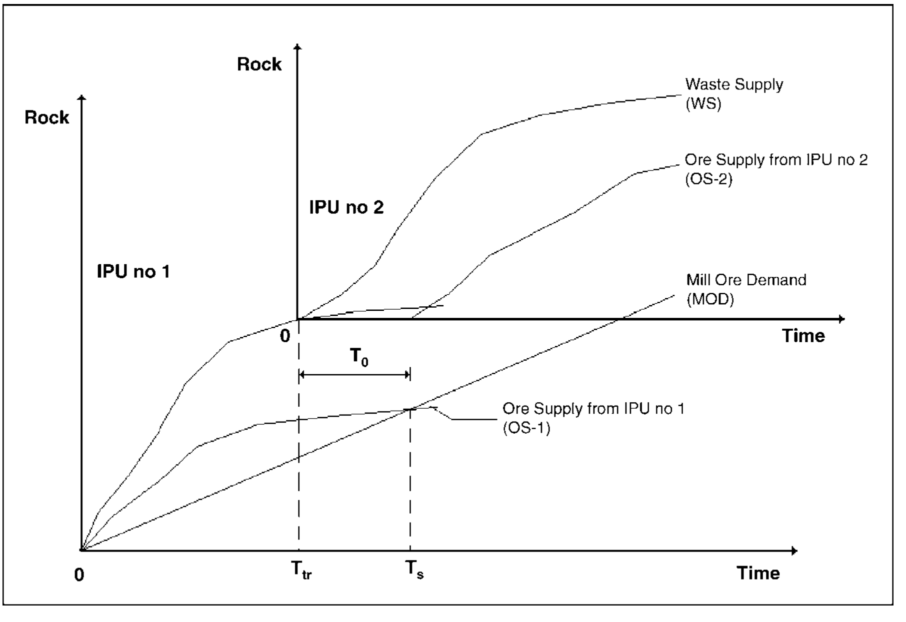

Fig. 2. Determining the time of transition of the mining operations from one IPU to another and related notation (please refer to the text for explanations).

mined (ore and waste) for two IPUs. More specifically, the figure shows the cumulative ore mined, that is, the ore supply to the mill (OS) and the cumulative waste mined (WS), which are characteristics of the pit supply in time. In addition, Figure 2 plots the cumulative mill ore demand (MOD) over the life of the two IPUs. The figure suggests that the pit supply of ore of IPU no. 1 (OS-1) can meet the mill ore demand up to time T_s. After that time the mill ore demand cannot be met because the ore supply from IPU no. 1 is below the MOD curve. Not meeting ore demand at the mill means that this is the time to start mining IPU no. 2 and increase the pit basic ore supply.

Hence, the time of transition T_{tr} *(1:2)* from IPU no. 1 to IPU no. 2 is

$$T_{tr}(1:2) = T_s - T_o \tag{9}$$

where T_s is the time at which the MOD and the OS-1 curves intersect and T_o is the time required for removal of the waste from IPU no. 2 before mine ore can be removed. Note that time T_s in Equation 9 determines when the ore supply of IPU no. 2 (OS-2) needs to be included in the exploitation process.

Equation 9 can be generalized as

$$T_{tr}(k:k+1) = T_{s_k} - T_{o_k}, \quad k = 1, N_{IPU} - 1 \tag{10}$$

where k means k-th IPU; N_{IPU} is the total number of IPUs of the mine design; T_{s_k} is the time at which the mill ore demand (MOD) intersects with the cumulative total ore production from the succeeding inclusion of the ore supply (OS) of k-1-th IPU; T_{o_k} is the time required for excavation of the waste benches of $k+1$-th IPU before mining of the first ore bench of the same IPU can commence.

Equations 9 and 10 reflect the need to meet mill production that is set *a priori* as mill ore demand per period of the life of mine. Thus, at any time, the OS curves must be higher than or equal to MOD curves, and their intersection defines the time of transition of the mining operations from one IPU to another.

In addition to the time of transition, the dynamics of transition can be further explored with respect to the geometrical compatibility of the formation of the overall working zone of the open pit mine. Figure 3 shows a cross-section of a mine consisting of three IPUs. IPU no. 1 is being mined and IPU no. 2 is planned to be included in the production process to meet the mill ore demand. The condition for the transition of the mining operations from IPU no. 1 to IPU no. 2 can be represented as

$$T'_{IPU-1} \leq T'_{IPU-2} \tag{11}$$

where T'_{IPU-1} is the time required for excavation of the rock residuals of IPU no. 1, determined by the place of transition and corresponding to the pit height $H_{tr}(1:2)$; T'_{IPU-2} is the time required for excavation of IPU no. 2 down to the bottom level of IPU no. 1 and corresponds to height H'_{IPU-2}.

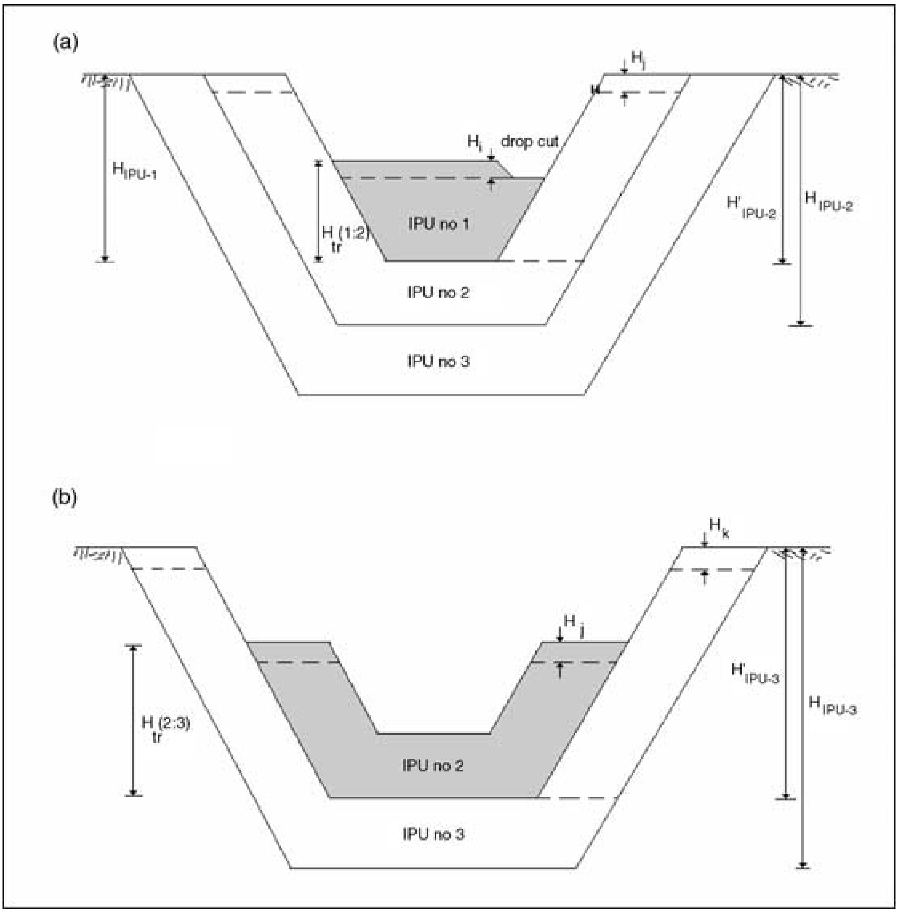

Fig. 3. Schematic representation of the transition from (a) IPU no. 1 to IPU no. 2; and (b) IPU no. 2 to IPU no. 3 (please refer to the text for discussion).

The rock residuals of IPU no. 1 can be defined as the rock mass to be mined within the IPU's outlines, restricted by the bench of transition to IPU no. 2 and the lowest bench of IPU no. 1. The time required for excavation of the rock residuals is determined by the difference between the total time of excavation of IPU no. 1 and the time of transition from Equation 9.

It is important to note that Equation 11 indicates that mining operations in IPU no. 1 must ensure a mining rate such that the excavation time of its rock residuals is less than or equal to the excavation time of IPU no. 2 down to the bottom level of IPU no. 1. In other words, the working zone of IPU no. 2 will follow or coincide with the working zone of IPU no. 1 down to its bottom level. To go below this is geometrically impossible, that is the working bench of IPU no. 2 cannot be beneath the working bench of IPU no. 1.

For the inclusion of IPU no. 3 in the mining process, as illustrated in Figure 3(b), Equation 11 can be rewritten as

$$T'_{IPU-2} \leq T'_{IPU-3} \tag{12}$$

where T'_{IPU-2} is the time required for excavation of the rock residuals of IPU no. 2, as determined from the place of transition and corresponding to the pit height $H_{tr}(1:2)$; T'_{IPU-3} is the time of mining of IPU no. 3 down to the bottom level of IPU no. 2, corresponding to the pit height H'_{IPU-3}.

Equations 11 and 12 both reflect the constraint that the working zone of the preceding IPU must follow or coincide with the working zone of the succeeding IPU to ensure feasible transitions of the mining operations.

Using Equation 7, Equation 11 can be rewritten as

$$\sum_{i=1}^{n'_{IPU-1}} \frac{H_i}{V_{v_i}} \leq \sum_{j=1}^{n'_{IPU-2}} \frac{H_j}{V_{v_j}} \tag{13}$$

where H_i is the height of i-th bench of IPU no. 1 (see also Figure 3); H_j is the height of j-th bench of IPU no. 2; n'_{IPU-1} is the number of benches of IPU no. 1 between its place of transition and its bottom level; n'_{IPU-2} is the number of benches of IPU no. 2 down to the bottom level of IPU no. 1.

Similarly, Equation 12 becomes

$$\sum_{j=1}^{n'_{IPU-2}} \frac{H_j}{V_{v_j}} \leq \sum_{k=1}^{n'_{IPU-3}} \frac{H_k}{V_{v_k}} \tag{14}$$

where H_j is the height of j-th bench of IPU no. 2 (see also Figure 3); H_k is the height of k-th bench of IPU no. 3; n'_{IPU-2} is the number of benches of IPU no. 2 between its place of transition and its bottom level; n'_{IPU-3} is the number of benches of IPU no. 3 down to the bottom level of IPU no. 2.

Lastly, it follows that the general forms of the equations for the transition dynamics are

$$T'_k \leq T'_{k+1} \tag{15}$$

$$\sum_{i=1}^{n'_k} \frac{H_i}{V_{v_i}} \leq \sum_{j=1}^{n'_{k+1}} \frac{H_j}{V_{v_j}} \tag{16}$$

where k denotes k-th IPU; i denotes the bench number of k-th IPU of the transition; j denotes the bench number of $k+1$-th IPU of the transition.

Expressing geometric constraints, Equations 15 and 16 indicate that the working zone of each succeeding IPU must follow or coincide with the working zone of the preceding IPU.

4. A CASE STUDY

The methods outlined in the previous sections are further explored in this section using data from Mt Keith Nickel Operations in Western Australia. Mt Keith Nickel Operations is part of WMC Resources, the largest nickel producer in Australia and the third largest worldwide. Mt Keith is a major nickel surface mine with measured reserves of over 280 million tonnes of nickel ore at 0.56% (1546 thousand tonnes of nickel metal) and a 20 year life of mine. The orebody consists mainly of fine-grained pentlandite, a nickel sulphide, hosted in a serpentinised olivine cumulate dunite rock of Archaean age. The Mt Keith open pit uses a conventional drill, blast and haul, truck and shovel operation, and is developed in stages. Pit designs are 2.5km long and 1.3km wide, with an overall depth expected to reach nearly 0.5km [10].

The case study presented here is based on an open pit optimization and long-term mine planning study undertaken by the mine. However, it should be noted that the IPUs developed in the example are not the same as the cutbacks used at the mine. The IPUs developed here are representative of the orebody at Mt Keith and of its key mining aspects when optimizing the pit, and aim to elucidate the concepts and practical aspects of the methods presented in this paper, rather than to conduct a study for the mine site.

The design of Mt Keith considered here consists of six IPUs derived from a pit optimization study using Whittle software [6,7]. The pit ore flow is divided into basic and secondary ore. The basic ore goes to the mill, and is defined as the ore having a grade higher than the mill-feed cutoff grade of 0.26% Ni. The secondary ore goes to stockpiles for blending with the primary ore and includes the marginal grade ore, low talk ore, arsenic ore and transition ore, and has a grade over 0.20%. The annual mill production in the Mt Keith source schedule is 11 million tonnes. The production schedule in this study starts in 1999 and runs to the year 2020.

4.1. A look at displacement velocities

The results obtained for the vertical velocity of mining operations at Mt Keith, given the six IPUs in the design considered, are discussed in this section, and are presented in plots of velocity versus bench number for each IPU from the top to the bottom. The bench height is 15m. IPU no. 1 is not considered because it represents a ‘‘year-to-date’’ stage covering the current state of the mining operations at Mt Keith mine, and includes insufficient rock quantities to generate meaningful calculations.

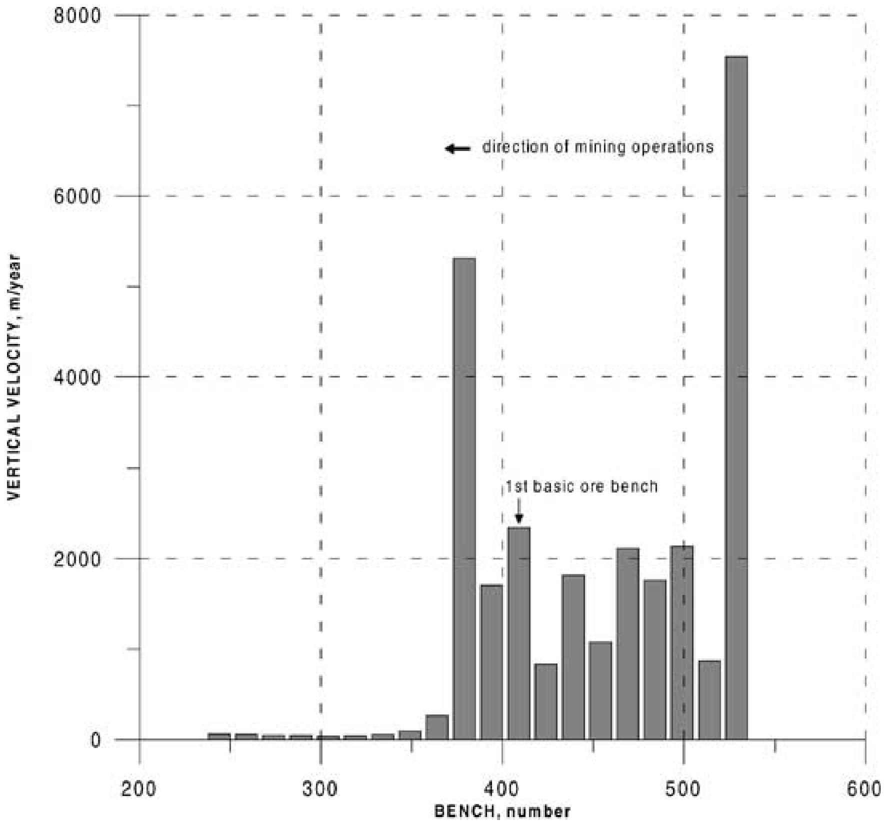

Fig. 4. Vertical velocity versus bench in IPU no. 2.

Figure 4 plots the velocity distribution of IPU no. 2, bench by bench. The direction of the mining operations with depth is marked on the figure, as is the first bench where ore is produced. IPU no. 2 has two parts with a relatively stable velocity variation. The first part includes the group of benches concluded between bench RL544 and bench RL379. The average velocity of the first part is high at about 1700m per year. This can be explained by the fact that the benches of this part of the IPU have already been mined and the remaining rock mass is small. The average velocity for the second part is about 50m per year, which indicates that the relevant benches represent a high ore proportion with little waste. The contrast in the velocity variation is due to the different technological state of both groups of benches.

Figures 5 and 6 show the vertical velocity variation in IPU no. 3 and IPU no. 4 respectively. The figures show a common trend in the vertical velocity variation with

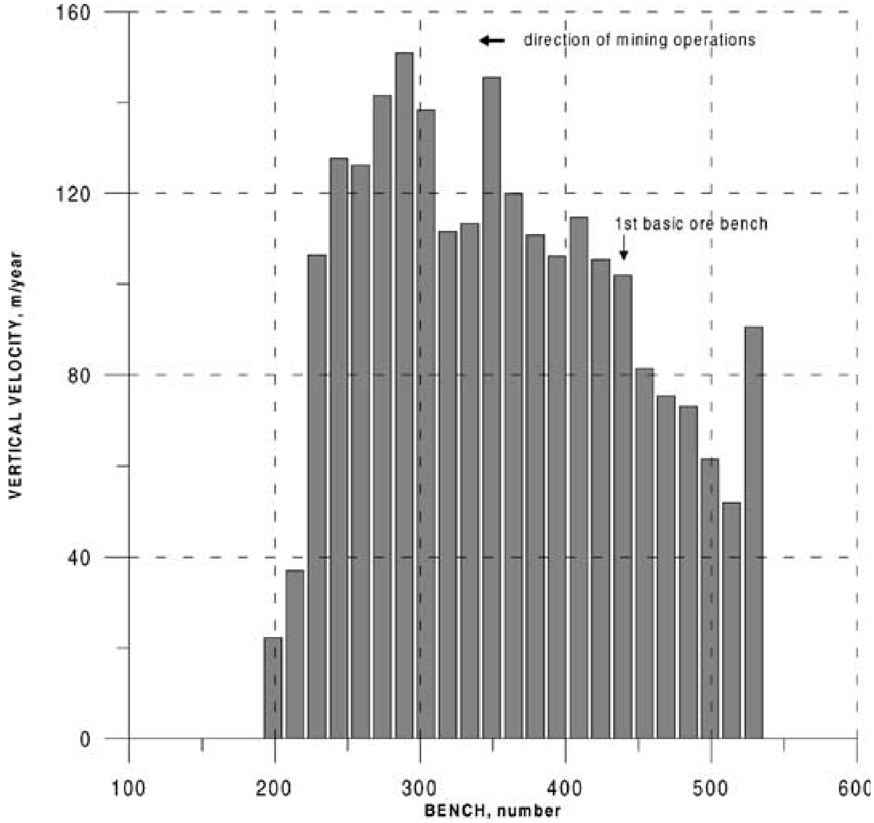

Fig. 5. Vertical velocity versus bench in IPU no. 3.

depth of both pit units. There is an initial increase in the velocity, due to the presence of large amounts of waste in the upper benches. The bench level corresponding to the first bench of ore is RL439. The average velocity for pit height between the upper bench and the first ore bench is about 75m per year in IPU no. 3, and about 70m per year in IPU no. 4. The velocity of IPU no. 3 continues to increase to 150m per year in bench RL289, and then to sharply decrease following the decrease in the quantities of rock at the lower part of the pit. The velocity of IPU no. 4 shows a different behaviour. After the first bench with ore, velocity reaches the maximum of 175m per year for the bench level RL379, then drops sharply before increasing again up to the bottom bench (level RL289) of the pit unit. This is due to the intentional increase in the mining intensity in that part of IPU no. 4 which contains mostly basic ore. The aim is to keep mining a large quantity of basic ore of high grade to feed the mill.

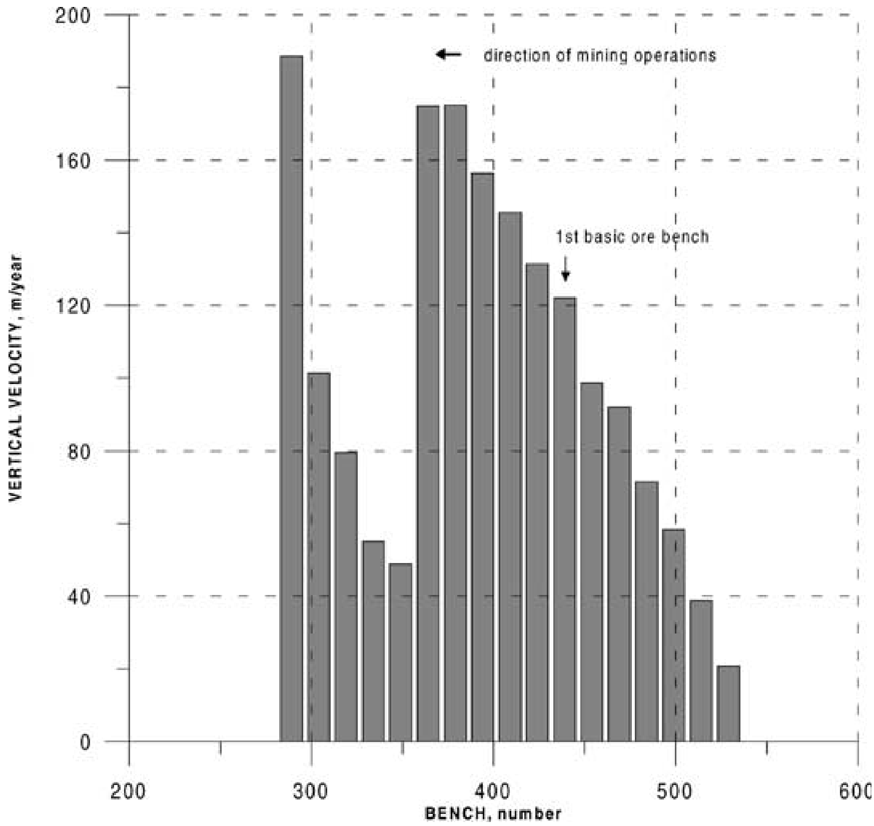

Fig. 6. Vertical velocity versus bench in IPU no. 4.

Like previous pit units, IPU no. 5 has its specific pattern of vertical velocity variation with depth, as shown in Figure 7. Initially the velocity is higher because of the presence of waste. In this case waste continues even after the first bench of basic ore (level RL424) is reached. The average velocity for pit height up to the first bench with ore is about 70m per year. The maximum velocity of 78m per year is reached at bench level RL334. After this bench the velocity drops sharply and continues at an average value of 40m per year to the bottom of the pit unit. This drop can be explained by the decrease in mining intensity that occurs through the increase of the excavation time of the benches.

The velocity variation of IPU no. 6 is shown in Figure 8. The velocity is initially quite low, which is due to large quantities of waste in the upper benches and the larger size of this pit unit. In subsequent benches, the velocity increases reaching a

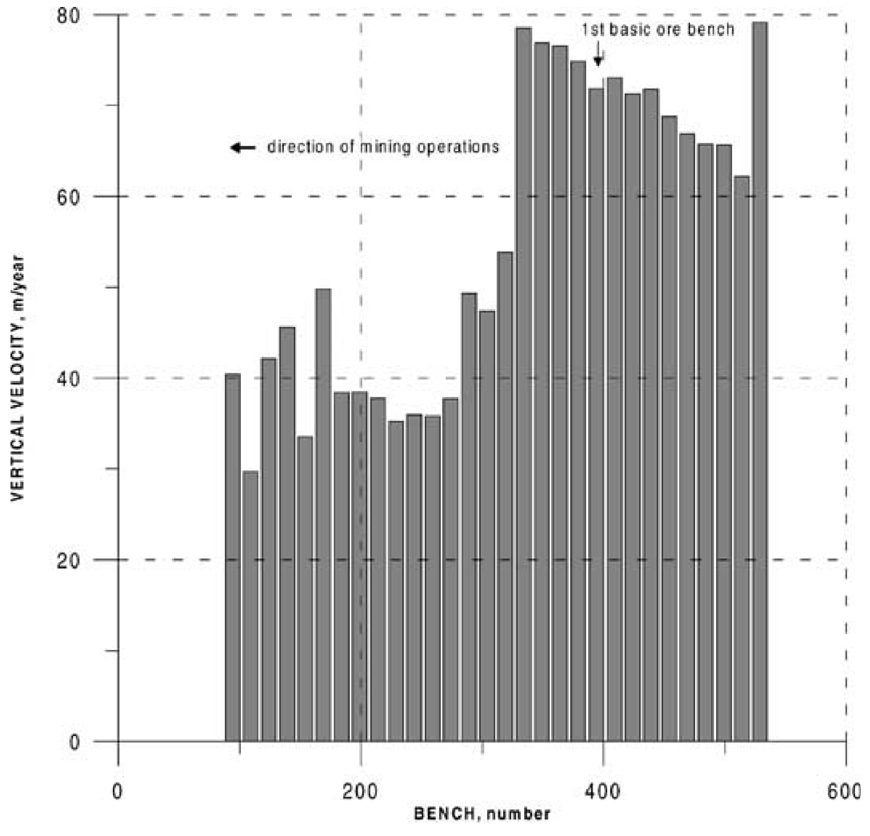

Fig. 7. Vertical velocity versus bench in IPU no. 5.

maximum of 60m per year in bench RL304. After a slight decrease in bench RL199, the vertical velocity increases and asymptotically reaches the end of the pit height range. The average velocity related to the height between the upper bench and first bench of basic ore is about 35m per year. This is the lowest average vertical velocity for all IPUs of Mt Keith.

4.2. Transitions of mining operations between IPUs

The production schedule from the pit optimization study considered here is assessed with respect to the requirements for transition dynamics. Table 1 provides results on the time of transition from one IPU to another and time of commencement of the related ore and waste supply for each pit unit, as per the concepts shown in Figure 2

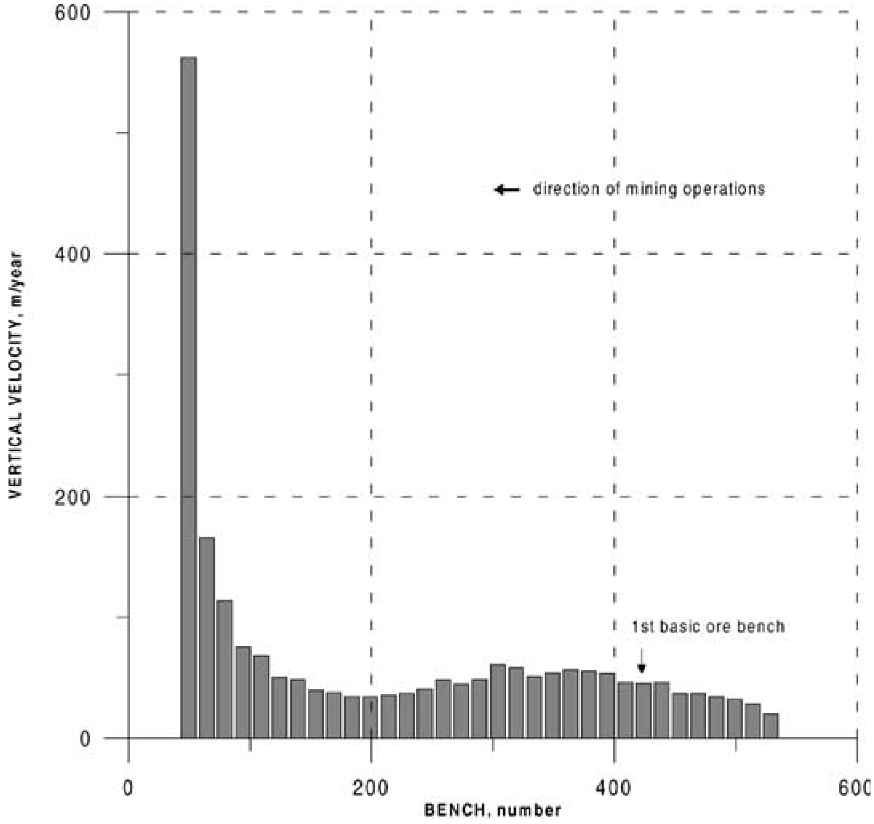

Fig. 8. Vertical velocity versus bench in IPU no. 6.

Table 1. Results of transition dynamics – Part 1.

IPUs in transition	Time of Waste Supply commencement years	Time of Ore Supply commencement years
1 : 2	0.05	0.15
2 : 3	0.50	1.05
3 : 4	3.06	3.87
4 : 5	5.85	7.77
5 : 6	12.11	14.63

Table 2. Results of the transition dynamics Part 2.

IPUs in transition	Time of transition years	Place of transition bench level (RL)	Constraints for transition dynamics (Eqs. 15 and 16)
1 : 2	0.0476	529	met
2 : 3	0.5032	409	met
3 : 4	3.0556	364	met
4 : 5	5.8457	425	met
5 : 6	12.1096	214	met

and discussed in Section 3. Table 2 shows the time and place of transitions. Table 1 shows the commencement time of waste supply for IPU no. 2 is 0.05 years, whereas the commencement time of ore supply is 0.15 years. Table 2 shows the transition of mining operations from IPU no. 1 to IPU no. 2 is 0.05 years, which is the commencement time of waste supply in IPU no. 2. This is earlier than the commencement time of ore supply from the pit (0.15 years), indicating that IPU no. 2 has in its upper part only waste benches, which have to be mined before the ore benches are exposed. The place of transition of the mining operations from IPU no. 1 to IPU no. 2 is the bench level RL529 of IPU no.1.

The results for the remaining transitions of mining operations show similar behaviour. The commencement time of the waste supply of each IPU is ahead of the commencement times of ore supply from the pit. Hence, the commencement time of the waste supply determines the time of transition of the mining operations from one IPU to another. The maximum delay of commencement time of ore supply with respect to the commencement time of waste supply (14.6 years compared to12.1 years) is related to the transition from IPU no. 5 to IPU no. 6. This delay is due to the large number of waste benches of IPU no. 6 at its upper part, where excavation needs 2.52 years before reaching the first bench with ore. The place of transition of mining operations is the bench level RL214 of IPU no. 6, which is the lowest bench level of all the assessments of the place of transition (see Table 2).

Table 2 also reports on whether the constraints for transition dynamics from one IPU to another, as described by Equations 15 and 16, are met. The fact that conditions are met for each transition means that the geometric compatibility of the formation of the overall working zone over the life of the mine is ensured, for the given design of pit units and production schedule considered here.

The results of the case study presented here show that each of the six IPUs of the Mt Keith open pit considered here has its own specific pattern of vertical velocity variation, and this variation reflects ore and waste present, mining capacities and mill demand. There is a common trend in all IPUs of an initial increase of the vertical velocity in order to intensify mining in the upper waste benches and access the first benches with ore faster. Meeting the conditions for transition dynamics in the six IPUs suggests that the schedule being considered is physically meaningful as far as geometric constraints are concerned. Generally, the analysis of velocities and transition constraints is a tool that can assist mine planning, particularly the evaluation of a given set of cutbacks.

5. CONCLUSIONS

Mining dynamics is defined in this paper as the relationship between the mining rate and the movement of mining operations conducted on the benches of a surface mine. This relationship describes the intensity of the development of the pit in space to meet ore demand at the mill. Meeting the mill ore demand is a key factor in optimizing production scheduling in surface mines. To characterize mining operations as part of long-term mine planning while complying with technical geometric constraints, the concept of displacement velocity within cutbacks or independent pit units was developed. The use of displacement velocity allows the place and time of transition of the mining operations from one independent pit unit to another to be determined as the conditions for meeting the mill ore demand.

To elucidate the methods, pit optimization data from Mt Keith nickel mine in Western Australia was used to assess the dynamics of mining operations for a set of six cutbacks generated through a conventional optimization study. The case study showed a large variation between IPUs in the intensity of the mining operations needed to meet mill ore demand, due to varying geometric constraints on transition dynamics. In addition, the method generated the time and location of transition of mining from pit unit to pit unit. Further, the method presented can contribute to the understanding of any mine plan and long-term production schedule, as well as to the search for better technological solutions for the regulation of waste mining rate, management of production equipment, scheduling, organization and management of production.

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