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Short-term open-pit mine production scheduling with hierarchical objectives

F. Manríquez, H. González & N. Morales
DELPHOS Mine Planning Laboratory, Department of Mining Engineering and Advanced Mining Technology Center (AMTC), Universidad de Chile, Santiago, Chile

ABSTRACT: Short-term mine scheduling in open-pit mines consists of meeting the objectives defined by the long-term mine production schedule. Short-term scheduling in open-pit mines has multiple hierarchical objectives to optimize. This work proposes an optimization methodology to generate a short-term open-pit mine production schedule optimizing multiple hierarchical objectives. For the generation of mine schedules, we propose an optimization model based on mixed-integer linear programming. This model considers the usual restrictions of mine sequencing and also takes into account both time and cost of movement between phases of each shovel. In order to optimize the multiple hierarchical short-term objectives, we apply the hierarchical and weighted sum methods in the proposed optimization model. We verify this methodology in a real open-pit mine case study. The results show that both methods generate short-term mine schedules optimizing the different short-term objectives.

1 INTRODUCTION

Short-term mine scheduling in open-pit mines consists of meeting the objectives defined by the long-term mine production schedule. Short-term scheduling in open-pit mines has multiple objectives to optimize. In some mine operations, these objectives are ranked in a descending order which are: (i) the minimization of the deviation between the ore sent to the ore processing plant and the ore processing capacity of the plant per period, (ii) the minimization of the deviation between the metal fines sent to the plant and the fines expected by the ore processing plant, and (iii) the overall minimization of the movement time/cost of the shovel fleet. This work proposes an optimization methodology to generate a short-term open-pit mine production schedule optimizing multiple hierarchical objectives. For the generation of mine schedules, we propose an optimization model based on mixed-integer linear programming (MILP). This model considers the usual restrictions of mine sequencing and also takes into account both time and cost of movement between phases of each shovel. In order to optimize the multiple hierarchical short-term objectives, we apply the hierarchical and weighted sum methods (Grodzevich & Romanko, 2006; Nehring *et al.*, 2018) in the proposed optimization model. We verify this methodology in a real open-pit mine case study. The remainder of this paper is organized as follows. Section 2 briefly reviews the existing literature related to short-term mine production scheduling in open-pit mines. Section 3 presents the proposed optimization model and explains the procedure to perform various objective optimization using both hierarchical and weighted sum methods. In section 4, we describe the open-pit mine case study conducted to generate short-term production schedules optimizing multiple objectives, applying both hierarchical and weighted sum methods. Section 5 reports the results and discussion of the case study. Finally, section 6 presents the conclusions of the work.

2 RELATED WORK

Researchers have mainly applied mathematical optimization to generate short-term production schedules in open-pit mines considering the optimization of multiples objectives. An excellent review of works related to short-term production scheduling in open-pit mines can be found in Blom *et al*. (2018). Smith (1998) describe a model to maximize ore production subject to ore quality constraints. Huang *et al*. (2009) describe a production scheduling tool based on MILP to solve short- and medium-term schedule problems for open-pit mines that involves multiple models, multiple processes, multiple destinations, and blending requirements. Eivazy & Askari-Nasab (2012) develop a MILP model for minimizing the overall cost of open-pit mines, considering multiple destinations. The model incorporates buffer and blending stockpiles, horizontal directional mining and decisions on ramps while controlling operational constraints such as head grade, mining and processing capacities, and mining precedence. L'Heureux *et al*. (2013) propose an optimization model based on MILP to determine the blocks to extract and their order, considering precedence among operational tasks, drilling, blasting, transportation, processing, movement of shovels, drills among others. Blom *et al*. (2014, 2016) propose an optimization problem based on MILP to address the short-term scheduling problem in open-pits networks. The authors also present a rolling-horizon-based algorithm for solving this model. Blom *et al*. (2017) presents a novel variation of the rolling horizon-based algorithm presented in Blom *et al*. (2014, 2016), in which multiple distinct schedules are generated, concurrently, each optimized concerning an ordered sequence of objectives. Matamoros & Dimitrakopoulos (2016) propose a formulation based on stochastic mixed integer programming. The objective function considers terms associated with operating fleet cost, mining cost, and penalty cost to penalize deviation from production target, expected fleet utilization and mining width. Fioroni *et al*. (2008) presented a MILP model to allocate shovels to mine faces and the number of trips that each type of truck fleet have to carry out to these faces, subject to production and blending constraints. The models are called by an open-pit truck-shovel simulation model, whenever a change in the mine operation system occurs, in order to update the allocation of shovels to the new operation state. Upadhyay & Askari-Nasab (2016, 2017, 2018) described a MILP model to allocate shovels to mine faces in order to: maximize production, meet desired head grade and tonnage at crushers and minimize shovel movements. This model is called by an open-pit truck-shovel simulation model, similarly than the work of Fioroni *et al*. (2008).

3 MATERIALS AND METHODS

In this section, we present the optimization model and describe the methodology to generate short-term mine production schedules optimizing various objective optimizations using the hierarchical and weighted sum methods.

3.1 *Optimization model*

The optimization model proposed is a shovel allocation problem based on MILP. The objective of the model is to provide shovel allocations to phases and benches over a one year scheduling horizon. We present the sets & indexes, variables and parameters of the optimization model in Tables 1, 2, and 3, respectively.

Here we describe the constraints of the proposed optimization model. The material extracted by the fleet of shovels of the bench b of the phase f along the planning horizon must be equal to the total material available (Equation 1). The total ore sent to the ore processing plant must be lower than the ore processing capacity (Equation 2). The shovel's operative time plus the shovel's movement time between the phases are lower or equal to the availability of the shovel (Equation 3). In order to assign operative time, a shovel p must be assigned to the bench b of the phase f (Equation 4). When a bench is finished, it cannot be assigned with any shovels (Equation 5). To assign a shovel p in a bench b of a phase f, that

Table 1. Optimization model's sets & indexes.

Symbol	Description
P,p	Set and index for shovels.
F,f	Set and index for phases.
$B(f),b$	Set for benches of phase f and index for benches.
T,t	Set and index for periods.
R,r	Set and index for routes.
$R(f)$	Set of routes that contains phase f.
$FR(r)$	Set of routes which the first phase is equal to the last phase of route r.
FC	Set of consecutive phases (f,f')

Table 2. Optimization model's variables.

Symbol	Description
$x_{p,f,b,t} \in [0,1]$	Time percentage of the period $t \in T$ where shovel $p \in P$ is operative in bench $b \in B$ of the phase $f \in F$.
$\overline{x}_{p,f,b,t} \in \{0,1\}$	Equal to 1 if shovel $p \in P$ is allocated in bench $b \in B$ of the phase $f \in F$ in period $t \in T$, 0 otherwise.
$z_{f,b,t} \in \{0,1\}$	Equal to 1 if bench $b \in B$ of phase $f \in F$ is inactive at period $t \in T$, 0 otherwise.
$\overline{z}_{f,b,t} \in \{0,1\}$	Equal to 1 if bench $b \in B$ of phase $f \in F$ finishes its exploitation in period $t \in T$ or later, 0 otherwise.
$\overline{w}_{p,f,t} \in \{0,1\}$	Equal to 1 if shovel $p \in P$ is allocated on phase $f \in F$ in period $t \in T$, 0 otherwise.
$\upsilon_{p,r,t} \in \{0,1\}$	Equal to 1 if shovel p goes through route r in period t, zero otherwise.
$D \in \mathbb{R}^+ \bigcup \{0\}$	Minimum maximum deviation between the processing plant capacity and the ore send to processing plant
$d_t^- \in \mathbb{R}^+ \bigcup \{0\}$	Positive deviation between the processing plant capacity and the ore send to processing plant
$G \in \mathbb{R}^+ \bigcup \{0\}$	Maximum deviation between the processing plant capacity and the ore send to processing plant
$g_t^+ \in \mathbb{R}^+ \bigcup \{0\}$	Positive deviation between the processing plant capacity and the ore send to processing plant
$g_t^- \in \mathbb{R}^+ \bigcup \{0\}$	Positive deviation between the processing plant capacity and the ore send to processing plant

Table 3. Optimization model time and cost parameters.

Symbol	Unit	Description
TT	[h]	Total time per period.
$TI_{p,r}$	[%]	Percentage over the nominal time of the period where shovel p needs to move between the phases of route r.
$AV_{p,t}$	[%]	Availability of shovel p in period t.
$CT_{p,r}$	[USD]	Movement cost of shovel p along the phases of route r.
$RM_{p,f,b}$	[t/h]	Maximum throughput of mined material by the shovel p, in the phase f, in the bench b.
$TM_{f,b}$	[t]	Total material to be mined in bench b in phase f.
$OF_{f,b}$	[%]	Percentage of ore material in the bench b of the phase f.
PC	[t]	Total capacity of the ore processing plant.
EG	[%]	Expected grade of the metal by the ore processing plant.
SG	[t/m^3]	Rock density.
BH	[m]	Bench height.
$AD_{f,b}$	[m]	Initial operative area of the bench b of the phase f where shovels can operate.
AS_p	[m^2]	Minimum operative area of shovel p.
$ML_{f,g}$	–	Maximum number of benches between consecutive phases f and g.
$mL_{f,g}$	–	Minimum number of benches between consecutive phases f and g.

shovel must be allocated in that phase f (Equation 6). To assign operative time in a bench b of a phase f in a shovel p, it must be allocated in that phase f (Equation 7). Bench b of phase f is not finished in period t until all the material are extracted (Equation 8). If a bench b of a phase f is finished in a period t, it remains finished in period $t + 1$. Constraints 10 controls the precedence between benches of the same phase. Thus, to a bench b of a certain phase f can be active, the upper bench must be finished. To assign operative time, the phase-bench must be active (Equation 11). Constraints 12 and 13 controls the precedence between benches of consecutive phases. Constraints 14 to 15 control the area available in the phase-bench in order to allocate shovels. Constraints 16 to 18 models the shovel movements between phases. At most just one route is performed by shovel p in period t (Equation 16). Constraint 17 links the binary variable $\overline{w}_{p,f,t}$ with the variable $\upsilon_{p,r,t}$. For each shovel p, the constraint 18 ensures that the route r of period t and the route s of period $t + 1$ are coherent, that is, the last phase f of the r route and the first phase of the s route is the same. The set $FR(t)$ represents the set of all the routes consistent with the r route. That is, the set of routes whose first phase is the same as the first phase of the r route. Constraints 19 and 20 model the deviation between the ore sent to the ore processing plant and the ore processing capacity per period. Constraints 21 to 23 model the deviation between the metal fines sent to ore processing capacity and the expected fines by the ore processing plant per period.

$$\sum_{p\in P, f\in F, b\in B} RM_{p,f,b} \cdot x_{p,f,b,t} \cdot TT = TM_{f,b} \quad \forall p \in F, b \in B(f) \tag{1}$$

$$\sum_{p\in P, f\in F, b\in B} RM_{p,f,b} \cdot x_{p,f,b,t} \cdot TT \leq PC \qquad \forall t \in T \tag{2}$$

$$\sum_{f\in F, b\in B(f)} x_{p,f,b,t} + \sum_{r\in R} TI_{p,r} \cdot v_{p,r,t} \leq AV_{p,t} \quad \forall p \in P, t \in T \tag{3}$$

$$\overline{x}_{p,f,b,t} \leq x_{p,f,b,t} \qquad \forall p \in P, f \in F, b \in B(f), t \in T \tag{4}$$

$$\overline{x}_{p,f,b,t} + \overline{z}_{f,b,t-1} \leq 1 \qquad \forall p \in P, f \in F, b \in B(f), t \in T \tag{5}$$

$$\overline{w}_{p,f,t} \geq \overline{x}_{p,f,b,t} \qquad \forall t \in T, f \in F, b \in B(f) \tag{6}$$

$$\overline{w}_{p,f,t} \geq x_{p,f,b,t} \qquad \forall p \in P, f \in F, b \in B(f) \tag{7}$$

$$\overline{z}_{f,b,t} \leq \sum_{p\in P, \tau\in\{1,\ldots,t\}} RM_{p,f,b} \cdot x_{p,f,b,\tau} \cdot TT \qquad \forall f \in F, b \in B(f), t \in T \tag{8}$$

$$\overline{z}_{f,b,t} \geq z_{f,b,t-1} \qquad \forall f \in F \tag{9}$$

$$z_{f,b,t} \leq \overline{z}_{f,b-1,t} \qquad \forall f \in F, b \in B(f), t \in T \tag{10}$$

$$x_{p,f,b,t} \leq z_{f,b,t} \qquad \forall p \in P, f \in F, b \in B(f), t \in T \tag{11}$$

$$z_{f,b,t} \geq \overline{z}_{f',(b'-ML_{f,f'}),t} \qquad \forall (f,f') \in FC, b \in B(f), b' \in B(f'), t \in T \tag{12}$$

$$z_{f,b,t} \leq \overline{z}_{f',(b'-mL_{f,f'}),t} \qquad \forall (f,f') \in FC, b \in B(f), b' \in B(f'), t \in T \tag{13}$$

$$\sum_{p\in P} AS_p \cdot \overline{x}_{p,f,b,t} \leq AD_{f,b} \qquad \forall f \in F, b \in B(f), t = 1 \tag{14}$$

$$\sum_{p\in P} AS_p \cdot \overline{x}_{p,f,b,t} \leq AD_{f,b} + \sum_{p\in P, \tau\in\{1,\ldots,t\}} \frac{RM_{p,f,b} \cdot x_{p,f,b,\tau} \cdot TT}{SG \cdot BH} \forall f \in F, b \in B(f), t \in T \setminus \{1\} \tag{15}$$

$$\sum_{r\in R} v_{p,r,t} \leq 1 \qquad \forall p \in P, t \in T \tag{16}$$

$$\overline{w}_{p,f,t} \leq \sum_{r\in R(f)} v_{p,r,t} \qquad \forall p \in P, t \in T, f \in F \tag{17}$$

$$\sum_{s\in FR(r)} v_{p,s,t} \geq v_{p,r,t-1} \qquad \forall t\in T\setminus\{1\}, p\in P, r\in R \tag{18}$$

$$d_t^- \leq D \qquad \forall t\in T \tag{19}$$

$$\sum_{p\in P, f\in F, b\in B} RM_{p,f,b}\cdot x_{p,f,b,t}\cdot TT + d_t^- = PC \qquad \forall t\in T \tag{20}$$

$$g_t^+ \leq G \qquad \forall t\in T \tag{21}$$

$$g_t^- \leq G \qquad \forall t\in T \tag{22}$$

$$\sum_{p\in P, f\in F, b\in B} RM_{p,f,b}\cdot x_{p,f,b,t}\cdot TT + g_t^- - g_t^+ = \sum_{p\in P, f\in F, b\in B} RM_{p,f,b}\cdot x_{p,f,b,t}\cdot OF_{f,b}\cdot EG \qquad \forall t\in T \tag{23}$$

3.2 *Multiple objective optimization methods*

In this work, we optimize the short-term objectives in the following hierarchical order:

1. Minimize the maximum deviation between ore sent to the ore processing plant and ore processing capacity per period: $f_1 = \min D$
2. Minimize the maximum deviation between metal fines and the expected metal fines expected by the ore processing plant per period: $f_2 = \min G$
3. Minimize overall shovel movement cost: $f_3 = \min \sum_{p\in P, r\in R, t\in T} CT_{p,r}\cdot v_{p,r,t}$

Below, we describe two methods to generate short-term mine production schedules optimizing multiple objectives: the weighted sum method and the hierarchical method.

3.2.1 *Weighted sum method*

The weighted sum method allows the multiple-objective optimization problem to be cast as a single-objective mathematical optimization problem. This single objective function is constructed as a sum of objective functions f_i multiplied by weighting coefficients w_i, hence the name. The coefficients w_i are computed as $w_i = u_i\theta_i$, where u_i are the weights assigned by the decision maker based on the hierarchy of the objectives and θ_i are the normalization factors. In this work, the normalization factors are computed as $\theta_i = z_i^{-1}$, where z_i is the value of the objective function of the optimization problem when solving for the single objective function f_i (Grodzevich & Romanko, 2006). In this way, the weighted sum method consists of two stages. The first one solves i optimization problems (corresponding to the i short-term objectives) in order to obtain the normalization coefficients θ_i. Then, an optimization problem is solved whose objective function corresponds to the weighted sum of all the short-term objectives considered. The coefficients w_i that multiply each of the objectives are calculated using the normalization coefficients θ_i obtained from the first stage and the weights u_i assigned by the decision maker based on the prioritization of the objectives. The following problems need to be solved in the context of the weighted sum method:

- mMDP: Minimize the maximum deviation between ore sent to the processing plant and ore processing capacity per period.
- mMDF: Minimize the maximum deviation between metal fines sent to the processing plant and expected metal fines by the ore processing plant per period.
- mD: Minimize the overall shovel fleet movement cost between phases.
- WS (1,2,3): Minimize the weighted sum of the three short-term objectives considered in this work.

3.2.2 *Hierarchical method*

The hierarchical method allows the decision maker to rank the objective functions in descending order of importance, from 1 to k. Each objective function is then minimized individually subject to a set of additional constraints that do not allow the values of each of the higher ranked functions to exceed a prescribed fraction of their optimal values obtained on the corresponding steps (Grodzevich & Romanko, 2006). In this work, these sets of additional constraints do not allow the values of each of the higher ranked functions to take no other than the same optimum value obtained on the corresponding steps. In the proposed optimization model, the sets of constraints that impose that the maximum deviation of ore processing capacity per period does not take another value than the obtained in the previously solved problem are 19 and 20. Analogously, the set of constraints that enforce that the maximum deviation of fines per period does not take another value than the obtained in the previously solved problem are 21 to 23. The following problems need to be solved in the context of the hierarchical method:

- mMDP: Minimize the maximum deviation between ore sent to the ore processing plant and the ore processing capacity per period.
- mMDF(mMDP): Minimize the maximum deviation between metal fines sent to the ore processing plant and the expected metal fines by ore processing plant per period, subject to the minimum maximum deviation between ore sent to the processing plant and the ore processing capacity per period.
- mD(mMDF(mMDP)): Minimize overall shovel movement between phases subject to: (i) minimum maximum deviation between ore sent to the processing plant and the ore processing capacity per period, and (ii) the minimum maximum deviation between metal fines sent to the processing plant and the expected metal fines by the ore processing capacity per period.

4 CASE STUDY

A case study of an open-pit copper mine is considered to verify the model. Year 4 is selected as the short-term schedule for the case study. The schedule requires 63.49 [Mt] of ore and 29.55 [Mt] of waste to be mined in year 4 with four phases (1, 2, 3 and 4). Figure 1 depicts the mine layout in year 4 with the road network, one plant crusher and two waste dumps. The plant has an annual ore capacity of 2.51 [Mt]. Plant crusher is desired to have ore with a copper grade of 1.1 [%]. Mine production operations are carried out in two shifts of 12 [h] daily and seven days a week. The mine employs a total of 2 electric shovels. Shovel 1 has a throughput of 4,114 [t/h] and shovel 2 has a throughput of 5,486 [t/h]. Both shovels have an availability of 80.0%. Shovel 1 requires a minimum operational area of 1,239 [m^2], whereas shovel 2 requires 1,491 [m^2]. The shovel average movement velocity is estimated at 0.24 [km/h], due to numerous curves and slopes of the road network for the mine layout case study. The operational cost of shovel movement is estimated at 1.00 [USD/m]. Table 4 shows the distances each shovel needs to travel between phases.

In this case study, the mine operation prioritizes the short-term objectives as shown in section 3.2. We generate a short-term mine production schedules. Comparing the hierarchical

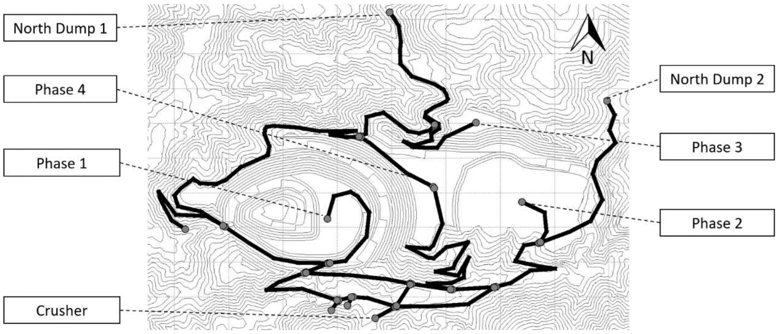

Figure 1. Mine layout with ramps and road network in year 4.

Table 4. Distance between phases.

Phases	1,2	1,3	1,4	2,3	2,4	3,4
Distance [m]	2,800	4,276	3,273	4,813	2,968	1,845

Table 5. Optimization of single optimization problem objectives.

Problem	mMDP	mMDF	mD
Maximum ore processing capacity deviation [%]	1.864%	8.237%	14.500%
Maximum positive deviation of copper fines [t]	6,462	4,967	6,734
Maximum negative deviation of copper fines [t]	6,754	4,967	6,945
Shovel fleet movement time [days]	12.5	9.5	4.0
Shovel fleet movement cost [kUSD]	71.9	54.6	22.8

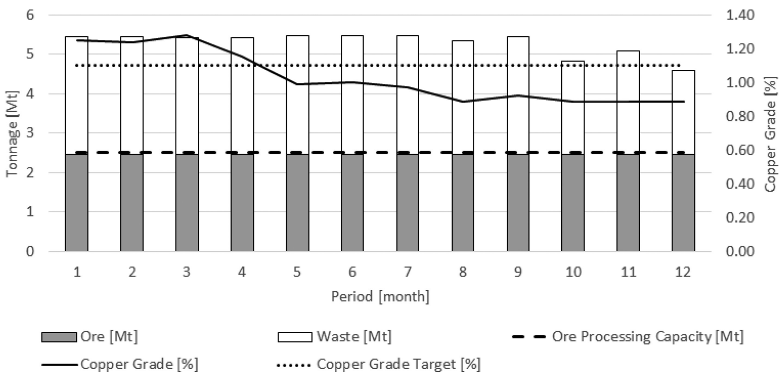

Figure 2. Mine short-term production schedule for the case study.

method with the weighted sum method in terms of: (i) minimum maximum deviation between ore and ore processing capacity per period, (ii) upper and lower maximum deviation between copper fines and expected copper fines in the ore processing capacity per period, (iii) Overall movement cost and time of shovel fleet, and finally (iv) resolution time. In the weighted sum method, the weights u_i assigned by the decision maker for each objective in decreasing order take the values of 10,000; 100 and 10.

5 RESULTS AND DISCUSSION

In the case study, the weighted sum method needs 22.11 [h] to be carried out (resolution of mMDP, mMDF, mD and WS(1,2,3)), while the hierarchical method needs 11.85 [h] (resolution of mMDP, mMDF(mMDP), mD(mMDP(mMDF)). Table 5 shows the results of the mD, mMDP, and mMDF problems.

Figure 2 shows in the final production schedule of the case study, whereas Table 6 compares deviations of plant capacity, deviations of copper fines and overall movements of the shovel fleet for problems associated with the hierarchical method (mMDP, mMDF(mMDP), mD(mMDF(mMDP))) and the problem associated with the weighted sum method (WS(1,2,3)).

From the Table 6 it is verified that each problem of the hierarchical method maintains the objectives imposed by the previous problems and at the same time diminishes or maintains the short-term objective that it wishes to minimize. In effect, it is observed that the mMDP

Table 6. Short-term objectives deviations of case study.

Problem	Hierarchical mMDP	Hierarchical mMDF (mMDP)	Hierarchical mD (mMDF (mMDP))	Weighted Sum WS(1,2,3)
Maximum ore processing capacity deviation [%]	1.864%	1.864%	1.864%	1.864%
Maximum positive deviation of copper fines [t]	6,462	4,484	4,484	4,484
Maximum negative deviation of copper fines [t]	6,754	5,202	5,202	5,202
Shovel fleet movement time [days]	12.5	10.2	10.2	10.2
Shovel fleet movement cost [kUSD]	71.9	58.9	58.9	58.9

problem obtained a maximum deviation of the plant processing capacity of 1.8%, whose level is maintained in the following problems mMDF(mMDP) and mD(mMDF(mMDP)). On the other hand, the problem mMDF(mMDP) decreased the positive and negative deviation of the copper fines concerning the mMDP problem. This deviation is maintained by the post problem mD(mMDF(mMDP)). Also, the problem mMDF(mMDP)) decreased the total days of blade movement obtained by the mMDP problem from 12.5 days to 10.2 days. Finally, problem mD(mMDF(mMDP)) maintained the level of deviations of plant capacity, deviations of copper fines and movement costs and movement times of the shovel fleet obtained by the mMDF problem (mMDP). On the other hand, it is verified that the application of the hierarchical method obtains the same value of the short-term objectives (problem mD(mMDF(mMDP))) than those obtained by the weighted sum method (problem WS(1,2,3)).

6 CONCLUSIONS

Short-term scheduling in open-pit mines needs several objectives to be optimized jointly. In some open-pit mine operations, these objectives are ranked in a descending order of importance: (i) the minimization of the deviation between the ore sent to the ore processing plant and the ore processing capacity of the plant, (ii) the minimization of the deviation between the metal fines sent to the ore processing plant and the metal fines expected by the ore processing plant and finally (iii) the overall minimization of the movement of the shovel fleet. This work proposes an optimization methodology to generate a short-term open-pit mine production schedule optimizing multiple hierarchical objectives. For the generation of mine schedules, we propose an optimization model based on mixed-integer linear programming. This model considers mining sequencing constraints, and also takes into account both time and cost of shovels movement between phases. For the optimization of the various short-term objectives, we apply the hierarchical method and the weighted sum method to a real open-pit mine case study. The results of the case study show that both methods are capable of generating short-term mine schedules by optimizing the various short-term objectives. Additionally, we verified that both methods obtain the same mine production schedule. This article shows the importance and impact of multiple objective optimization methods for the generation of short-term mine production schedules in open-pit mines. This work is part of a Ph.D. research, which was supported by the Advanced Mining Technology Center (AMTC) and the CONICYT Basal Project under Grant FB0809.

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