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Algorithms for multi-parameter constrained compositing of borehole assay intervals from economic aspects ☆

Xiaogang Ma [a,b], Emmanuel John M. Carranza [b], Freek D. van der Meer [b,c], Chonglong Wu [a,d,*], Xialin Zhang [a]

[a] School of Computer Science, China University of Geosciences, Wuhan 430074, Hubei, China
[b] Department of Earth Systems Analysis, International Institute for Geo-Information Science and Earth Observation (ITC), Hengelosestraat 99, P.O. Box 6, 7500 AA Enschede, The Netherlands
[c] Department of Physical Geography, Faculty of Geosciences, Utrecht University, P.O. Box 80115, 3508 TC Utrecht, The Netherlands
[d] State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, Hubei, China

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ABSTRACT

Compositing of borehole assay intervals based on economic aspects is a primary step when the cross-sectional method is applied in orebody modelling and mineral resources estimation. The compositing is important because the resulting ore composites eventually determine the outlines of orebody models. However, numerous boreholes and borehole intervals make ore compositing tedious and time-consuming for manual work. A computer program for compositing is desirable to facilitate the task and to obtain accurate results. In the design of computer algorithms for such a computer program, dilution is the most difficult part because dilution means adding waste intervals into an ore composite in order to transfer it from unminable to minable and this causes some special situations in a compositing procedure. In order to obtain economically optimized compositing results, we paid special attention to dilution in the designed algorithms. A demo program has been developed to test and implement these algorithms using borehole assay datasets from a mine site in China. Results show the accuracy of designed computer algorithms and the feasibility of applying a computer program in compositing of borehole assay intervals.

1. Introduction

The cross-sectional method is a conventional technique for initial estimation of mineral resources in roughly tabular deposits using borehole or adit data (Hustrulid and Kuchta, 2006; Scott and Whateley, 1995; Sinclair and Blackwell, 2002). For a metal deposit, if well-defined geological limits to an orebody are not readily apparent, it is possible to produce an orebody model based on economic criteria (e.g., cut-off grade) (Bonham-Carter, 1994; Green, 1991; Ranta et al., 1984). Firstly, borehole assay intervals are composited and projected to predetermined vertical sections. Then, outlines of an orebody are delineated in each section. Finally, a 3D orebody model is set up by considering all sections together (Fig. 1). Compositing of borehole intervals is an essential step in orebody modelling because the resulting ore composites represent orebody limits along boreholes and subsequently determine the outlines of an orebody model.

Compared to compositing of borehole assay intervals based on a single physical parameter (e.g., bench height, constant length or geological unit), compositing based on economic aspects is more difficult as it is often constrained by multiple parameters, such as a minimum mining length (L_m) (Table 1) and a cut-off grade (G_m) (Table 2) (Diering, 1992; Noble, 1992). This leads to composites of variable lengths for a group of boreholes. In this situation, the numerous boreholes and borehole intervals make ore compositing tedious and time-consuming for manual work. Therefore, a computer program is desirable as an aided tool for a mining geologist.

Davis (1998) adapted the ore compositing procedure in Annels (1991) and described a looping algorithm using L_m and G_m (Fig. 2). This algorithm begins with the first assay interval of a borehole and goes downward until the bottom end. Several properties of an assay interval are used (i.e., L_s, G_s, *Index* and *Label*) (Tables 1–3). A finite number of consecutive ore intervals (i.e., *Label*=1) are regarded as an initial ore composite (IOC), whose properties are L_c (Table 1) and G_c (Table 2). Since the G_c of an IOC must be $G_c \geq G_m$, there are two types of IOC by considering L_c: (1) $L_c \geq L_m$ or (2)

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* Corresponding author at: School of Computer Science, China University of Geosciences, Wuhan 430074, Hubei, China. Tel.: +86 27 67883087; fax: +86 27 87562370.

E-mail addresses: xiaogang@itc.nl (X. Ma), carranza@itc.nl (E.J.M. Carranza), vdmeer@itc.nl (F.D. van der Meer), chonglongwu@gmail.com (C. Wu), zhangxialin@cug.edu.cn (X. Zhang).

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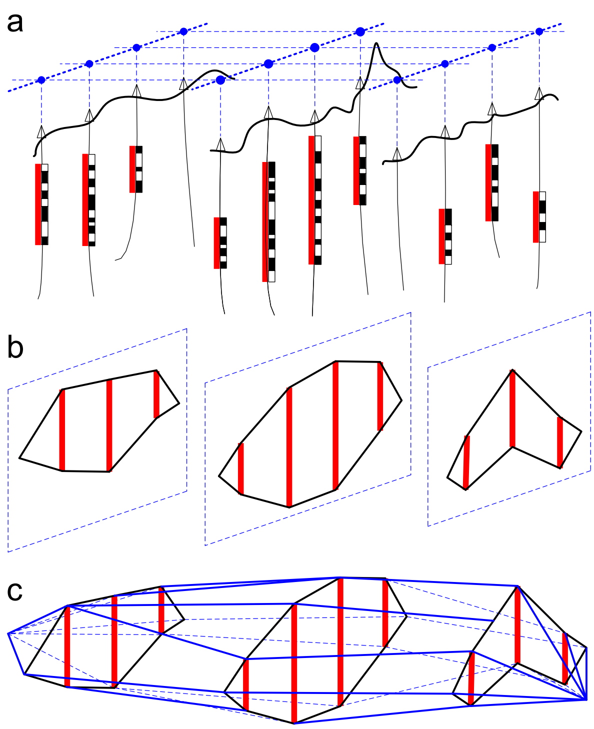

Fig. 1. Concept of orebody modelling based on borehole ore composites derived cross-sectional method: (a) minable ore composites determined in each borehole, in which short black and white blocks stand for borehole assay intervals, while a bold red line attached to a group of intervals stands for a minable ore composite; (b) orebody outline in each cross section based on minable ore composites; and (c) 3D orebody model interpolated from cross sections. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Properties and/or constrained parameters related to length of intervals and composites.

Parameter	Meaning
L_m	Minimum mining length. The thinnest ore zone that can be extracted by the mining method employed
L_s	True thickness of an assay interval. In a tabular deposit, if θ is the intersection angle between the orebody and the borehole axis, then L_s=original length of an interval $\times$ sin θ
L_c	Length of an IOC. The sum of L_s of intervals within an IOC
L_{cd}	Length of a DOC

Table 2
Properties and/or constrained parameters related to grade of intervals and composites.

Parameter	Meaning
G_m	Cut-off grade. The lowest grade set to distinguish economic profitable ore from waste in a given deposit
G_{uc}	Ultrahigh cut grade. A G_s greater than or equal to G_{uc} is regarded as abnormal and a possible solution is replacing it with another reasonable value. In this paper, such a G_s is replaced by G_{uc}
G_s	Assay grade of an interval, which has already been validated by G_{uc}
G_c	Weighted average grade of an IOC. The average of G_s weighted by L_s of every interval within an IOC
G_{cd}	Weighted average grade of a DOC

$L_c < L_m$. An IOC of the first type is directly classified as a pure minable ore composite (PMOC). An IOC of the second type with metal accumulation (i.e., $G_c \times L_c$) (Annels, 1991; Wellmer, 1989) satisfying the condition $G_cL_c \geq G_mL_m$ is also classified as a PMOC,

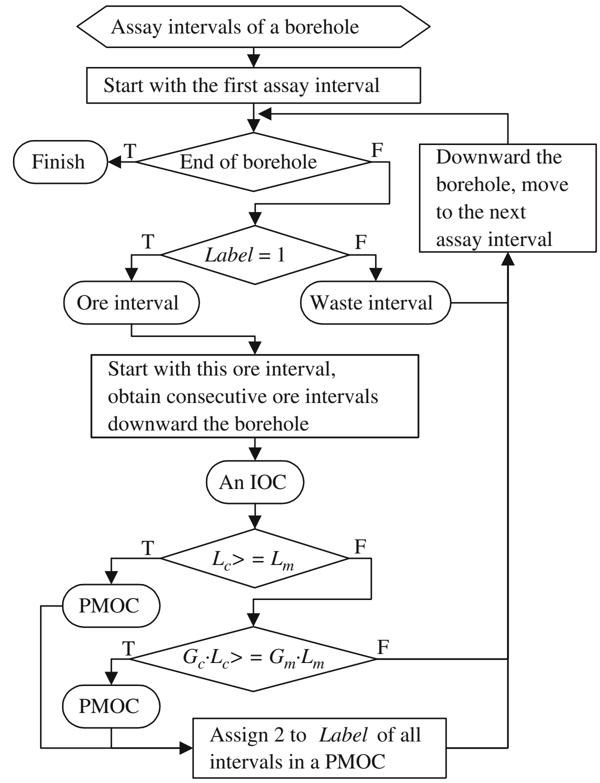

Fig. 2. Compositing procedure of PMOCs (adapted from Annels (1991) and Davis (1998)). "T" means true and "F" means false.

Table 3
Other properties of an assay interval used in compositing procedure.

Parameter	Meaning
Label	Label of an assay interval within a borehole. Before compositing it is initialized with two possible values: 0 or 1. "0" means waste (i.e., $G_s < G_m$) and "1" means ore (i.e., $G_s \geq G_m$). In a compositing result it is assigned with three possible values: 0, 1 or 2. "0" means waste, "1" means unminable ore and "2" means minable ore
Index	Index of an assay interval within a borehole. In this paper the index of assay intervals within a borehole is assigned in increasing numerical order from the first interval to the last. The *Index* begins with 1 and increases to the total number of the assay intervals

but if it satisfies the condition $G_cL_c < G_mL_m$, then it is temporarily regarded as an unminable IOC.

For IOCs temporarily regarded as unminable, dilution can be used to determine if some of them can be minable. Dilution is widely applied in a mining plan (Henning and Mitri, 2008; Tatman, 2001) and it is also used in orebody delineation in order to avoid loss in mineral resources estimation (Annels, 1991; Davis, 1998; Villaescusa, 1998). In borehole interval compositing, dilution means including waste intervals to an IOC in order to derive a diluted ore composite (DOC), whose properties (i.e., L_{cd} and G_{cd}) (Tables 1 and 2) satisfy the conditions $L_{cd} \geq L_m$ and $G_{cd} \geq G_m$. If these conditions are met, then a dilution case is regarded as successful and a DOC is a diluted minable ore composite (DMOC), otherwise the dilution case is abandoned and the IOC being diluted is classified finally as an unminable ore composite (UOC) (Fig. 3). A problem arising here is that a dilution case may possibly result in several DMOCs of an IOC and an optimum choice should be made among them. Diering (1992) and

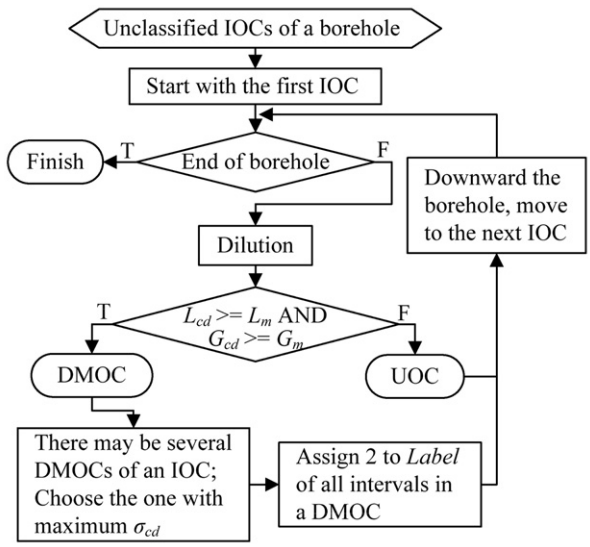

Fig. 3. Dilution procedure to determine an economically optimized DMOC. "T" means true and "F" means false.

Davis (1998) proposed that an economically optimized DMOC is a DOC with a maximum profit value (σ_{cd}) defined as

$$\sigma_{cd} = (G_{cd} - G_m)L_{cd}. \tag{1}$$

Although Diering (1992) and Davis (1998) have separately developed computer programs for compositing of borehole assay intervals, details of their algorithms for dilution are not available in published literature. Although the parameters L_m, G_m and σ_{cd} are applicable constraints for classification of an economically optimized DMOC, using them in a computerized algorithm for that purpose needs detailed investigations. If a computer program follows the compositing procedure described in Figs. 2 and 3, it may encounter a special situation where some unclassified short IOCs are truncated by some short waste intervals. In this special situation, dilution of an IOC may involve not only waste intervals but also IOCs, PMOCs or DMOCs. Another special situation that a compositing algorithm may encounter is where it may be necessary to combine a DMOC with existing IOCs, PMOCs or DMOCs in order to derive an economically optimized DMOC. These special situations that may be encountered in compositing and dilution procedures need further solutions.

In this paper, we discuss algorithms for compositing of borehole assay intervals with special attention to dilution. An idea dilution procedure is a looping or iterative algorithm designed to tackle the sorts of special situations mentioned, so that it can resolve a finite number of dilution cases and reclassify every IOC in terms of economic aspects. The remainder of this paper is organized as follows. Section 2 discusses the meaning of constrained parameters and derived conditions for compositing with dilution. Section 3 explains and demonstrates the design of algorithms for a dilution case and a common solution to special dilution results. Section 4 presents a dialog-based demo program implementing the designed algorithms. Finally, Section 5 highlights the findings of the study.

2. Compositing with dilution

2.1. Constraints and stopping point of a successful dilution case

In order to obtain an economically optimized DMOC, it is essential to find a proper stopping point of a dilution case that can result in DMOCs. The G_m, which is generally the lowest grade of ore that provides a balance between all costs and incomes, or in other words, the breakeven point (Camisani-Calzolari et al., 1985; Krautkraemer, 1988), is an instructive basis for determining the stopping point. The G_m of a mine site is influenced by many factors, such as geological, economic and mining conditions (Annels, 1991). If π is the economic profit, then a simplified equation for G_m is defined as (Gao, 2002)

$$G_m = (\pi + Q(C_p + C_{fp}))/PQGR(1-\alpha). \tag{2}$$

The meaning of each parameter used in Eq. (2) is given in Table 4.

At the breakeven point, the income is equal to the cost, which means that $\pi = 0$. Therefore the G_m can be calculated as

$$G_m = (C_p + C_{fp})/PR(1-\alpha). \tag{3}$$

In a dilution case the resulting length of a DOC is $L_{cd} \geq L_m$, but in order to be a DMOC its grade must be $G_{cd} \geq G_m$. Because the grade of any waste interval is $G_s < G_m$, one intuitively expects from Eq. (3) that diluting an IOC inevitably results in a DOC that would cause economic loss rather than profit. Therefore, the number of waste intervals added in a dilution case should be rigorously constrained.

In order to demonstrate more transparently the stopping point of a dilution case, we can use the σ_{cd} shown in Eq. (1), which can be transformed into a detailed version as follows. In Eq. (1), the G_{cd} is the average grade weighted by the length of every interval (L_{si}; $i = 1,2,\ldots,n$) within a DOC, thus: $G_{cd} = \sum_{i=1}^{n} G_{si}L_{si} / \sum_{i=1}^{n} L_{si}$. Because $L_{cd} = \sum_{i=1}^{n} L_{si}$, Eq. (1) can be transformed into

$$\sigma_{cd} = \sum_{i=1}^{n} (G_{si} - G_m)L_{si}. \tag{4}$$

For a waste interval the value of $(G_{si} - G_m)L_{si}$ is negative. Eq. (4) indicates that the more waste interval is added to a DOC, the higher the economic loss, although adding more waste intervals results in the increase of L_{cd} and $G_{cd} \times L_{cd}$. Therefore, in the stepwise addition of waste intervals in order to dilute an IOC, once $L_{cd} \geq L_m$ and $G_{cd} \geq G_m$, meaning that an IOC is successfully diluted, then the dilution is stopped in order to keep the economic loss at a minimum value.

2.2. Economically optimized DMOC

Finding the stopping point of a successful dilution case, which is constrained by $L_{cd} \geq L_m$ and $G_{cd} \geq G_m$, should be a stepwise procedure, whereby the effect of adding a waste interval in each step is monitored. As the stepwise dilution can result in increase of intervals upward or downward of a borehole, there are a number of choices of adding waste intervals. Fig. 4 points out that the number of dilution choices in a dilution step is directly related to the number of the added waste intervals.

In order to determine an economically optimized DMOC, the DOC derived in each dilution choice should be analyzed. The L_{cd} and G_{cd} of a DOC can be shown as

$$L_{cd} = L_c + \sum_{i=1}^{n} L_{si}, \tag{5}$$

Table 4
Parameters used to explain cut-off grade and economically optimized dilution.

Parameter	Meaning
π	Economic profit
P	Unit price of ore product
Q	Volume of exploitation
R	Mining recovery ratio
α	Mining dilution ratio
C_p	Unit variable cost
C_{fp}	Unit fixed cost
σ_{cd}	Profit value of a DOC
σ_s	Profit value of an interval

and

$$G_{cd} = \left(G_c L_c + \sum_{i=1}^{n} G_{si} L_{si} \right) \bigg/ \left(L_c + \sum_{i=1}^{n} L_{si} \right). \tag{6}$$

The i (i=1,2,…,n) in Eqs. (5) and (6) means the number of waste intervals added in a dilution case is equal to the number of dilution steps. For every dilution step i, there are i+1 choices of permutation of adding waste intervals. If a dilution case can find one or more DMOCs from the i+1 choices of step i, then the increase of i is stopped. Among all the possible DMOCs, the one with the maximum σ_{cd} is considered an economically optimized DMOC.

2.3. Dilution involving ore intervals

The aforementioned methods for determining an economically optimized DMOC can also be applied in a dilution case in which not only waste intervals but also ore intervals are added to a DOC, although in such a case more controls are needed.

The first control is inspecting the σ_{cd} of all DOCs resulting from the i+1 dilution choices at every dilution step i. As shown in Fig. 5, in any dilution step, if the σ_{cd} of a DOC is negative, the relevant dilution choice should be abandoned. Moreover, if a DOC in a subsequent step (e.g., step 3 in Fig. 5) contains a DOC with negative σ_{cd} detected in a preceding step (e.g., step 2 in Fig. 5), and even if the σ_{cd} of a DOC in a subsequent step is positive, its relevant dilution choice should also be abandoned. The third choice in step 3 and the fourth choice in step 4 in Fig. 5 show such cases. The inspection of σ_{cd} at each dilution step ensures that a DOC with negative σ_{cd} is not hidden (i.e., become positive again) by subsequently added ore intervals.

The second control is detecting the stopping point of an unsuccessful dilution case of an IOC. Because a dilution case is a stepwise procedure, if a preceding dilution step cannot result in a DMOC, more extra intervals (i.e., waste interval and ore intervals) will be added in the following steps. Without a proper control, a dilution case may add all the intervals of a borehole to a DOC, even if it is possible that no DMOCs can be derived in such a case. Therefore, a dilution case should be stopped at a point when it can be regarded

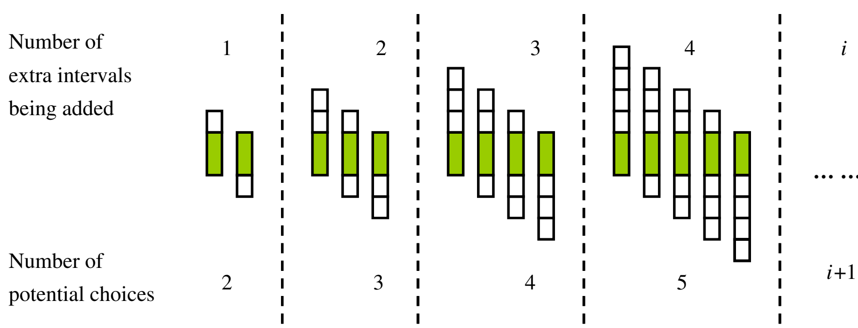

Fig. 4. Possible dilution choices in each dilution step. A green block is an IOC and white blocks are waste intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

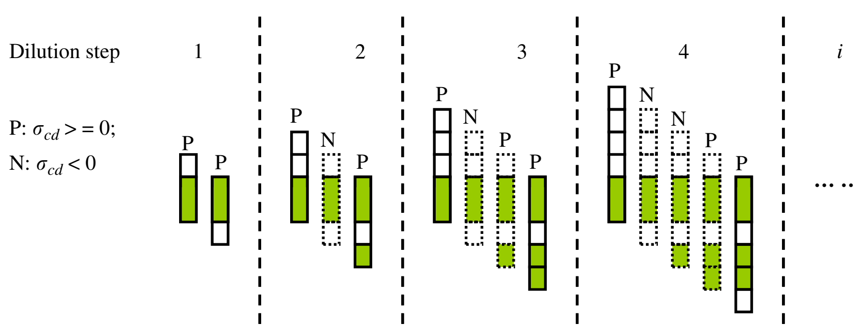

Fig. 5. Inspection of σ_{cd} of each dilution choice. A green block is an IOC. White blocks are waste intervals. A dotted rectangle means that a DOC is abandoned in a dilution procedure. "P" means positive and "N" means negative. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

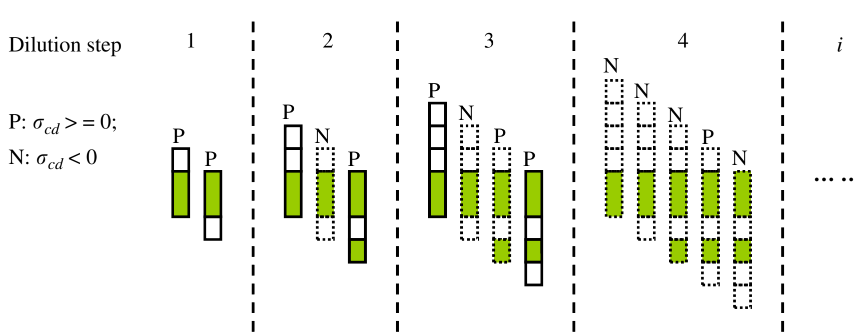

Fig. 6. Inspection of stopping point of an unsuccessful dilution case. "P" means positive and "N" means negative.

Table 5
Example of special DMOC results.

Index	L_s (m)	G_s (g/t)	***Label***			
			Step 1	**Step 2**	**Step 3**	**Final output**
218	0.68	0.68	0	0	0	0
219	0.8	2.22	2	2	2	2
220	0.89	1.7	2 L_c: 3.69	2	2	2
221	1.00	3.18	2 G_c: 2.45	2	2	2
222	1.00	2.58	2	2 L_{cd}: 3.05	2	2 L_{cd}: 7.74
223	1.05	0.76	0	2 G_{cd}: 1.54	2	2 G_{cd}: 1.84
224	1.00	1.31	1	2 σ_{cd}: 1.65	2 L_{cd}: 3.00	2
225	1.00	0.48	0	0	2 G_{cd}: 1.47	2
226	1.00	2.62	1	1	2 σ_{cd}: 1.41	2
227	1.00	0.62	0	0	0	0

Constrained parameters: L_m=3 m; G_m=1 g/t.

unsuccessful. Similar to the first control, another possible control is detecting the abandoning condition of all the i+1 dilution choices at every dilution step i. If the i+1 dilution choices are all abandoned at a step i, then the dilution case of an IOC is regarded unsuccessful and should be stopped. The dilution step 4 in Fig. 6 shows such a special case. As the dilution procedure goes downward along a borehole, an unsuccessful dilution case means only the relevant IOC will be classified as an UOC, while no change is made to any extra interval involved. Then, the dilution procedure will continue to start a new dilution case with the next IOC.

The third control is reprocessing the result of a DMOC. When both waste and ore intervals are added in a dilution case, a DMOC result may get adjacent to the existing IOCs, PMOCs or DMOCs. Therefore, a DMOC and its preceding and following intervals should be scanned to see the possibility of combining that DMOC with the existing adjacent IOCs, PMOCs or DMOCs. Table 5 shows such special dilution results with actual borehole data. The compositing procedure is shown in four columns. Column "Step 1" shows the result of one PMOC and two unclassified IOCs; column "Step 2" shows the DMOC of an IOC (i.e., interval 224); column "Step 3" shows the DMOC of another IOC (i.e., interval 226) and column "Final output" shows the final result. In "Step 2" the dilution case adds an ore interval (i.e., interval 222) of the previous PMOC. The resulted DMOC is combined with the previous PMOC. Then in "Step 3" the dilution case adds an ore interval (i.e., interval 224) of the previous DMOC. The resulted DMOC is combined with the previous DMOC, which generates the result shown in "Final output".

3. Algorithms for a dilution case

3.1. Properties of operational sample

Each assay interval within a borehole can be regarded as a distinct operational sample in the compositing procedure. In our study, an array Sample has been set up to store the assay intervals of a borehole, in which a single interval record consists of four properties: *Index*, L_s, G_s and *Label* (Tables 1–3). The interval records stored in the array *Sample* are arranged in sequential order according to their *Index*.

Following Figs. 2 and 3, the compositing procedure consists of two stages: (1) compositing of PMOCs and (2) dilution of unclassified IOCs. Either stage is a looping construct that is implemented to the whole records of *Sample*. The *Label* of all interval records in *Sample* is initialized with 0 (i.e., $G_s < G_m$) or 1 (i.e., $G_s \geq G_m$) before stage (1). During stage (1) the *Label* of intervals within every PMOC (i.e., only ore intervals) is assigned 2. During stage (2) the *Label* of intervals within every DMOC (i.e., ore intervals and waste intervals) is assigned 2.

3.2. Nested looping construct of a dilution case

As described in Section 2, a dilution case needs a special algorithm to find an economically optimized DMOC for an unclassified IOC. In our study, a nested looping construct (Fig. 7) has been designed for a dilution case. If i is the number of intervals added in a dilution case, then the first level of the looping construct is the stepwise increase of i. For each assigned i, the second level of the looping construct is scanning the i+1

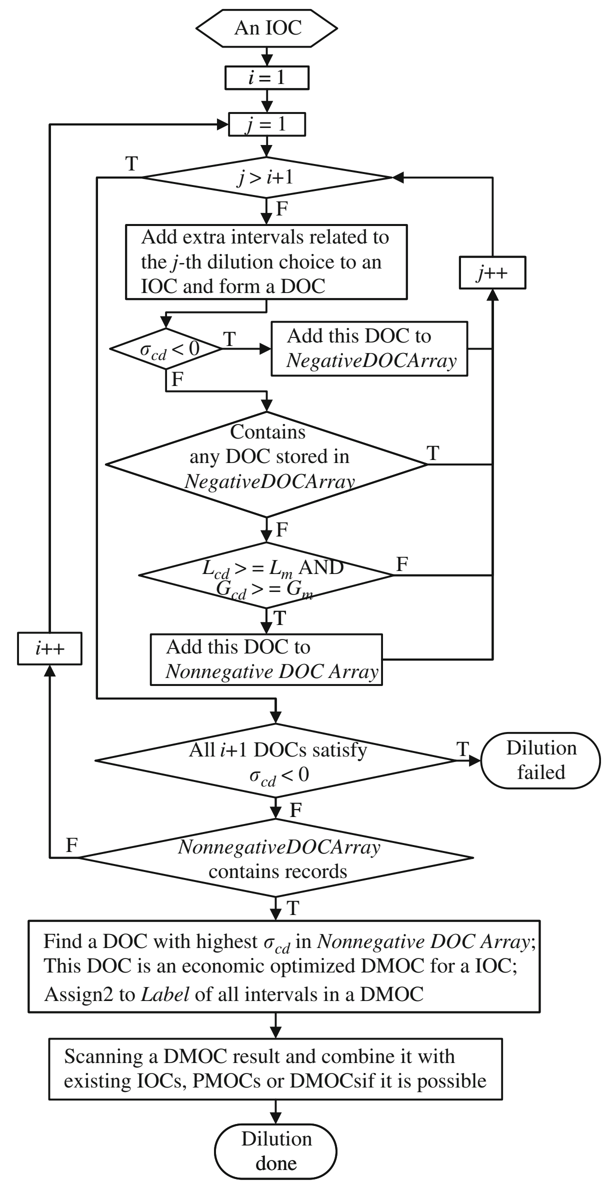

Fig. 7. Nested looping construct of an algorithm for dilution. "T" means true and "F" means false.

Table 6
Parameters used in nested looping construct of a dilution case.

Parameter	**Meaning**
i	Number of intervals added in a dilution case
j	One of the i+1 dilution choices
NegativeDOCArray	A array used to store DOCs, which satisfy $\sigma_{cd} < 0$ during a dilution case
NonnegativeDOCArray	A array used to store DOCs which satisfy $L_{cd} \geq L_m$ and $G_{cd} \geq G_m$during a dilution case

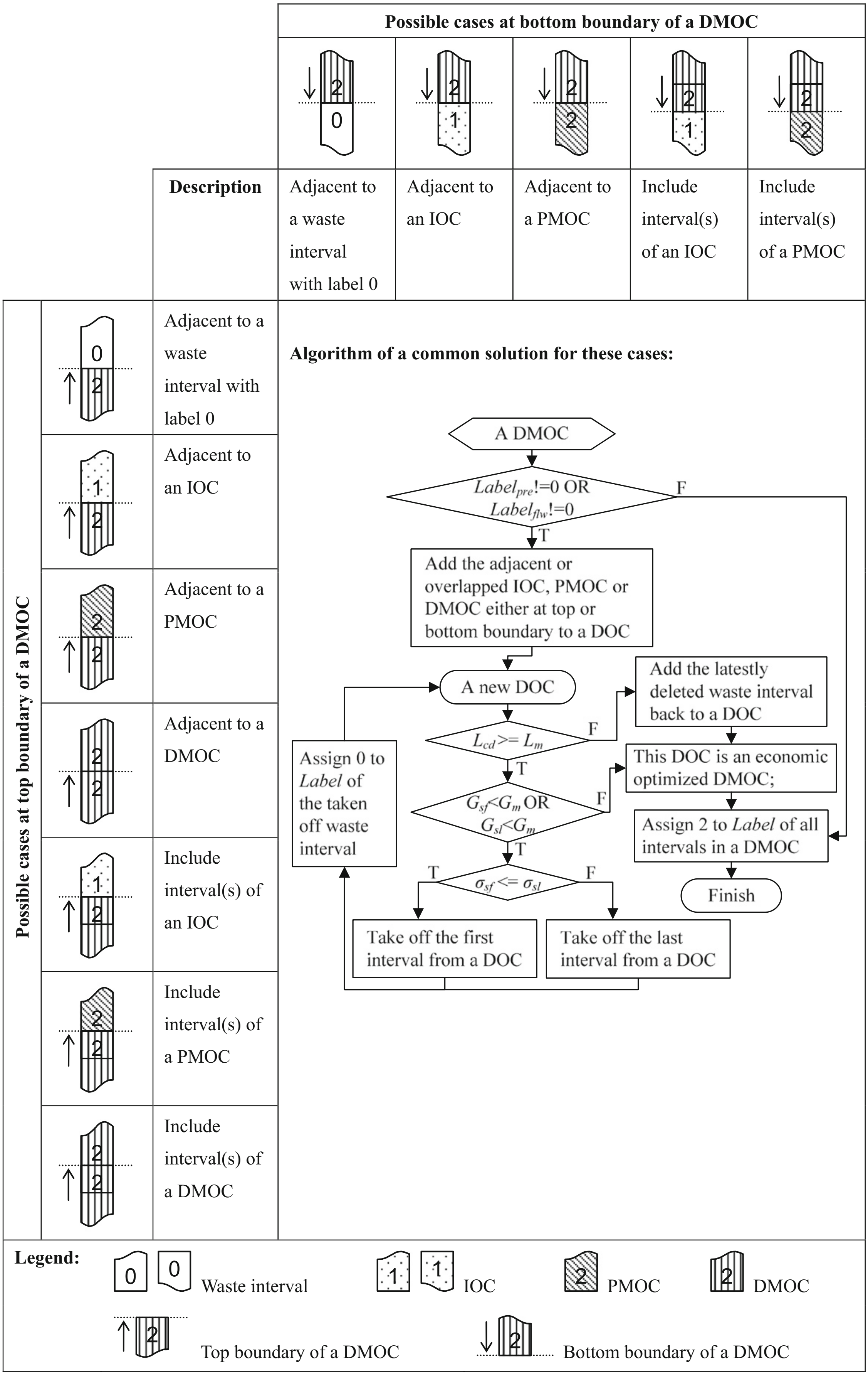

Fig. 8. Possible cases of top and bottom boundaries of a DMOC and a common solution. “T” means true and “F” means false.

dilution choices one by one. Table 6 lists the parameters used in the flow chart in Fig. 7.

3.3. Solution to special dilution results

As described in Section 2.3, if a dilution case involves not only waste intervals but also ore intervals and results in a DMOC, then it is possible that that DMOC can be combined with the existing adjacent IOCs, PMOCs or DMOCS. The last rectangle of the flow chart in Fig. 7 points out when to do the reprocessing a DMOC results in a dilution case. Fig. 8 shows the possible cases of a DMOC result and a commonly suitable solution, in which another parameter, the profit value of an interval (σ_s) (Table 4), is used:

$$\sigma_s = (G_s - G_m)L_s. \tag{7}$$

Because the dilution procedure goes downward along a borehole, all existing DMOCs will be located above an ongoing dilution case. Therefore, the bottom boundary of a new DMOC result will not be adjacent to or overlap with a DMOC below it. When a DMOC is combined with the existing IOCs, DMOCs or PMOCs and a new DMOC is formed, it is possible that a few waste intervals included in this new DMOC (i.e., waste intervals being located at the top or bottom of a new DMOC) can be taken away, while the L_{cd} of the new DMOC should be kept as $L_{cd} \geq L_m$. Table 7 lists the parameters used in the flow chart in Fig. 8.

4. Demo program and results

In order to test and implement the algorithms for compositing of PMOCs and DMOCs, a dialog-based program has been developed using Microsoft® Visual C++ 6.0. Raw borehole assay interval records are stored in a database created using Microsoft® Office Access 2003. Compositing can be performed via a user interface consisting of four parts (Fig. 9): constrained parameters setting, demo borehole choosing, control buttons and compositing result. Two methods are set optional: (1) allowing for minimum metal accumulation (i.e., if $G_c \geq G_m$ and $L_c < L_m$, but $G_c L_c \geq G_m L_{cn}$ so that an IOC can be classified as a PMOC) and (2) allowing dilution.

As the aim of the demo program is testing the feasibility of the designed algorithms, the developed program simplifies input and output functions and processes only one borehole each time it is executed. We have tested the demo program with eight boreholes in a gold mine. All the testing cases obtained desirable results.

Table 7
Parameters used in a common solution to special DMOC results.

Parameter	Meaning
$Label_{pre}$	Label of the previous interval of a DMOC
$Label_{flw}$	Label of the following interval of a DMOC
G_{sf}	Assay grade of the first interval of a DOC
G_{sl}	Assay grade of the last interval of a DOC
σ_{sf}	σ_s of the first interval of a DOC
σ_{sl}	σ_s of the last interval of a DOC

5. Conclusions

Compositing of borehole assay intervals based on economic aspects is an initial step prior to plotting 2D outlines and 3D modelling of an orebody. As boreholes and borehole intervals of a mine site are numerous, it is desirable to have a computer program for borehole interval compositing. In the compositing algorithms discussed here, the classification of a pure minable ore composite is easier than that of a diluted minable ore composite. The latter is derived from a dilution case, in which special situations may arise such that not only waste intervals but also ore intervals are in re-compositing. With minimum mining length, cut-off grade and maximum profit value of a diluted ore composite as constraints, algorithms for compositing involving dilution have been studied in detail. Solutions to two key problems were studied: (1) finding economically optimized diluted minable ore composites in dilution cases and (2) dealing with special situations in dilution cases. A demo program has been developed to test and implement the designed algorithms using borehole datasets from a gold mine. The compositing results satisfy various sets of constrained parameters and prove the feasibility of the designed algorithms.

As a part of the cross-sectional method, the compositing method discussed here assumes that values (e.g., assayed grade and true thickness) of borehole assay intervals to be composited are free of errors. It tends to be applied in the initial modelling of orebodies in a mineral deposit, without comprehensive and precise consideration of distribution and covariance of samples as what geostatistics does. Therefore, in order to avoid misleading results, a reliable estimation of mineral resources may apply several methods and compare

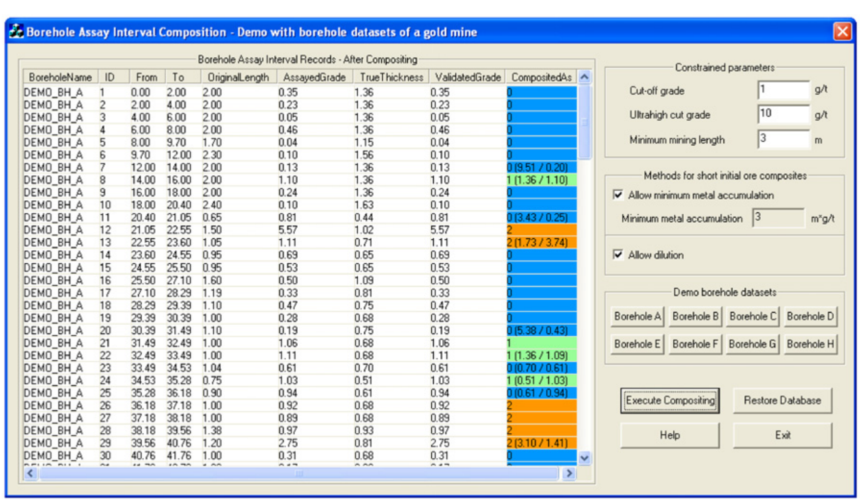

Fig. 9. User interface of demo program. Compositing results are shown in column "CompositedAs": Label "2" and red filling color stand for PMOCs and DMOCs; Label "1" and green filling color stand for UMOCs; and label "0" and blue filling color stand for waste composites (i.e., a group of finite waste intervals). Total length and average grade of each composite are given at the end interval of a composite. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

between the separated results. In conclusion, though with certain assumptions for applications, the compositing method discussed here provides an efficient way for the initial establishment of orebody limits along boreholes. The resulted orebody limits can be used in the rapid estimation of mineral resources before geostatistics is used for a precise estimation.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cageo.2010.01.005.

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