

# **Resource Assessment Economic Filter (RAEF)—A Graphical User Interface Supporting Implementation of Simple Engineering Mine Cost Analyses of Quantitative Mineral Resource Assessment Simulations**

Chapter 23 of  
Section C, Computer Programs  
**Book 7, Automated Data Processing and Computations**

Techniques and Methods 7–C23



# **Resource Assessment Economic Filter (RAEF)—A Graphical User Interface Supporting Implementation of Simple Engineering Mine Cost Analyses of Quantitative Mineral Resource Assessment Simulations**

By Jason L. Shapiro and Gilpin R. Robinson, Jr.

Chapter 23 of  
Section C, Computer Programs  
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Software support for probability calculations in three-part mineral resource assessments

Techniques and Methods 7–C23

**U.S. Department of the Interior**  
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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
Area		
square kilometer (km²)	247.1	acre
square kilometer (km²)	0.3861	square mile (mi²)
Mass		
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]

## Abbreviations

CE	Chemical Engineering
CRAN	Comprehensive R Archive Network
CSV	comma-separated values
GUI	graphical user interface
IRR	investment rate of return
MRR	metallurgical recovery rate
MS	Marshall-Swift
MSC	Marshall-Swift cost updating index
NPV	net present value
PMF	probability mass function
PV	present value of production
PVD	net present value of deposit
RAEF	Resource Assessment Economic Filter
SX/EW	solvent extraction and electrowinning
USGS	U.S. Geological Survey



# Resource Assessment Economic Filter (RAEF)—A Graphical User Interface Supporting Implementation of Simple Engineering Mine Cost Analyses of Quantitative Mineral Resource Assessment Simulations

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## Abstract

Economic evaluations of undiscovered mineral resources provide important context in which to consider the results of quantitative mineral resource assessments. The U.S. Geological Survey economic analysis method uses a simple engineering cost model approach developed by the U.S. Bureau of Mines that applies mine and mill engineering cost equations to simulated undiscovered deposits. The important characteristics of these deposits are derived from Monte Carlo simulations that combine probabilistic estimates of undiscovered deposits that might occur in a study area and a grade-tonnage model defined for a specific deposit type. This report describes the Resource Assessment Economic Filter (RAEF), a graphical user interface (GUI) tool that applies a set of mine cost equations to the deposits under consideration. RAEF, which is written in the open-source statistical programming language R, is an easy-to-use tool to apply user-defined mine, mill, and study area parameters to simulated deposits. For a given deposit type, it estimates the undiscovered resources that might be economic to extract. In addition, RAEF provides a series of graphical, tabular, and statistical summaries that document the results of the economic filter analysis.

## Introduction

Economic filter analysis is important for assessing whether some portion of a quantitative undiscovered mineral resource estimate might be economic to extract. Economic filtering of undiscovered mineral resource estimates is accomplished by using mine, mill, and mine waste cost models appropriate for the deposit type under consideration and Monte Carlo simulation results derived from three-part quantitative mineral resource assessments (Singer and Menzie, 2010; Ellefsen, 2017a, b; Shapiro, 2018). This report describes

Resource Assessment Economic Filter (RAEF), a graphical user interface (GUI) tool that applies a set of engineering mine cost equations to quantitative mineral resource assessment simulations. An economic filter analysis is similar to a prefeasibility mineral property evaluation accomplished by applying simple engineering cost models to the grade, tonnage, and location characteristics of a discovered mineral prospect. In a mineral resource assessment, the simple engineering cost model approach is applied to a series of simulated deposits derived from Monte Carlo sampling of grade and tonnage characteristics defined by a grade-tonnage model for specific deposit types (Singer and Menzie, 2010). The simple engineering cost models used by RAEF are cost-updated versions of cost models developed by the U.S. Bureau of Mines for a variety of mine, mill, and mine waste management options (Camm, 1991; Smith, 1992). The cost models are implemented using the analysis workflow described by Robinson and Menzie (2012). This report describes use of RAEF with Monte Carlo simulation results generated by the MapMark4 program (Ellefsen, 2017a, b) as implemented by MapMark4GUI (Shapiro, 2018). RAEF facilitates use of the U.S. Geological Survey (USGS) three-part assessment method and other quantitative mineral resource assessment methods by providing further information on simulated undiscovered deposits that represent the likely grade and tonnage characteristics of undiscovered deposits (Singer and Menzie, 2010).

The RAEF GUI tool organizes and defines a set of economic filter parameters, including undiscovered deposit simulation results, tract area and cost inflation factors, depth profile of undiscovered deposits, mine and mill type selections appropriate for the deposit type, and engineering cost models for a variety of mine types and mill options. The RAEF tool was created using the open-source statistical programming language R. RAEF provides a convenient way to apply multiple cost models and mine and mill options to a set of simulated mineral deposits without the need to write or edit computer programming code.

## Background

The economic filter approach applies a prefeasibility mineral evaluation analysis (Camm, 1991) to a set of simulated deposits, building on the grade-tonnage model analysis described by Robinson and Menzie (2012). Input parameters for the economic filter analysis include a Monte Carlo-derived series of individual grade and tonnage simulation results based on a grade-tonnage model for the deposit type under consideration, study area features related to mine cost setting, and a depth distribution defined for the undiscovered deposits. In the simple engineering approach, simulated deposit tonnage values are used to estimate mine life, mine capacity, and capital and operating costs for mine and mill types appropriate for the deposit type and depth setting under consideration. The cost models use a power law equation form

$$Y=A(x)^B \quad (1)$$

where

- $Y$      is the cost estimate,
- $x$      is a tonnage variable representing the deposit tonnage or the mine or mill capacity in tons per year, and
- $A$  and  $B$      are fitted coefficients defined by geometric regression using a range of cost information from known mining and milling sites (Camm, 1991, 1994).

Simulated grades and the commodity values define the production value of the simulated deposit. The present value (PV) of production is a function of production value, operating costs, mine life, and the investment rate of return (IRR) assumed to secure mine development financing. RAEF assumes a default 15-percent IRR, but the rate can be modified. The net present value (NPV) of the simulated deposit is the production PV minus the capital costs.

The mine and mill cost equations of Camm (1991, 1994) have been cost-updated using the Marshall-Swift (MS) engineering cost index averaged over the 1989–2008 time period, adjusted to 2008 U.S. dollars (Robinson and Menzie, 2012). The commodity values have been similarly updated using values averaged over 1989–2008, adjusted to 2008 U.S. dollars (Robinson and Menzie, 2012). The commodity value data are set to the same cost basis used by Doggett and Leveille (2010) and Robinson and Menzie (2012).

## Mining and Mill Engineering Cost Models

Mining and mill engineering cost models estimate the capital and operating costs to develop mineral deposits and to recover commodities on the basis of deposit type characteristics, tonnages, grades, and depth estimates. These models are applied to the Monte Carlo simulation results of USGS three-part mineral resource assessments (Singer and Menzie,

2010) to provide an estimate of the fraction of the estimated in-ground resources that might be economic to recover. RAEF uses cost-updated, simple engineering models based on U.S. Bureau of Mines cost models (Camm, 1991, 1994).

Mining and mill cost models provide estimates of typical development and operational costs for a variety of mine and mill types. Camm (1991) described cost models that can be used to evaluate mine development scenarios. The cost models are discussed further in the “Economic Filter Process” section.

## Commodity Values and Cost Updating

Commodity values fluctuate frequently relative to mine lifetimes, which are the basis of mine development planning. The commodity values in RAEF are averaged on a 20-year basis (and adjusted to a base year) to reflect average ore value over a reasonable mine lifetime. Because engineering costs and commodity values change over time, cost models must be updated on the basis of a base-year cost index for consistency with the cost basis of commodity values. In RAEF, costs and commodity values are set to a default 2008 U.S. dollar basis.

Engineering cost indices are used to update the capital and operating costs to erect and operate a mine plant from a particular time to a specified base year (Robinson and Menzie, 2012, p. 8–9). The index is a dimensionless ratio of actual price for the time period of interest compared to the price for a selected base time period. Cost indices are composites of changes in raw material, energy, labor, and construction costs for specific industry sectors. Available indices include the Chemical Engineering (CE) and Marshall-Swift (MS) indices. The CE index consists of four major components—equipment, construction labor, buildings, and engineering and supervision. The MS index consists of two major components—process-industry equipment average and all-industry equipment average. The MS index was published monthly in “Chemical Engineering” until April 2012. The CE index is published monthly in “Chemical Engineering.” Both the CE and MS indices are based on Bureau of Labor Statistics data that are reported on a month and year series. The cost index should be defined on the same time and monetary basis as the commodity value parameters.

To update cost estimates from period A to period B, period A’s cost is multiplied by the ratio of period B’s index over period A’s index using the following formula:

$$Cost_B = Cost_A \left( \frac{Index_B}{Index_A} \right) \quad (2)$$

To update the costs for a given mine cost equation, the index for the specified date is divided by the base-year cost index, and the cost equation is multiplied by this factor (Camm, 1991, p. 6). This factor is the cost updating index (the RAEF MS index variable) and should be compatible with the base year defining the commodity prices used in the calculations. The variable used in RAEF to update the cost parameters in the Camm (1991) equations was calculated as

(average MS index 1989–2008)/(1989 MS index), resulting in a Marshall-Swift cost updating index (MSC) of 1.26 (Robinson and Menzie, 2012, p. 9).

The RAEF GUI dialog allows users to customize the cost basis and cost equation parameters in the economic evaluations. Users can edit the MSC (default value of 1.26) by clicking the “Marshall-Swift Cost (1.26)” button in the dialog. Users can also modify the cost equation parameters by defining capital and operating cost inflation parameters that are based on the location and environment of the assessment tract. The simple engineering cost models are calibrated using mine information from established mining areas with adequate infrastructure (Camm, 1991). Mining areas lacking infrastructure and those sited in harsh environments or remote localities are likely to have increased mine capital and operating costs relative to more habitable areas with adequate infrastructure. The cost parameters are modified by adding capital and operating cost inflation factors to the cost equations. These inflation factors are user-defined estimates of capital and operating costs in the assessment area relative to costs in typical areas. The default value for the capital and operating cost inflation factors is 1, which reflects a typical mine cost environment. Higher numbers reflect increasing mining costs in the assessment area; these values are used for assessment areas where the user determines that a higher cost basis is required.

## Resource Assessment Economic Filter Summary

RAEF is an R GUI package that applies a simple engineering mine cost analysis to a series of simulated deposits with defined ore tonnage and grade attributes calculated by using Monte Carlo sampling of an appropriate mineral deposit grade-tonnage model (Singer and Menzie, 2010). These simulated deposits represent the likely grade and tonnage characteristics of undiscovered deposits and are a component of most quantitative mineral resource assessment methods, such as the USGS three-part assessment method (Singer and Menzie, 2010).

The RAEF tool automates a series of simple engineering mine model calculations on the basis of user-supplied information on mine and beneficiation methods, mineral deposit type characteristics, simulated ore tonnage and grade estimates, undiscovered deposit depth profiles, and regional cost features. The calculations evaluate the fraction of simulated deposits with tonnage and grade characteristics that provide a positive return on investment on the basis of the engineering cost model analysis. This analysis provides an estimate of economic recoverable resources in the study area and an appraisal of the risk of failure in the study area, defined by the fraction of simulated deposits that are not economic. RAEF provides a simple engineering economic analysis for each simulation deposit input and creates a series of supplementary statistical tables and graphics to summarize the results.

## Input Parameters

RAEF requires a set of user-defined parameters to successfully run the economic filter analysis. There are two options for running the analysis: (1) running with a GUI and (2) running as a batch run process. The GUI option allows users to specify each parameter individually when prompted by a program dialog. The batch run option allows users to enter a comma-separated values (CSV) file of run parameters to implement all user-defined parameters at once. The required parameters are discussed below in the order of input to the GUI.

### Monte Carlo Simulation Input File

The first input parameter is the name and location of the Monte Carlo simulation input file. This file is calculated from a user-defined probability mass function (PMF) that estimates the likelihood of undiscovered deposits in the study area and the mineral deposit grade-tonnage model that defines the statistical distribution of ore tonnage and ore grade distributions in the deposit type of interest. The simulation input file must include the simulated ore tonnage (in metric tons), commodity grades (in percent), and in-ground contained resources (in metric tons) for each commodity, indexed by the number of deposits defined by the PMF model. Programs that produce simulated deposit files in the format required by RAEF include MapMark4 (Ellefsen, 2017a, b) and MapMark4GUI (Shapiro, 2018). RAEF will accept the formatted simulation run output from the MapMark4GUI package (*RunID\_05\_Sim\_EF.csv*) as input (Shapiro, 2018). In this report, italic in file names indicates where user-entered run names will be incorporated; for example, *RunID\_05\_Sim\_EF.csv* for MapMark4GUI output and *EF\_01\_Parameters\_RunName.csv* for RAEF output.

The simulation file must have four index columns that precede each simulated deposit tonnage and ore grade feature. The first column is a row index for the entire file. This index is not used in RAEF calculations. The second column is an index number for each individual simulation group. Each individual simulation can contain no deposits (listed as 0) or some positive integer number of deposits, as defined by randomly sampling the PMF. The third column lists the number of deposits associated with the simulation index group in column 2. The fourth column lists the count number sequence of the number of deposits given in column 3. The fifth column reports the simulated ore tonnage for the deposit number in the fourth column, and the subsequent columns report the ore grades of commodities (in percent) and the contained commodity resources (in metric tons) for the deposit in the fourth column. Example simulation files are included in the tutorial exercise folder in the RAEF Package directory.

As an alternative to the standard simulation input file, users can submit a simulated deposit file generated by sampling the grade-tonnage model. This option is useful when the grade-tonnage model has incomplete grade data (described in the “Empirical Mode” section).

## Deposit Type Geometry, Tract Area, Depth Profile, and Mine Type

The next set of input parameters required for RAEF involves information about the deposit type and study area, including deposit type ore body characteristics, tract area, depth profile of the undiscovered deposits, and mine and mill type selections. The first parameter is the deposit type geometry class, which is used to guide the selection of mining methods and their cost models. Geometry class options include (1) flat-bedded/stratiform, (2) massive/disseminated, and (3) vein/steep. Flat-bedded/stratiform ore bodies have layered ore mineralization with large lateral extent; examples include Mississippi Valley-type lead-zinc deposits and platinum-group deposits in layered mafic or ultramafic intrusions, such as the Merensky Reef, South Africa, and the J-M Reef, Stillwater Complex, Montana. Massive/disseminated deposits refer to large, irregular ore bodies that are typically mined using bulk-mining methods; examples include porphyry copper and stock work molybdenum deposits and sedimentary-hosted gold deposits. Vein/steep deposit ore bodies have mineralization with large vertical extent; for example, orogenic gold deposits.

The RAEF process uses the deposit type geometry classification and depth-level estimates to determine the appropriate mine type, according to the depth to top of deposit criteria reported in Smith (1992, p. 6). Mine types refer to the mining techniques used to excavate the mineralized rock. RAEF uses four common hard-rock mine types for analysis. Other mine cost models can be entered manually, as described in the “Mine and Mill Methods” section. The deposit type geometry classes in RAEF are listed below with their corresponding mine type options:

- Flat-bedded/stratiform deposits
  - Open pit (depth < 61meters [m])
  - Room-and-pillar (depth > 61m)
- Massive/disseminated deposits
  - Open pit (depth < 61m)
  - Block caving (depth > 61m)
- Vein/steep deposits
  - Vertical crater retreat (the only mine option for vein/steep deposits)

The next user-defined parameter in this set is the estimated depth profile criteria for undiscovered deposits in the assessment area. The depth profile information specifies (1) the minimum and maximum depths to the top of undiscovered deposits considered appropriate for the assessment area, (2) the number of depth intervals within this range to be assigned a fraction of the undiscovered deposit estimate, and (3) the minimum and maximum depth for each depth interval. Undiscovered deposits can occur anywhere in the upper part

of the Earth’s crust. The depth profile specifies the distribution of deposits by depth. Deposit depths in each depth interval are assigned randomly according to the interval’s depth range and the fraction of deposits assigned to that depth range. For example, undiscovered deposits could be more common near the Earth’s surface, more common at depth, or uniformly distributed by depth. Users can select up to four depth intervals and must specify the decimal fraction of undiscovered deposits assigned to each depth interval. The decimal fractions for all depth intervals must sum to 1.

The next parameter is the area of the permissive tract in square kilometers. The permissive tract area is used to normalize some RAEF results on an area basis. The area must be a numeric input greater than zero.

## Mill Method

The next user-defined input parameter is the mill method selection, which defines the beneficiation methods for commodities to be recovered and the costs and metallurgical recovery rates (MRRs) for each commodity. The economic cost equations also vary on the basis of the mill method selection. The mill method selection is based on the type and number of commodities; many mills are oriented to specific commodities or a set number of commodities to be recovered. RAEF allows for the selection of up to two mill methods and allows users to assign specific commodities to different mill types.

The default mill method option selections in RAEF are shown in the GUI dialog. The default mill methods are recommended on the basis of the number of commodities in the Monte Carlo simulation input file. If a default mill method is chosen, it will be used for all commodities. For the one-, two-, and three-product flotation mill options (options 1 through 3 below), the specified recoveries are based on various mineral combinations with differing recovery rates (Smith, 1992, p. 19).

The default mill methods for a four-commodity study are listed below:

1. 1 - Product Flotation
2. 2 - Product Flotation
3. 3 - Product Flotation
4. 3 - Product Flotation (Omit lowest value commodity)
5. Customize Mill Options
6. None

If the analysis includes more than three commodities, RAEF includes a default option for a three-product flotation mill with the lowest value commodity omitted for each simulated deposit in the study (option 4). The three highest value commodities will be recovered and considered in the economic filter calculations. No resources will be reported for the lowest value commodity.

Other default mill options include the ability to define a customized mill selection (option 5) and the ability to forgo mill costs in the economic filter analysis (option 6). Option 5 (Customize Mill Options) allows users to specify mill methods by commodity or define a new mill option. Option 6 (the “None” default option) ignores beneficiation costs in the RAEF analysis and reports complete commodity recovery.

Figure 1 is an example of the Customize Mill Option dialog. The dialog allows users to select a mill method for each commodity by using the corresponding drop-down menus. The dialog will display the MRR table to help guide mill method selection. Users can select up to two different mill methods. The mill methods that can be chosen include the following:

- 1 - Product Flotation
- 2 - Product Flotation
- 3 - Product Flotation
- SX/EW
- CCD

- CIP
- Au Heap Leach
- Au Float/Roast/Leach
- Au Free Milling
- User Define
- None

Solvent extraction and electrowinning (SX/EW) is a hydrometallurgical process that extracts copper from crushed ore by using leach solutions that selectively bind to copper in the solvent. Copper is extracted from the solvent by a strong acid, which then deposits pure copper onto cathodes through an electrolytic procedure (electrowinning). SX/EW processing is commonly used by the copper industry, where it accounts for 20 percent of worldwide copper production. SX/EW methods are also applied to a range of other metals, including cobalt, nickel, zinc, and uranium.

The 'Customize' dialog box allows users to select a mill option for each commodity. The commodities listed are Cu, Mo, Au, and Ag, each with a 'Select a mill option' dropdown menu. Below this, a message states: 'Please select a mill option for each commodity. You can only select up to 2 mill types'.

The 'Open Mill Metallurgical Recovery Rate Table' is displayed, showing the following data:

Commod	CCD	CIP	AuHeapLea	AuFloatRoastLeac	AuFreeMilling	SX_EW	X1_Produ	X2_Produ	MVTore	X3_Produ	PGMore	AIIR
Cu	0.00	0.00	0.0	0.00	0.00	0.45	0.91	0.91	0.00	0.91	0.75	1
Mo	0.00	0.00	0.0	0.00	0.00	0.00	0.90	0.63	0.00	0.63	0.00	1
Au	0.92	0.89	0.7	0.88	0.93	0.00	0.76	0.76	0.00	0.76	0.00	1
Ag	0.74	0.50	0.4	0.65	0.00	0.00	0.80	0.80	0.00	0.80	0.00	1
Pb	0.00	0.00	0.0	0.00	0.00	0.00	0.90	0.90	0.95	0.90	0.00	1
Zn	0.00	0.00	0.0	0.00	0.00	0.00	0.90	0.90	0.76	0.90	0.00	1
Pt	0.00	0.00	0.0	0.00	0.00	0.00	0.91	0.91	0.00	0.91	0.00	1
Pd	0.00	0.00	0.0	0.00	0.00	0.00	0.83	0.83	0.00	0.83	0.00	1
Ni	0.00	0.00	0.0	0.00	0.00	0.00	0.75	0.75	0.00	0.75	0.00	1
Co	0.00	0.00	0.0	0.00	0.00	0.00	0.00	0.65	0.00	0.65	0.00	1

**Figure 1.** Example of the Customize Mill Option dialog. Commodities in this example are copper (Cu), molybdenum (Mo), gold (Au), silver (Ag), lead (Pb), zinc (Zn), platinum (Pt), palladium (Pd), nickel (Ni), and cobalt (Co).

Counter current decantation (CCD) is a mill method that uses cyanide solution to leach gold (Au) and recover the gold solution through a decantation process. Carbon in pulp (CIP) is a mill method that uses a sequence of cyanide solutions to leach gold from crushed ore. The gold is concentrated by adsorption onto carbon substrate in special tanks.

The User Define option in the Customize Mill Option dialog allows users to specify parameters for a new mill option in RAEF. Selection of the User Define option will launch a new dialog, as shown in figure 2. In the new dialog, users will be asked to enter the capital and operating cost equation parameters. The cost parameters include an equation constant and an exponent term. For example, the capital cost for the three-product flotation mill option is calculated as  $83,600 \times \text{Mill Capacity}^{0.703}$ , where 83,600 is the constant and 0.703 is the mill capacity exponent. Users must also define the MRR of the commodity for the specific mill.

Specific commodities can be withdrawn from the economic calculations by selecting “None” in the Customize Mill Option for the corresponding commodity drop-down menu. Selection of this option will result in no cost and no recovery for that specific commodity.

The next input parameter is the days of operation per year for the mine. Default options are (1) full-time operation at 350 days per year and (2) restricted time at 260 days per year. Underground mines and mines in harsh environments are more likely to operate on a restricted schedule (Smith, 1992).

RAEF uses a default investment rate of return (IRR) of 0.15 (15 percent per year) for the calculations. The IRR is equivalent to the interest rate required to secure capital funding for mine development. The IRR can be changed by clicking “Change Default Investment Rate of Return” and entering a new value in the text box when using the GUI option or by entering a new value in the pre-set parameters file when using the batch run option.

## Waste Management

The final RAEF input parameter is the selection of waste management options. Waste management choices include (1) a tailings pond and dam and (2) an optional tailings pond liner. The liner can be selected only if the tailings pond and dam have been chosen.

## Economic Filter Process

RAEF estimates aggregate costs and revenue features over estimated mine lifetimes for a variety of mine and mill options (based on simulated deposit characteristics) to estimate potentially recoverable resources. The analysis calculates mine capacity, mine lifetime, and mine and mill costs defined by simulated deposit tonnage. The ore grades and commodity values define mine revenue over the mine lifetime. Net present value (NPV) using a deferred rate of return is calculated by using the capital costs and operating costs offset by mine revenue (Camm, 1991; Robinson and Menzie, 2012).

The value of the production estimate is based on total ore value, mill capacity, and the days of operation of the mine and mill (Robinson and Menzie, 2012, p. 5). The present value of a mine determines the present value of the mine derived from the production value adjusted for mine lifetime. Using an IRR (default value is 15 percent per year), RAEF estimates the present value of the mine revenue over mine lifetime as follows (Robinson and Menzie, 2012, p. 5):

$$PV = \frac{1 - \frac{1}{0.15^{Life}}}{0.15} \times \text{value of production} \quad (3)$$

Enter user define mill parameters for: Cu

Enter metallurgical recovery rate (decimal fraction)

Enter the capital cost equation parameters: Constant and the Power log. Example Flotation 3 equation is:  $83600 * Cml^{0.708}$

Name of user defined mill?

\$ constant for capital Cost

Power log for capital cost

Enter the operating cost equation parameters: Constant and the Power log. Example Flotation 3 equation is:  $153 * Cml^{(-0.344)}$

\$ constant for operating Cost

Power log for operating cost

Submit User Define Mill

**Figure 2.** Example of the User Define dialog for the commodity copper (Cu).

The net present value of the deposit (PVD) is the present value minus the total capital costs (TotK) (Robinson and Menzie, 2012, p. 5):

$$PVD = PV - TotK \quad (4)$$

The PVD is the value of the mining process after accounting for the cash flow, rate of return (IRR), and costs (Robinson and Menzie, 2012). During the RAEF process, simulated mines with a negative PVD are assigned a resource value and a contained resources value of zero. Simulated mines with a positive PVD are assigned a resource value equivalent to the resources recovered by mine and mill selections and a deposit value equal to the PVD result. For simulated deposits with a positive PVD, recovered resource estimates are calculated as follows (Robinson and Menzie, 2012):

$$\text{ore recovery factor} \times \text{ore tonnage} \times \text{commodity grade} \quad (5)$$

The potential economic analysis is done for each simulated deposit, with the results aggregated by the index criteria of the Monte Carlo simulation input file. The series of economic filter process steps and results is written to an output file named “EF\_02\_Output\_RunID.csv,” which stores the parameters, variables, and results calculated for each simulated deposit. The variable names and calculation steps are explained in a supplemental table (RAEFVariableGlossary.xlsx) that is included in the RAEF zip file. This glossary lists the variables and describes their calculation and use in the RAEF analysis.

## Resource Assessment Economic Filter Zip File

The RAEF zip file includes all of the important files to run RAEF analysis; documentation to understand program installation, operation, processes, and file output; and sample tutorial exercises. Specifically, the RAEF zip file includes (1) the R-script code for the RAEF GUI (RunRAEF.R), (2) the R-script to install the required packages (InstallPackages.R), (3) a batch file template (BatchFileTemplate.xlsx), (4) a glossary of the program variables (RAEFVariableGlossary.xlsx) that are reported in the output file named “EF\_02\_Output\_Run-Name.csv,” (5) RAEF Quick Start documentation that provides a step-by-step installation and operation guide for RAEF (RAEFQuickStart.pdf), (6) this RAEF user’s guide document (RAEFUserGuide.pdf), and (7) the RAEF Package directory.

## Resource Assessment Economic Filter Package Directory

The RAEF Package directory is organized into four folders: (1) AuxFiles (auxiliary files), (2) MapMark4Results, (3) Output, and (4) TUTORIAL\_Pkg. The Package directory file address must be entered in RAEF GUI for the program to run successfully.

The AuxFiles folder includes the program files that support RAEF. AuxFiles has three subfolders that house the key process files. The subfolders include (1) RScripts, a set of internal process R scripts; (2) ValueTabs, a set of key tables used by RAEF during calculations; and (3) Images, the two image files used by RAEF GUI. The RScripts subfolder has a number of internal process R scripts that help RAEF to run and calculate the estimated resources. These scripts do not need to be accessed or edited to run RAEF. The second subfolder, ValueTabs, includes the key tables that support the resource economic calculations—the resource MRR table and the commodity value table. The MRRs and commodity values are set to defaults. Users can edit the default rates and values in these tables or in the GUI dialog.

The second folder in the Package directory, MapMark4Results, provides sample MapMark4GUI run results that can be used to test and learn the RAEF GUI processes. The sample file (Run1\_01234\_05\_SIM\_EF.csv) can be entered as the grade-tonnage model for an RAEF run.

The third folder, Output, contains a set of sample RAEF results that are for a case study with a porphyry tract and open pit and block caving mine types. This folder can be used to store RAEF run outputs; however, it is not required to use this folder as the output directory for the RAEF runs. The use of unique output folders that pertain to specific RAEF runs is recommended.

The fourth folder, TUTORIAL\_pkg, contains input files and sample output files for tutorial exercises that can help users understand RAEF program operation. These tutorial exercises are discussed in the accompanying QuickStart document.

## Installation Comments

### Required Software

RAEF was developed for use with an R console, and installation of an R console is required to run RAEF. The R console window is where computations are performed to read and process R-scripts. The Comprehensive R Archive Network (CRAN) 64- or 32-bit R console is recommended to run RAEF. To download the R console for Windows, go to the CRAN R project website (<https://cran.r-project.org/bin/windows/base>). At the website, click on the “Download R for Windows” link and follow the instructions provided at the website to complete the installation. The version available for download will be the current release.

## Required Packages

When working with R, many processes are dependent on external packages that can be installed and uploaded to the R console for future work. RAEF requires a selection of R packages to run. R packages need only be installed once so long as the packages have not been removed or edited; however, packages can be reinstalled multiple times without errors.

A script provided in the GUI package (InstallPackages.R) installs the required packages automatically. The following R packages are required for the RAEF GUI to operate:

- ggplot2
- gWidgets
- gWidgetsstcltk
- dplyr
- compositions
- mvtnorm
- ks
- reshape2
- reshape
- Hmisc
- Pid
- Akima
- sqldf

## Inputs to Resource Assessment Economic Filter

RAEF requires three input files to successfully run the economic analysis. The required input files are MapMark4GUI simulation results (*RunID\_05\_Sim\_EF.csv*) or an equivalent file, the commodity value table (*CValues.csv*), and the MRR table (*MillR.csv*).

RAEF uses the MapMark4GUI simulation results to enter simulated deposits into RAEF. The MapMark4GUI simulation results file includes ore tonnages, ore commodity grades, and in-ground contained resources for each simulated deposit. Operational details about MapMark4 results can be found in Ellefsen (2017a, b); operational details and a description of MapMark4GUI output can be found in Shapiro (2018).

The commodity value table and the MRR table are stored in the ValueTabs folder within the AuxFiles folder of the Package directory. The commodity value table lists assigned values for a series of commodities. The values are 1989–2008 averages reported in 2008 U.S. dollars per metric ton of

commodity. This file is accessed automatically by RAEF.

Users can edit or add new commodity values to the table by using a CSV editor, such as Microsoft Excel. If a commodity is not listed in the value table, the program will ask the user to enter the commodity value in a pop-up dialog during the RAEF run. If entered in the dialog, the commodity and value will not be saved permanently to the ValueTabs folder.

The final input file is the MRR table, which lists the MRR for each commodity on the basis of the mill method selected. MRRs are the rates of recovery for each commodity using specific mill methods and may differ by commodity and mill type. The rates are reported in decimal fractions; for example, an MRR of 0.91 corresponds to a 91-percent recovery rate for that commodity and mill type. The MRR table used in RAEF is from Smith (1992, p. 19). The MRR table (*MillR.csv*) is included in the auxiliary folder, and the default rates in the *MillR.csv* table can be revised using the GUI option.

## Graphical User Interface Option Versus Batch Run Option

RAEF can be launched and run using two methods: (1) GUI option and (2) batch run option using a pre-set parameters input file. When using the GUI option, users enter the RAEF run parameters into the GUI dialog when prompted by the program. This option allows users to see all available run options and renders a visual demonstration of the RAEF process workflow. The GUI option is recommended for novice RAEF users, users who want to explore different variables from previous runs, or users who wish to create a pre-set parameters template file.

When using the batch run option, users can input a pre-set parameters file into the system and proceed directly to the prompts to confirm the data and run the analysis without going through multiple dialog steps and entering parameters directly into RAEF. Additionally, the batch run option allows users to run RAEF processes with parameters similar to those from previous runs by submitting an RAEF parameters output file into the system. This option is useful for situations where multiple assessment tracts are evaluated using similar RAEF run parameters. The batch run option gives users the ability to edit or change the variables easily. Because depth estimates are randomly selected during each run, the run output will not be identical to previous runs even if the same input parameters are used.

## Graphical User Interface Option

Running RAEF using the GUI option requires users to enter the economic filter parameters that guide the analysis and the creation of summary tables and graphs. In the GUI dialog box (fig. 3), users enter a series of parameter options, starting in the upper left-hand corner and proceeding down and to the right. The RAEF dialog has five sections of user

**Figure 3.** Example of the Resource Assessment Economic Filter graphical user interface dialog with options selected for a case study using open pit and block caving mine types and the three-product flotation mill option (omitting the lowest value commodity).

input: (1) input files, (2) deposit information, (3) mine and mill methods, (4) days of operation, and (5) waste management. The GUI option allows users to see the available parameter choices while running RAEF interactively. Figure 3 shows an example of the RAEF GUI dialog with options assigned for a case study using a deposit simulation file based on a porphyry copper deposit grade-tonnage model. Porphyry copper deposits are assigned a massive/disseminated ore body geometry. For this deposit-type geometry class, open pit mine methods are assigned to deposits located less than 61 meters below cover rock; block caving mine methods are assigned to deposits located at greater depths. The reported commodities in the porphyry copper grade-tonnage model are copper, molybdenum, gold, and silver. In this example, the user selected a three-product flotation mill omitting recovery of the lowest value commodity, as determined by ore grade, commodity value, and MRR. The mine was assigned a full-time operation schedule of 350 days per year. Waste management options of a tailings pond with dam and liner were selected.

## Input Files

The first section in the GUI (input files) is where users identify the location of the Monte Carlo simulation input file (MapMark4GUI output file or equivalent), the location of the

output folder directory to contain the results of the analysis, and a run name to be attached to output files. The working directory is the folder where the RAEF run output files will be saved. The run name will be added to the beginning of each output file. It is recommended that the working directory name and run name be short character strings that identify a specific resource assessment tract (working directory name) and a unique set of RAEF parameters (run name).

## Deposit Information

The second section in the GUI is for input of mineral deposit and study area information that includes the geometry class of the deposit ore body, the study area size, and a depth profile describing the distribution of undiscovered deposits. The selection of a deposit ore body geometry class results in RAEF assigning appropriate mine types for the run. The area of the assessment tract is entered in square kilometers. The final part of the section is a user-defined depth profile describing the distribution of undiscovered deposits in the assessment tract. Users enter the minimum and maximum depths (in meters) for the undiscovered deposit distribution in the text boxes labeled “Min” and “Max,” respectively. The minimum and maximum depth criteria are typically assigned to assessment tracts during an initial assessment study. Users can

choose between one and four depth intervals to describe the distribution of undiscovered deposits by depth. Deposit depths are assigned randomly throughout each depth interval during the RAEF analysis. A choice of one depth interval results in a uniform distribution of undiscovered deposits. A choice of multiple depth intervals with assigned fractions of the total deposits allows users to skew the depth distribution to favor shallow, deep, or intermediate depths for deposit occurrence.

After the number of depth intervals has been selected, a new dialog will open and ask for further details on the assigned depth intervals (fig. 4). For each interval, users enter the minimum depth, maximum depth, and fraction of deposits assigned to the interval. The deposit fractions for all intervals must sum to 1. In the example dialog shown in figure 4, there are three intervals with depth ranges of 0–250, 251–500, and 501–1,000 meters; deposit fractions assigned to each interval are 0.1, 0.2, and 0.7, respectively.

**Figure 4.** Example of the depth profile interval dialog for three depth intervals.

## Mine and Mill Methods

In the third section of the GUI, mine and mill beneficiation methods are assigned. Mine types are assigned according to the deposit ore body geometry. Mill options include a series of default mill types, user-defined customized mill types, and no beneficiation method or costs. To assign or define a mill type not included in the list of default mill types, users can select the Customize Mill Option as the mill type selection. The Customize Mill Option enables users to assign individual mill types to specific commodities (up to two mill types per run). Users also can forgo the mill cost in the RAEF calculation by selecting “None” to run the economic filter analysis with the mine costs only.

The Customize Mill Option permits users to assign individual commodities to mill types that are in the RAEF model but not offered as default choices. In the Customize Mill Option dialog, the commodities from the MapMark4GUI simulation input file are displayed with a drop-down menu below each commodity abbreviation. In each drop-down menu is a list of available mill methods that users can select. The drop-down menu also has choices of “None” and “User Define” for mills. Users must make a selection for each commodity by clicking on the mill choice in the drop-down menu. Users can choose up to two mill methods per run, not including “None.”

Users also can define a mill for the RAEF program process by clicking “User Define” in the drop-down menu for mill selection. The user-defined cost parameters include the constant and the exponent for the mill capacity. For example, the capital cost for the three-product flotation mill option is calculated as  $83,600 \times \text{Mill Capacity}^{0.703}$ , where 83,600 is the constant and 0.703 is the mill capacity exponent. Users also must define the MRR of the commodity for the custom mill. Figure 2 shows the dialog where users input parameters for a user-defined mill. Additionally, users can select “None” in the drop-down menu as the mill type for specific commodities. Selection of this option results in no recovery of that commodity during the RAEF run.

## Days of Operation

The fourth RAEF GUI section is where users specify the days of operation for the mine. The default options are full-time operation at 350 days per year or restricted time at 260 days per year.

## Waste Management

The fifth section of the GUI is where users select waste rock management options. Waste management choices include (1) a tailings pond and dam and (2) an optional tailings pond liner. The liner can be selected only if the tailings pond and dam have been chosen. Users can choose whether to add the cost of these waste management options to the economic analysis.

## Changes to Default Parameters

The GUI provides options to change the RAEF default parameters for mine and mill costs and MRRs. MRRs for specific commodities and mill methods can be modified by clicking the “Metallurgical Recovery Rate” button in the GUI. Clicking this button opens a new dialog that allows users to edit the recovery rates for specific commodities.

The next option allows users to change the cost updating index (MSC). The default MSC value is set at 1.26, which adjusts the Camm (1991) mine and mill cost parameters to a 2008 U.S. dollar basis. The cost updating methodology is

described in the “Commodity Values and Cost Updating” section. Users can update the MSC by clicking on the button “Marshall-Swift Cost (1.26).” Users also can change the investment rate of return (IRR) from the default value of 0.15 (15 percent).

The final parameters that can be changed are the capital and operating cost inflation factors. These inflation factors are study area-specific estimates of cost inflation factors that reflect increased mine capital and operating cost features of the study area. The default value for both inflation factors is 1, which indicates cost settings typical of mining areas in the western United States and most developed countries. High-cost mining areas in harsh environments or areas lacking infrastructure typically have capital costs inflated by a factor of 1.8 or higher and operating costs inflated by a factor of 1.4 or higher. Higher inflation factors reflect increasing capital and operating mining costs in the study area. Users can change the cost inflation factors by clicking the “Operating Cost Inflation Factor(1)” and “Capital Cost Inflation Factor(1)” buttons.

## Run RAEF Process

Once all parameters have been entered, users can start the RAEF process by clicking “Run RAEF Process.” The process will start by downloading a summary of the parameters as a CSV file (EF\_01\_Parameters\_RunName.csv). After the parameters are set and downloaded, the RAEF process is started. The RAEF process will write output results to a CSV file (EF\_02\_Output\_RunName.csv).

After the completion of the RAEF computation, a set of tables and graphs is created to summarize the economic filter results. The output tables and graphs are described in the sections “Economic Filter Results” and “Ore Grade and Ore Value Tonnage Graphs.” To run another RAEF process, users can keep the RAEF GUI startup dialog box open and relaunch the selected RAEF mode.

In addition to the parameters input, the GUI dialog also displays the status of the RAEF process using the status bar at the bottom of the GUI. Once the RAEF process has started, the status bar will read “RAEF Process Started” until the process is done. If the process was successful, the status bar will read “RAEF Run Completed.” If the run was not successful, the status bar will print the last step that was completed. The GUI will also print the start and completion times of the process run under the “Run RAEF Process” button. Figure 3 provides an example of the status messages for a successful RAEF process run.

## Batch Run Option

Running RAEF with the batch run option is done by selecting “Launch with PreSet Parameters” in the startup dialog. This option allows users to enter a pre-set parameters file and quickly run the economic filter process.

To run RAEF in batch mode, a pre-set parameters input file listing the user-specified run parameters must be created. The parameters are the same as those defined using the GUI option. Table 1 provides a list of available RAEF parameter choices, and the parameters must be entered in the input file using the same case, spelling, and spacing shown in table 1. Table 2 provides an example of a pre-set parameters input file. Each parameter must be entered in the order that is shown in table 2. Parameter values can be edited and changed in the file. In the input file (as shown in table 2), column A contains the parameter names and column B contains the parameter input values. The format of the pre-set parameters input file is similar to that of the RAEF parameters output file (*RunID\_EF\_01\_InputParameters.csv*). Previous parameters output files can be used as pre-set parameters input files, as long as the output names and addresses are updated for the new run. Previous run files could be used either to run a duplicate economic filter analysis with the same input parameters or to run a similar analysis with edited input parameters.

Once the launch button has been clicked, the RAEF process will start. A new window will open, showing the status of the process and the start and completion times. Figure 5 provides an example of the status dialog for a successful run.

**Table 1.** List of available batch input parameter options for the pre-set parameters input file.

Parameter	Options
Number of depth intervals	1 2 3 4
Deposit type	Flat-bedded / stratiform Ore body massive / disseminated Vein deposit / steep
Mill type (default)	1 - Product Flotation 2 - Product Flotation 3 - Product Flotation 3 - Product Flotation (Omit lowest value commodity)
Days of operation	350 260
Tailings pond?	Tailings Pond and Dam “NA” if not selected
Liner	Liner “NA” if not selected

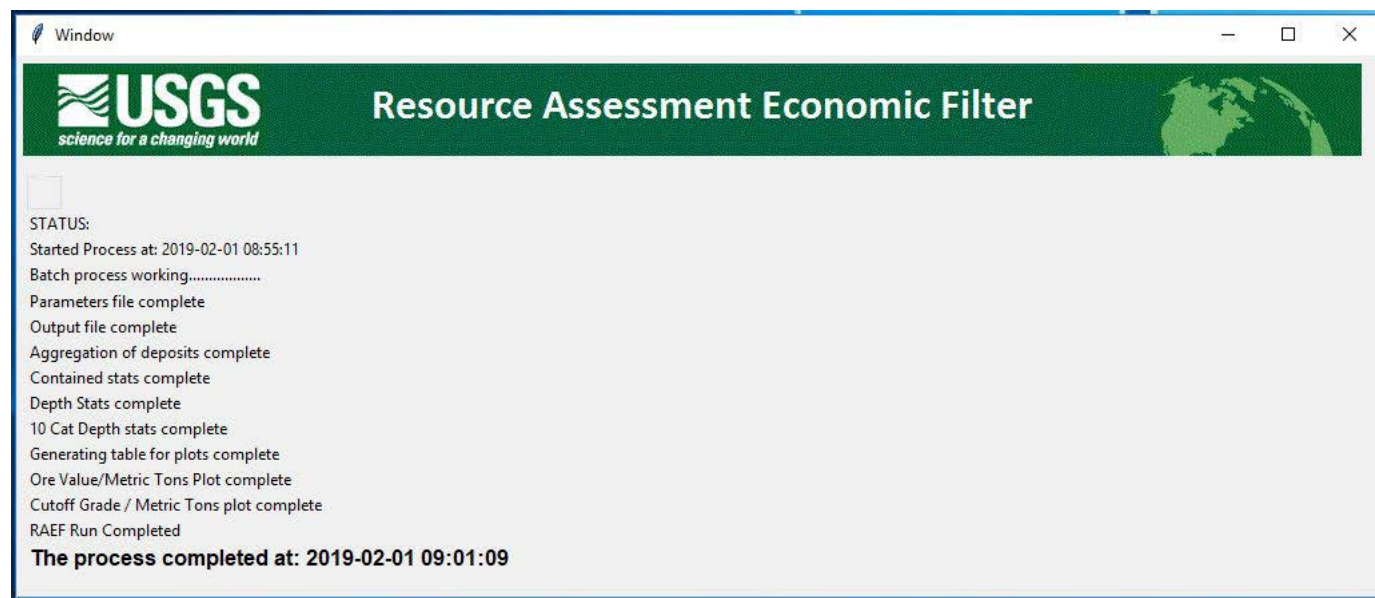
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**Table 2.** Example of a pre-set parameters input file using open pit and block caving mine types.

<b>A</b>		<b>B</b>
1	Date	Thu Dec 13 2018
2	Time	11:19:30 AM
3	Econ Filter File	F:/RAEF/Package/TUTORIAL_Pkg/Inputs/T1/A/Porphyry_05_SIM_EF.csv
4	Working Directory	F:/T01
5	Run Name	A
6	Number of Depth Intervals	3
7	Min1	0
8	Max1	250
9	Per1	0.1
10	Min2	251
11	Max2	500
12	Per2	0.2
13	Min3	501
14	Max3	1000
15	Per3	0.7
16	Min4	0
17	Max4	0
18	Per4	0
19	Deposit Type	Ore body massive / disseminated
20	Mine Method	Mine Method is based on depth to the top of the deposit, if depth > 61m: Block Caving, if depth < 61m: Open Pit
21	Mill Type 1	3 - Product Flotation
22	Mill Type 2	NA
23	Days of Operation	350
24	Environment Choice 1	Tailings Pond and Dam
25	Liner?	Liner
26	MSC	1.26
27	Investment Rate of Return	0.15
28	Cap Cost Inflation Factor	1
29	Operating Cost Inflation Factor	1
30	Area	1000000
31	User Define Mill Name (if applicable)	NONE
32	User Define: Mill Capital Cost Constant	0
33	User Define: Mill Capital Cost Power log	0
34	User Define: Mill Operating Cost Constant	0
35	User Define: Mill Operating Cost Power log	0
36	Custom_Mill_Option1	No set custom mill option for commodity #1
37	Custom_Mill_Option2	No set custom mill option for commodity #2
38	Custom_Mill_Option3	No set custom mill option for commodity #3
39	Custom_Mill_Option4	No set custom mill option for commodity #4
40	Custom_Mill_Option5	No set custom mill option for commodity #5
41	Custom_Mill_Option6	No set custom mill option for commodity #6

**Table 2.** Example of a pre-set parameters input file using open pit and block caving mine types.—Continued

	A	B
42	CV_Cu	3813.958
43	MRR_Cu	0.91
44	CV_Mo	23567.174
45	MRR_Mo	0.63
46	CV_Au	16557636.25
47	MRR_Au	0.76
48	CV_Ag	257849.015
49	MRR_Ag	0.8

**Figure 5.** Example of the batch run status dialog.

## Resource Assessment Economic Filter Startup Dialog

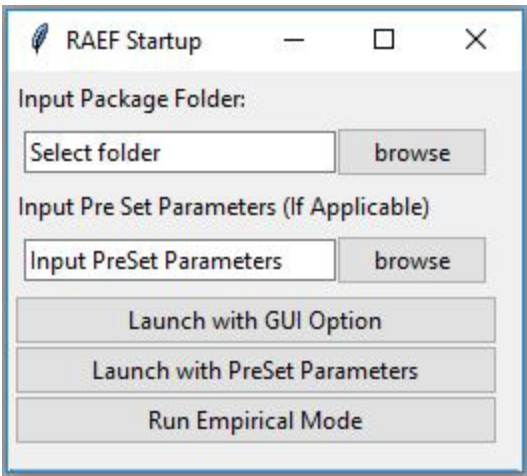
Running the RunRAEF.R script will first open the RAEF startup dialog (fig. 6), which is the central base for the RAEF options. This dialog is where users decide to launch and run RAEF with the GUI option (without pre-set parameters) or the batch run option (with pre-set parameters). Users can also develop an empirical input dataset using a grade-tonnage model by selecting “Run Empirical Mode.”

The startup dialog can stay open throughout the process, allowing users to reopen RAEF modes and perform multiple RAEF runs without the need to re-read the R-script code, thus saving time. It is recommended that users leave this dialog open during the processes until the RAEF runs are complete.

## Economic Filter Results

After completion of RAEF analysis, the economic filter results are written as a CSV table (EF\_02\_Output\_RunName.csv) showing the RAEF computation steps and results for each simulated deposit. The corresponding table RAEFVariableGlossary.xlsx (included in the RAEF zip file) provides a description of the RAEF computation workflow, parameters, and results.

RAEF provides a series of six statistical tables that summarize the economic filter results and two graphs that portray calculated mine cutoff grades as a function of ore tonnage and deposit depth. The first of the statistical tables aggregates the deposit results by the simulation run index and reports cumulative ore tonnage of the deposits, the tonnage of the



**Figure 6.** Example of the Resource Assessment Economic Filter (RAEF) startup dialog.

in-ground contained resources, the tonnage of the recovered resources, and the NPV estimates. Table 3 shows an example of the aggregated results. The aggregated results are saved to a file named “EF\_03\_AggregateD\_Totals\_RunName.csv.”

RAEF uses the aggregated data to summarize in-ground contained resources and the recovered resources. The summary table provides statistics on means, maximums, standard deviations, percentiles, probability of zero resources, and probability of values greater than the mean for the simulated undiscovered resources. These commodity statistics are tabulated by row in a file named “EF\_04\_Contained\_Stats\_RunName.csv.” Table 4 shows an example of this table.

**Table 3.** Example of the aggregated deposit results.

[Columns “Cu\_Con” through “Ag\_Con” list the contained in-ground mineral resource tonnage for each commodity in metric tons. Columns “Cu\_Rec” through “Ag\_Rec” list the recovered mineral resource tonnage for each commodity in metric tons. Commodities included in this table are copper (Cu), molybdenum (Mo), gold (Au), and silver (Ag). SimIndex, simulation index number; Ore, deposit ore tonnage in metric tons; NPV\_Tract, net present value of the tract; NA, no deposits were defined for the simulation index group]

	SimIndex	Ore	Cu_Con	Mo_Con	Au_Con	Ag_Con	Cu_Rec	Mo_Rec	Au_Rec	Ag_Rec	NPV_Tract
1	1	6.17E+08	3,279,125	969,98.83	82.64264	606.8684	0	0	0	0	0
2	2	4.55E+08	1,939,475	60,707.8	105.0698	482.7161	0	0	0	0	0
3	3	76,665,941	385,438.1	1,713.129	2.667975	152.5683	0	0	0	0	0
4	4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
5	5	2.44E+08	861,546.2	11,704.12	60.05166	685.5726	0	0	0	0	0
6	6	2.01E+09	1,250,5451	114,137	155.7458	3,581.3	0	0	0	0	0

RAEF tabulates statistics by deposit depth categories to provide estimates of mean contained and recovered resources by commodity for the user-defined depth intervals. The reporting unit is metric tons of commodity. These estimates are written as the EF\_05\_Depth\_Stats\_RunName.csv file. Table 5 shows an example of this output file for an analysis with three depth intervals.

RAEF also tabulates the mean resources summarized by 10 equal depth intervals defined by the depth range specified for the assessment. Depth intervals are set as ((maximum depth – minimum depth)/10). This table is written as the file EF\_06\_10Depth\_Stats\_RunName.csv. Table 6 shows an example of this output file.

## Ore Grade and Ore Value Tonnage Graphs

RAEF generates two graphs that show estimated ore deposit cutoff grade and recovered ore value as a function of ore tonnage, mine type, and deposit depth. The cutoff grade is the lowest grade or value of ore material in a deposit that has reasonable prospects for application of a feasible mining method. It is the ore grade at which the revenue generated by the mining and beneficiation enterprise is equal to the capital and operating costs of producing the revenue. The cutoff grade varies as a function of ore deposit tonnage, deposit depth, and mine and mill methods. In one RAEF output graph, cutoff grade is expressed as copper equivalent grade (CuEQ%); in the other, cutoff grade is expressed as ore value (in dollars per ton) based on the metallurgical recovery.

**Table 4.** Example of the statistics for the in-ground contained resources and the recovered resources.

[The table reports statistics for the deposit ore tonnage in metric tons (Ore), contained in-ground mineral resource tonnage for each commodity in metric tons (rows “Cu\_Con” through “Ag\_Con”), recovered mineral resource tonnage for each commodity in metric tons (rows “Cu\_Rec” through “Ag\_Rec”), net present value of the tract (NPV\_Tract), and net present value of the area (NPV\_Area). Statistics include the mean (Mean), maximum (Max), minimum (Min), median, standard deviation (STD), percentiles of the ore tonnage and grades from the 99th percentile to the 1st percentile (columns “P99” to “P1”), probability of zero resources (Prob of Zero), and probability of resources greater than the mean (Prob > Mean). Commodities included in this example are copper (Cu), molybdenum (Mo), gold (Au), and silver (Ag)]

	Mean	Max	Min	Median	STD	P99	P90	P80	P70	P60	P50	P40	P30	P20	P10	P1	Prob of Zero	Prob > Mean
Ore	1.77E+09	4.31E+10	0	4.61E+08	3.47E+09	0	0	0	16,014,490	2.03E+08	4.61E+08	8.57E+08	1.46E+09	2.56E+09	4.86E+09	1.81E+10	0.2982	0.26325
Cu_Con	7,609,219	3.2E+08	0	1,892,066	15,834,691	0	0	0	52,618	799,884	1,892,066	3,455,919	6,019,941	10,641,428	20,739,391	78,674,585	0.2982	0.25815
Mo_Con	239,160	1,442,0593	0	41,254	631,706	0	0	0	643	15,859	41,254	83,729	150,763	278,384	601,178	3,041,112	0.2982	0.2241
Au_Con	335	37,376	0	35	1,164	0	0	0	0	13	35	77	154	318	782	4,668	0.2982	0.1938
Ag_Con	4043	232,239	0	756	10,538	0	0	0	15	299	756	1,470	2,671	4930	10,409	47,641	0.2982	0.2323
Cu_Rec	1,553,270	2.76E+08	0	0	8,345,448	0	0	0	0	0	0	0	0	0	556,962	35,898,925	0.8984	0.0913
Mo_Rec	27,824	6,315,534	0	0	194,761	0	0	0	0	0	0	0	0	0	0	656,678	0.91035	0.07475
Au_Rec	82	26,929	0	0	633	0	0	0	0	0	0	0	0	0	0	1,986	0.91615	0.06665
Ag_Rec	272	165,630	0	0	3,172	0	0	0	0	0	0	0	0	0	0	7,014	0.9681	0.03125
NPV_Tract	1.71E+08	2.35E+10	0	0	9.78E+08	0	0	0	0	0	0	0	0	0	8,661,685	4.11E+09	0.8984	0.08335
NPV_Area	171.0052																	

**Table 5.** Example of the statistics for the in-ground contained resources and the recovered resources by user-defined depth interval.

[For each depth category, the table lists the mean statistic for each in-ground contained commodity tonnage in metric tons (Cu\_Con\_Mean, Mo\_Con\_Mean, Au\_Con\_Mean, Ag\_Con\_Mean), the mean statistic for each recovered commodity tonnage in metric tons: (Cu\_Rec\_Mean, Mo\_Rec\_Mean, Au\_Rec\_Mean, Ag\_Rec\_Mean), and the probability of zero resources (ProbOfZero). The commodities included in this example are copper (Cu), molybdenum (Mo), gold (Au), and silver (Ag). The first column lists each depth category, along with the depth interval in meters and the corresponding deposit fraction. For example, “Depth\_Cat\_1\_0-250\_0.1” represents depth category 1, which ranges from 0 to 250 meters and has a deposit fraction of 0.1]

Depth	Cu_Con_Mean	Cu_Rec_Mean	Mo_Con_Mean	Mo_Rec_Mean	Au_Con_Mean	Au_Rec_Mean	Ag_Con_Mean	Ag_Rec_Mean	ProbOfZero
Depth_Cat_1_0-250_0.1	719,404	355,289	22,120	6,928	33	15	386	66	0.6752
Depth_Cat_2_251-500_0.2	1,544,583	385,106	50,017	6,553	69	21	815	77	0.8858
Depth_Cat_3_501-1000_0.7	5,345,232	812,875	167,023	14,343	233	46	2842	129	0.9417

**Table 6.** Example of the statistics for the in-ground contained resources and recovered resources by 10 equal depth intervals.

[For each depth category, the table lists the mean statistic for each in-ground contained commodity tonnage in metric tons (Cu\_Con\_Mean, Mo\_Con\_Mean, Au\_Con\_Mean, Ag\_Con\_Mean), the mean statistic for each recovered commodity tonnage in metric tons (Cu\_Rec\_Mean, Mo\_Rec\_Mean, Au\_Rec\_Mean, Ag\_Rec\_Mean), and the probability of zero resources (Prob0Zero). The commodities included in this example are copper (Cu), molybdenum (Mo), gold (Au), and silver (Ag). The first column lists each depth category, along with the corresponding maximum depth level in meters. For example, "Depth\_Cat\_1\_Max:\_100" represents depth category 1, which has a maximum depth of 100 meters]

Depth	Cu_Con_Mean	Cu_Rec_Mean	Mo_Con_Mean	Mo_Rec_Mean	Au_Con_Mean	Au_Rec_Mean	Ag_Con_Mean	Ag_Rec_Mean	Prob0Zero
Depth_Cat_1_Max:_100	327,896	221,797	10,140	4,345	16	9	178	43	0.445701
Depth_Cat_2_Max:_200	258,517	95,449	7,596	1,818	13	5	139	17	0.819932
Depth_Cat_3_Max:_300	444,839	136,331	12,532	2,225	19	7	225	24	0.852496
Depth_Cat_4_Max:_400	602,476	157,114	20,522	2,920	27	9	318	36	0.878425
Depth_Cat_5_Max:_500	630,259	129,705	21,346	2,173	27	7	341	24	0.910372
Depth_Cat_6_Max:_600	1,076,652	239,081	31,381	3,687	45	11	567	32	0.90883
Depth_Cat_7_Max:_700	1,093,982	187,527	34,443	2,997	47	11	563	27	0.930361
Depth_Cat_8_Max:_800	1,067,533	138,118	33,827	2,691	46	8	572	33	0.951204
Depth_Cat_9_Max:_900	1,022,980	152,669	32,735	3,158	47	9	569	22	0.950429
Depth_Cat_10_Max:_1000	1,084,084	9,5480	34,638	1,811	48	8	572	14	0.967639

Copper equivalence (CuEQ%) is used by the mining industry to compare economic ore grades incorporating a variety of byproduct metals. Copper equivalence (CuEQ%) is calculated as

$$CuEQ\% = G_{Cu} \times [\sum_i R_i V_i G_i] / (R_{Cu} V_{Cu} G_{Cu}) \quad (6)$$

where

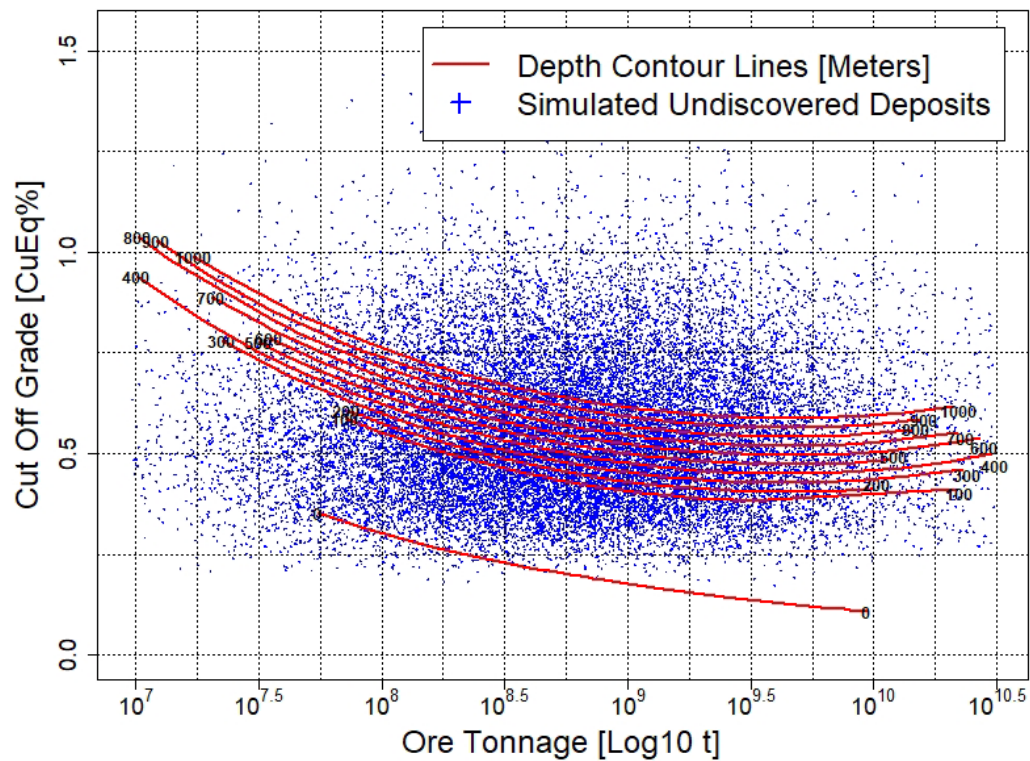
- $R$  is the respective metallurgical recovery rate;
- $V$  is time-averaged metal price per ton; and
- $G$  is metal commodity grade in percent of ore for the suite of potentially recoverable commodities,  $i$ , relative to copper (Cu).

Metal equivalent calculations, such as those for copper equivalence (CuEQ%), are used to compare similar deposits with different metal grade components using a similar metric. The metal equivalence calculation uses the sum of ore commodity component grades times commodity values times commodity MRRs to portray the ore value in terms of an equivalent representative copper grade or recovered ore value. The sets of depth contours in figures 7 and 8 show how variations of ore tonnage and deposit depth influence the cutoff grade in the economic analysis.

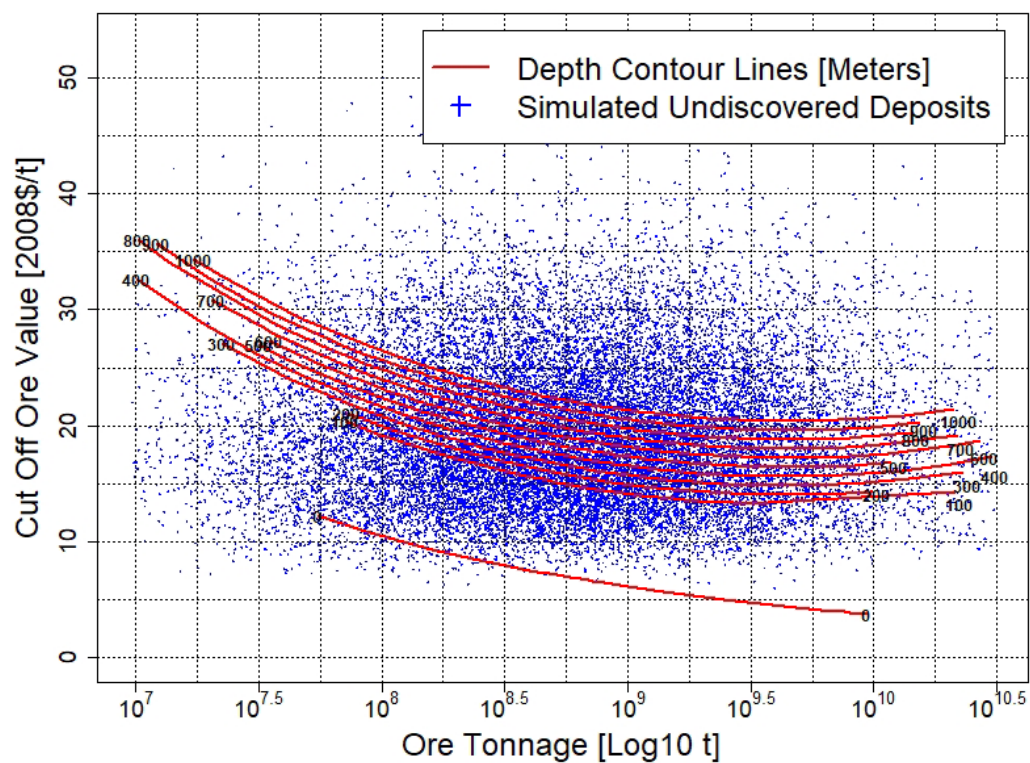
## Empirical Mode

The MapMark4 and MapMark4GUI programs require use of a deposit grade-tonnage model with complete data to create the simulated deposit file. If a deposit grade-tonnage model is missing grade values, the simulated deposit file is modified by randomly sampling the deposit grade-tonnage model for replacement of the original simulated deposit values. RAEF provides an empirical mode option for sampling a grade-tonnage model that is missing grade values to create a substitute simulation file using the MapMark4GUI simulation file as a template. This option can be used to evaluate the effects of inputting data or deleting records from the grade-tonnage model in the economic filter analysis.

To create the empirical mode model for RAEF, a sample MapMark4GUI simulation file that applies the PMF estimates of interest will need to be created and (or) selected. The sample simulation file defines the deposit aggregation structure and the number of grade commodities to be included in the empirical simulation file. A previous MapMark4GUI simulation output file that contains the needed parameters is a convenient file to use. Once a sample simulation file has been prepared, click "Run Empirical Mode" in the RAEF startup dialog to launch the Empirical Option dialog. Browse and select the MapMark4GUI simulation file to be used as the empirical model template, the grade-tonnage model that will be used to generate the empirical simulation file, and the output directory where the empirical simulation file should be stored. Enter a name for the empirical run in the text box, and then click "Create Empirical Model" for RAEF to



**Figure 7.** Example copper equivalent (CuEq%) grade/tonnage plot showing cutoff grade versus deposit tonnage as a function of depth to top of the deposit in meters.



**Figure 8.** Example ore value/tonnage plot showing cutoff ore value versus deposit tonnage as a function of depth to top of the deposit in meters. The cutoff ore value is the metallurgical recovery value of the recovered commodities in ore material.

create the empirical simulation file by randomly sampling the grade-tonnage model data. The empirical file will be named “RunName\_EmpTable.csv.” After the model has been created, the empirical model file is submitted instead of the MapMark4GUI simulation file in the RAEF dialog.

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