Mine Planning for Resource Sustainability

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A Solution to Complex Problems

By

Emmanuel K. Chanda and Micah Nehring

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Dedicated with love to our wives:

Mary Malyangu Chanda and Carley McKey

ENDORSEMENT

"MINE PLANNING FOR RESOURCE SUSTANABILITY – A SOLUTION TO COMPLEX PROBLEMS"

Over the last three decades, the adoption of new technologies has brought about enormous changes in Mine Planning. The buzzword has been the integration of mine operations and services across the organization and also with the customers. While the new age mine planning remained largely confined to the needs and demand of the individual mines, computer-enabled networks helped make the interconnections among the own company units, corporate, transportation and logistics, and recently with the trading verticals, to take advantage of the knowledge and wisdom of price fluctuations. In the near future, we will see the mine planning permeating into the corporate decision-making sales and purchases.

Within this context, this book, entitled," Mine planning for resource sustainability- A solution to complex problems" by Professor Emmanuel K Chanda and Dr. Micah Nehring assumes significance. The book aims to espouse the virtues of resource conservation and sustainability in the realms of mining. Written by two acclaimed and enthusiastic mining engineers, who have been reputed teachers themselves, the text book character of the book cannot be missed. Spread in 10 chapters, the book makes a comprehensive contemporary treatment of the needs of knowledge and wisdom in mine planning by the students, professionals and followers of mining. Every chapter is added with exercises that will be of great help to the teachers and learners of Mine Planning. This is the first book of its kind to offer a simple yet detailed step-by-step guide on solving traditional and future mine planning problems.

I wish the authors grand success and global recognition. I also wish the book gets its rightful place in the libraries and personal collection of mining teachers.

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Chief Editor, Journal of Mines Metals & Fuels

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About the Authors

Emmanuel K Chanda

Emmanuel K Chanda is recognised as an expert in mine planning using computers and operations research models. His experience in the mining sector and academia spans five continents – Africa and the Middle East, Australia, Europe, North and South America. Chanda received his doctorate degree in mining Engineering from the Technical University of Berlin, West Germany; a master of engineering (Engineer of Mines) from the Colorado School of Mines, USA, and a bachelor of mineral sciences in mining engineering from the University of Zambia. Currently, he is Professor and Head of Mining Engineering at the University of Zambia, School of Mines in Lusaka. Chanda worked as Mine Planning Superintendent at Zambia Consolidated Copper Mines Ltd, Kitwe; Associate Professor and Head of Mining Engineering Department at the Western Australian School of Mines (Curtin University of Technology, Australia); Associate Professor/Director of Teaching and Mining Program Leader and Chairman of Mining Education Australia Program Leaders Committee at the University of Adelaide, Australia. Chanda has been a recipient of the American Fulbright Senior Research Fellowship tenable at Colorado School of Mines. He is a member of the Engineering Institution of Zambia, the Australasian Institute of Mining and Metallurgy and the Society of Mining Professors. His research interests are mine optimisation, mining technology and digital transformation in the minerals industry.

Micah Nehring

Micah Nehring is an academic within the School of Mechanical and Mining Engineering at The University of Queensland (UQ), after having worked as a Mining Engineer in Mount Isa (Australia) and then completing his doctorate degree in Mining Engineering from The University of Queensland. He leads the Mine Production Optimisation and Scheduling group which is heavily focused on delivering high quality optimisation models that include the incorporation of pre-concentration, In-Pit-Crusher-Conveyor (IPCC) systems and more recently Environmental, Social, Governance (ESG) aspect into the mine planning process. Micah's research outputs have been published in numerous high-ranking journals. He is a member of the Australasian Institute of Mining and Metallurgy (AusIMM) and the Society of Mining Professors (SOMP).

PREFACE

This book is a product of many years of teaching, research and consultations by the authors, in the area of Mine Planning. This book addresses principles and problems of mine planning in the context of sustainability. Sustainable mining refers to the development of our minerals and energy resources, in a way that maximises the economic and social benefits, while minimising the environmental impacts of mining. Mine Planning is the key to ensuring sustainable extraction of minerals and energy resources.

The emphasis on problem solving and the assumption of the use of spreadsheets are points of differentiation from previous mining texts. Mining planning is a data intensive activity that generates numbers that are useful in decision-making. Mathematical techniques such as linear programming, simulation and networks are useful tools and this book demonstrates how these techniques are applied to mine planning. It is not the intention of this text to delve into the theory of such techniques but to present the basic principles and application to mining problems, through a series of worked examples. The book presents a variety of mine planning problems together with solutions. Some parts should be of interest to researchers and practitioners specialized in mathematical modelling of mining systems. Students of operations research looking at practical application of OR will find some chapters really interesting.

Remember, "*Failing to plan is planning to fail*". Poorly planned mining operations fare badly in sustainability criteria and may face premature closure. This book will help all those involved in the business of mine planning to improve their technical capability in this vital link to sustainable mining.

Organization

Each Chapter begins with an introduction highlighting fundamental principles related to the exercises in that chapter. Next, the exercises that follow give a description of the problem and the solution showing all the steps and workings for each exercise. Some exercises require the use of Excel spreadsheet analysis to solve and evaluate the "what if" scenarios. In such exercises screenshots of the spreadsheets are presented with clear indication of the formulas used in each cell. Furthermore, some chapters provide additional exercises for which only the final answer is shown. Students in mining engineering as well as practicing engineers will find this book a useful reference.

ACKNOWLEDGEMENTS

This book is a product of over forty years of experience in mine planning both in academia and industry. Thanks go to Mining Education Australia. It was during the authors' involvement with this Programme that some of the examples in this book were developed.

Milimo showed her editing skills by reading the manuscript and making numerous suggestions and changes. Yusha Li typed some of the text and checked the Excel solutions to some of the exercises.

CHAPTER 1

INTRODUCTION: FUNDAMENTAL CONCEPTS

Some of the fundamental concepts required for sound mine planning are introduced in this Chapter.

1.0.1 Block Valuation

For the purpose of determining the content of the valuable metal or mineral (as well as numerous other characteristics) within an orebody, the orebody is generally broken into a number of smaller more manageable segments or blocks. The combination of all the blocks that comprise an orebody is known as a block model. These blocks may all be uniform in size or they may vary in size depending on the characteristics of the orebody. Block dimensions should be compatible with the size of equipment that may be used in the exploitation of the deposit. Block models are generally created from drill-hole data with geo-statistical techniques used to interpolate between drill-holes.

Block valuation forms the basis for all mine planning activities. The creation of a new mine plan or the evaluation of an existing mine plan can only take place once a value is attributed to each of the blocks under consideration.

Each block is valued by taking into account:

- The revenue obtained through the sale of the valuable mineral/product contained within the block.
- The cost of mining the block.
- The cost of processing the block in order to obtain the valuable mineral/product within it.

The selection of a mining method, process route and scale of operation in particular will strongly influence the value that can be attributed to each block due to the differing costs associated with each option. Sequencing and scheduling to obtain a mine plan is then generally performed on the basis of accessing and mining each block with a general focus on mining those blocks with the highest value as soon as possible. This mine plan provides the operational cash flow input for a detailed financial technical model. The financial technical model is used to determine the Net Present Value (NPV) of the project after also incorporating items such as taxation and depreciation.

Capital Costs should not be incorporated into the valuation of blocks as this is a separate assessment. Block valuation contributes toward determining the operational value of the deposit. The capital cost required in order to achieve the operational value is then assessed. If the operational value is well beyond the capital cost then the project is more likely to move to the next stage of evaluation.

The value of each block can be calculated using Equation 1.0.1.

$BV = R - MC - PC$	Equation 1.0.1

Where:
BV: Block value ($)
R: Revenue ($)
MC: Mining cost ($)
PC: Processing cost ($)

It is important to note that processing cost is only applied to blocks that are considered to be ore which are therefore sent to the processing plant. This may require an initial cut-off grade calculation to be carried out (as discussed in Chapter 6). Since processing of waste material does not occur, cost is not applicable to these blocks.

The Revenue (R) of each block is calculated using Equation 1.0.2:

$R = P \text{ x } r \text{ x } g \text{ x } T$	Equation 1.0.2

Where:
P: Price of commodity ($/g)
r: Metallurgical recovery (%)
g: Grade (g/t)
T: Tonnes of material being processed (t)

Only those blocks that are considered ore will contribute positive revenue via the sale of metal. Since blocks that are considered waste are not sent to the processing plant for extraction of the valuable metal, there will be no revenue contribution from these blocks.

The Mining cost (MC) of each block is calculated using Equation 1.0.3:

$MC = mc \times T$	Equation 1.0.3

Where:
mc: Mining cost per tonne of material ($/t)
T: Tonnes of material being mined (t)

The processing cost (PC) of each block is calculated using Equation 1.0.4:

$PC = pc \times T$	Equation 1.0.4

Where:
pc: Processing cost per tonne of material ($/t)
T: Tonnes of material being processed (t)

1.0.2 Equivalent Grade

Most metalliferous deposits contain multiple metals. As an example, gold is commonly associated with copper. Nickel and cobalt are often found together and so too are zinc, lead and silver. The minor metals in these types of multi-element deposits are commonly referred to as co-products. For evaluation purposes, co-product metals may be conveniently represented as an 'equivalent' grade of the main metal. The equivalent grade of all minor metals to the main metal across an entire deposit or for a single block, can be calculated using Equation 1.0.5:

$EQG_m = \frac{((g_m \times P_m \times r_m) + (g_{c1} \times P_{c1} \times r_{c1}) + \ldots (g_{cn} \times P_{cn} \times r_{cn}))}{P_m \times r_m}$	Equation 1.0.5

Where:
EQG: Equivalent grade (% or g/t)
g: Grade (% or g/t)
P: Price of commodity ($/t or $/g)
r: Recovery (%)
$_m$: main metal
$_{c1}$: co-product 1
$_{cn}$: co-product n

1.0.3 Time value of money

NPV (Net Present Value) calculations essentially form the basis for comparing multiple alternatives to any given mine planning scenario. The NPV of a project is simply the sum of all future cash flows discounted to the present. An in-depth knowledge of the time value of money and opportunity cost concepts is vital for mine planners. At the heart of determining the NPV is Equation 1.0.6.

$PV = \frac{FV}{(1+i)^n}$	Equation 1.0.6

Where:
PV: Present Value
FV: Future Value
i: Interest Rate
n: number of compounding periods

If the same cash flow repeats itself over numerous years, then Equations 1.0.7 and 1.0.8 may simplify the process of determining NPVs.

$A = PV \times \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$	Equation 1.0.7

$A = FV \times \left[\frac{i}{(1+i)^n - 1}\right]$	Equation 1.0.8

Where:
A: Annuity
PV: Present Value
FV: Future Value
i: Interest Rate
n: number of compounding periods

Equations to simplify NPV computations for cash flows that increase at a certain rate each period (gradient series) are also available. More in depth financial literature may be consulted for readers wanting to familiarise themselves with these.

Another important and common financial concept is the Internal Rate of Return (IRR). The IRR is simply the discount rate that causes the NPV of a series of cash flows to equal $0. As such, IRR cannot be calculated where all cash flows in a project are positive. While IRR does not provide a valuation of projects it provides a good means for ranking competing projects and assessing the return for each dollar invested into a project.

Numerous other financial metrics may also be used in the evaluation of companies including Payback Period, Cost Benefit Ratio, etc. It is also important to understand the difference between Nominal and Effective Interest Rates as well as Simple and Compound Interest. If readers want to familiarise themselves in more detail with these concepts, it is recommended they consult more appropriate financial literature.

1.0.4 Total Shareholder Return (TSR)

One of the most accepted measures used to gauge overall financial performance in business is Total Shareholder Return (TSR). When measuring TSR over a certain period of time, the share price at the beginning of the period is compared to the share price at the end of the period (the higher the TSR the better). Dividends that are paid during the period are also considered in this calculation given by Equation 1.0.9.

$$TSR = \frac{P_i - P_{i-1} + \sum_i \quad Div}{P_{i-1}}$$	Equation 1.0.9

Where:
TSR: Total shareholder return
P_i: Price at end of period
P_{i-1}: Price at beginning of period
Div: Dividends

In evaluating mining project, NPV is very often used as a proxy for total shareholder return. When the objective is to maximise NPV, this is essentially maximising total shareholder return.

Exercise 1.1 Description

Consider the 45-block grade block model (vertical cross-section) shown in Figure 1.1.1 for a copper deposit whose grades are expressed in percent copper (% Cu).

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Level 1
0.0	0.0	0.5	0.7	0.8	0.0	0.6	0.0	0.0	Level 2
0.0	0.0	0.6	0.0	0.0	0.0	0.7	0.0	0.0	Level 3
0.0	0.0	0.0	1.0	0.9	0.0	0.0	0.0	0.0	Level 4
0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	Level 5

Figure 1.1.1 Copper (% Cu) block model (vertical cross section)

The following parameters apply to the potential exploitation of this copper deposit:

Rock within each block:	2Mt
Metallurgical recovery:	83%
Copper price:	$4,300/t Cu
Processing cost:	$14.7/t ore
Mining OPEX:	$2.0/t level 1 +$0.20/t for each lower level

Value these blocks based on the open pit exploitation of this deposit (generate an open pit mining economic block model)

Exercise 1.1. Solution

The value ($M) of each block is calculated by subtracting the mining cost and processing cost from the revenue. The economic block model is shown in Figure 1.1.2.

#a001 -4.0	#b001 -4.0	#c001 -4.0	#d001 -4.0	#e001 -4.0	#f001 -4.0	#g001 -4.0	#h001 -4.0	#i001 -4.0	Level 1
#a002 -4.4	#b002 -4.4	#c002 +1.9	#d002 +16.2	#e002 +23.3	#f002 -4.4	#g002 +9.0	#h002 -4.4	#i002 -4.4	Level 2
#a003 -4.8	#b003 -4.8	#c003 +8.6	#d003 -4.8	#e003 -4.8	#f003 -4.8	#g003 +15.8	#h003 -4.8	#i003 -4.8	Level 3
#a004 -5.2	#b004 -5.2	#c004 -5.2	#d004 +36.8	#e004 -5.2	#f004 -5.2	#g004 -5.2	#h004 -5.2	#i004 -5.2	Level 4
#a005 -5.6	#b005 -5.6	#c005 -5.6	#d005 -5.6	#e005 +7.8	#f005 -5.6	#g005 -5.6	#h005 -5.6	#i005 -5.6	Level 5

Figure 1.1.2. Open pit economic block model ($M)

Those blocks without copper mineralisation are only considered for mining (no processing) and therefore only have the mining cost applied to them.

The centre column of block values are calculated as follows:
Block #e001: -(2Mt x \$2.0/t)=-\$4.0M.
Block #e002: +(2Mt x 0.8%Cu x 83% x \$4,300/t)-(2Mt x \$14.7/t)-(2Mt x \$2.2/t)=+\$23.3M.
Block #e003: -(2Mt x \$2.4/t)=-\$4.8M.
Block #e004: -(2Mt x \$2.6/t)=-\$5.2M.
Block #e005: +(2Mt x 0.8%Cu x 83% x \$4,300/t)-(2Mt x \$14.7/t)-(2Mt x \$2.8/t)=+\$7.8M.

Exercise 1.2 Description
The following data applies to a mineral block:

- 200 grams of contained gold in total
- 100 tonnes of rock/ore
- Selling price of gold \$11.25 per gram
- Cost of processing \$12.00 per tonne
- Cost of mining \$1.20 per tonne
- Block Value = Revenue – Total Costs = \$817.5

What is the metallurgical recovery associated with this block?

Exercise 1.2 Solution
Total Costs = (\$12.00/t + \$1.20/t) x 100 = \$1,320.00
Revenue = Block Value + Total Costs = \$817.50 + \$1,320.00 = \$2,137.50
200 g Au x \$11.25/g = \$2,250.00 x Recovery
Recovery = \$2,137.50/\$2,250.00 = 0.95
Recovery = 95%

Exercise 1.3 Description
Consider a volcanogenic massive sulphide deposit with the reported grades and recoveries contained in Table 1.3.1.

Table 1.3.1. Reported grades for a massive sulphide deposit

Metal	Grade	Recovery (%)	Price (\$)
Copper	3.20%	91	4,650/t
Zinc	0.19%	84	970/t
Lead	0.80%	79	1,020/t
Silver	15.0g/t	63	0.49/g
Gold	2.5g/t	72	32.1/g

What is the Cu-equivalent grade of this deposit?

Exercise 1.3 Solution
The total value of each unit of ore is calculated as shown in Table 1.3.2.

Table 1.3.2. Calculation of equivalent grade

Metal	Grade	Recovery (%)	Price ($)	Value (price x grade)
Copper	3.20%	91	4,650/t	135.41
Zinc	0.19%	84	970/t	1.55
Lead	0.80%	79	1,020/t	6.44
Silver	15.0g/t	63	0.49/g	4.63
Gold	2.5g/t	72	32.1/g	57.78
Total				**205.81**

By dividing the total value by the copper price and recovery, the Cu-equivalent grade is calculated:

$$\frac{205.81}{\$4{,}650/t \times 0.91} \times 100 = 4.86\%\ Cu$$

The Cu-equivalent grade is thus 4.86% Cu.

Exercise 1.4 Description
What is the difference in present value of $300,000 to be received in 5 years from now as part of the sale of an exploration lease if interest is 8% pa compounded annually, rather than compounded quarterly?

Exercise 1.4 Solution
Compounded Annually: $PV = \frac{\$300{,}000.00}{(1+0.08)^5} = \$204{,}174.96$

Compounded Quarterly: $PV = \frac{\$300{,}000.00}{(1+\frac{0.08}{4})^{5\times 4}} = \$201{,}891.40$

The difference in present value is $204,174.96 - $201,891.40 = $2,283.56.

Exercise 1.5 Description
For a capital investment of $5 million, a small mine returns an annual profit of $1.5m for a mine life of 5 years. A 12% annually compounded interest rate applies.

What is the future value of this mine (at the end of 5 years)?

Exercise 1.5 Solution

$$FV = -\$5{,}000{,}000 \times (1 + 0.12)^5 = -\$8{,}811{,}708.42$$

$$FV = +\$1{,}500{,}000 \times (1 + 0.12)^4 = +\$2{,}360{,}279.04$$

$$FV = +\$1{,}500{,}000 \times (1 + 0.12)^3 = +\$2{,}107{,}392.00$$

$$FV = +\$1{,}500{,}000 \times (1 + 0.12)^2 = +\$1{,}881{,}600.00$$

$$FV = +\$1{,}500{,}000 \times (1 + 0.12)^1 = +\$1{,}680{,}000.00$$

$$FV = +\$1{,}500{,}000 \times (1 + 0.12)^0 = +\$1{,}500{,}000.00$$

FV = -$8,881,708.42 + $2,360,279.04 + $2,107,392.00 + $1,881,600.00 + $1,680,000.00 + $1,500,000.00 = $717,562.62
The future value is $717,562.62.

Exercise 1.6 Description

The ABC Mining Company has recently accumulated total funds of $85,000,000 (by setting aside an annual annuity for the past 20 years) for an environmental bond associated with the expansion of its operations.

What annual annuity did the ABC Mining Company have to put aside for the last 20 years in order to have reached $85,000,000 when applying an interest rate of 5.6% pa compounded annually, and what annual annuity is the company able to draw down over the next 25 years of operations to carry out progressive site rehabilitation when applying an interest rate of 4.2% pa compound annually? (Assume no money is left over at the end of the 25-year period).

Exercise 1.6 Solution

$$A = FV \times \left[\frac{i}{(1 + i)^n - 1}\right]$$

$$A = \$85{,}000{,}000 \times \left[\frac{0.056}{(1 + 0.056)^{20} - 1}\right]$$

$$A = \$2{,}411{,}871.25$$

$$A = PV \times \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

$$A = \$85{,}000{,}000 \times \left[\frac{0.042(1+0.042)^{25}}{(1+0.042)^{25} - 1}\right]$$

$$A = \$5{,}556{,}640.79$$

The ABC Mining Company would have had to put aside $2,411,871.25 each year for the last 20 years in order to reach $85,000,000. The ABC Mining Company is able to draw down $5,556,640.79 each year for the next 25 years to carry out progressive site rehabilitation.

Exercise 1.7 Description
An effective interest rate of 19.25% corresponds to a nominal interest rate of 18% compounded at what frequency?

Exercise 1.7 Solution
Using trial and error

Monthly: $(1 + \frac{0.18}{12})^{12} - 1 = 0.1956$

Quarterly: $(1 + \frac{0.18}{4})^{4} - 1 = 0.1925$

Biannually: $(1 + \frac{0.18}{2})^{2} - 1 = 0.1881$

Therefore, the answer is Quarterly.

Exercise 1.8 Description
How much more would you earn on your $5,000 at 5.8% pa over a 6-year period if you put it into an account that compounds yearly as opposed to a simple interest account?

Exercise 1.8 Solution

$$FV = \$5{,}000 \ \times (1 + 0.058)^6 = \ \$7{,}012.68$$

$$FV = \$5{,}000 \ \times (1 + (0.058 \times 6) = \ \$6{,}740.00$$

The difference in compound and simple interest is $7,012.68 - $6,740.00 = $272.68.

Exercise 1.9 Description
Consider the annual cash flows resulting from the exploitation of a small gold deposit as shown in Figure 1.9.1.

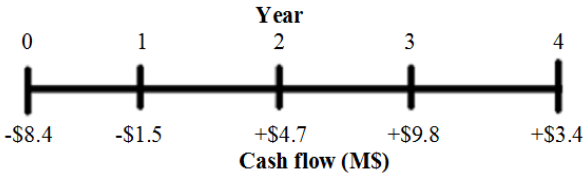

Figure 1.9.1. Cash flow stream for gold mining project

What is the Net Present Value (NPV) of this stream of cash flows when a 12%pa discount rate is applied?

Exercise 1.9 Solution
The NPV is the sum of the present value of all cash flows. The present value of each cash flow using the 12%pa discount rate is thus calculated and summed.

$$\frac{-\$8.4M}{(1+0.12)^0}+\frac{-\$1.5M}{(1+0.12)^1}+\frac{+\$4.7M}{(1+0.12)^2}+\frac{+\$9.8M}{(1+0.12)^3}+\frac{+\$3.4M}{(1+0.12)^4}$$
$$=\$3.14M$$

The Net Present Value (NPV) of this stream of cash flows when a 12%pa discount rate is applied is therefore $3.14M?

Exercise 1.10 Description
Consider the annual cash flows resulting from the exploitation of a nickel deposit as shown in Figure 1.10.1.

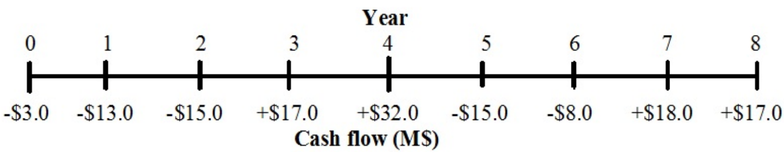

Figure 1.10.1. Cash flow stream for nickel mining project

Graph the Net Present Values (NPV) generated by this series of cash flows at discount rates of between 15%pa and 30%pa, at 1%pa increments. What is the Internal Rate of Return (IRR) for this project?

Exercise 1.10 Solution

The Internal Rate of Return (IRR) is the discount rate at which the Net Present Value (NPV) for a series of cash flows is equal to 0. Table 1.10.1 shows the Net Present Values (NPV) generated by this series of cash flows at discount rates of between 15%pa and 30%pa, at 1%pa increments.

Table 1.10.1. NPV at discount rates of 15%pa - 30%pa

Discount Rate	Net Present Value
15%pa	$5.24M
16%pa	$4.34M
17%pa	$3.50M
18%pa	$2.72M
19%pa	$1.98M
20%pa	$1.29M
21%pa	$0.64M
22%pa	$0.04M
23%pa	-$0.53M
24%pa	-$1.07M
25%pa	-$1.57M
26%pa	-$2.05M
27%pa	-$2.49M
28%pa	-$2.91M
29%pa	-$3.31M
30%pa	-$3.68M

Figure 1.10.2 presents this data as a graph.

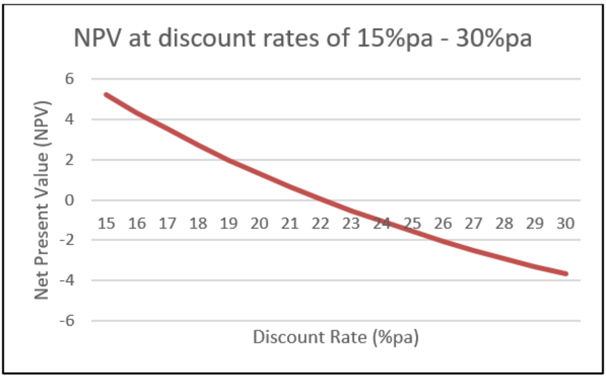

Figure 1.10.2. Graph of NPV at discount rates of 15%pa - 30%pa

From the data contained in Table 1.10.1 and graphically displayed in Figure 1.10.2, it can be inferred that the Internal Rate of Return (IRR) occurs between discount rates 22% per annum and 23%per annum (likely to be close to 22.1%pa).

Exercise 1.11 Description
A $400,000 portfolio of mining stocks returns $25,000 annually in dividends.

If the stocks are expected neither to appreciate nor to depreciate in price in the coming future and there is an opportunity cost of capital of 5% annually, how much value is being creating annually, exclusive of taxes?

Exercise 1.11 Solution
Dividends = $25,000.00
Opportunity cost = $400,000.00 x 5% = $20,000.00
Value added = $25,000.00 - $20,000.00 = $5,000.00

Exercise 1.12 Description
A shareholding in a mining company generates the following results:

Purchase price: $3.50
Current price: $6.20
Total sum of dividends received since purchase: $0.42

What is the Total Shareholder Return (TSR) for this company?

Exercise 1.12 Solution

$$TSR = \frac{P_i - P_{i-1} + \sum_i \quad Div}{P_{i-1}}$$

$$TSR = \frac{\$6.20 - \$3.50 + \$0.42}{\$3.50} = 0.89$$

The Total Shareholder Return is 0.89.

Exercise 1.13 Description (block valuation)

Consider the 70-block grade block model (vertical cross-section) shown in Figure 1.13.1 for a nickel laterite deposit whose grades are expressed in percent nickel (% Ni).

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Level 1
0.0	0.0	0.0	0.6	0.7	0.7	0.6	0.0	0.0	0.6	0.0	0.0	0.0	0.0	Level 2
0.0	0.7	0.7	0.8	0.7	0.8	0.8	0.7	0.8	0.0	0.7	0.0	0.6	0.0	Level 3
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.7	0.8	0.0	0.0	Level 4
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Level 5

Figure 1.13.1 Nickel (% Ni) block model (vertical cross section)

The following parameters apply to the potential exploitation of this nickel laterite deposit:

Rock within each block: 1Mt
Metallurgical recovery: 91%
Nickel price: $9,500/t Ni
Processing cost: $11.5/t ore
Mining OPEX: $1.8/t level 1 +$0.10/t for each lower level

Value these blocks based on the open pit exploitation of this deposit (generate an open pit mining economic block model)

Exercise 1.13 Solution

The value ($M) of each block is calculated by subtracting the mining cost and processing cost from the revenue. The economic block model is shown in Figure 1.13.2.

#a001 -1.8	#b001 -1.8	#c001 -1.8	#d001 -1.8	#e001 -1.8	#f001 -1.8	#g001 -1.8	#h001 -1.8	#i001 -1.8	#j001 -1.8	#k001 -1.8	#l001 -1.8	#m001 -1.8	#n001 -1.8	Level 1
#a002 -1.9	#b002 -1.9	#c002 -1.9	#d002 +38.5	#e002 +47.1	#f002 +47.1	#g002 +38.5	#h002 -1.9	#i002 -1.9	#j002 +38.5	#k002 -1.9	#l002 -1.9	#m002 -1.9	#n002 -1.9	Level 2
#a003 -2.0	#b003 +47.0	#c003 +47.0	#d003 +55.7	#e003 +47.0	#f003 +55.7	#g003 +55.7	#h003 +47.0	#i003 +55.7	#j003 -2.0	#k003 +47.0	#l003 -2.0	#m003 +38.4	#n003 -2.0	Level 3
#a004 -2.1	#b004 -2.1	#c004 -2.1	#d004 -2.1	#e004 -2.1	#f004 -2.1	#g004 -2.1	#h004 -2.1	#i004 -2.1	#j004 +64.2	#k004 +46.9	#l004 +55.6	#m004 -2.1	#n004 -2.1	Level 4
#a005 -2.2	#b005 -2.2	#c005 -2.2	#d005 -2.2	#e005 -2.2	#f005 -2.2	#g005 -2.2	#h005 -2.2	#i005 -2.2	#j005 -2.2	#k005 -2.2	#l005 -2.2	#m005 -2.2	#n005 -2.2	Level 5

Figure 1.13.2. Economic block model ($M) for nickel deposit

Those blocks without nickel mineralisation are only considered for mining (no processing) and therefore only have the mining cost applied to them.

Column j block values are calculated as follows:
Block #j001: -(1Mt x $1.8/t)=-$1.8M.
Block #j002: +(1Mt x 0.6%Ni x 91% x $9,500/t)-(1Mt x $11.5/t)-(1Mt x $1.9/t)=+$38.5M.
Block #j003: -(1Mt x $2.0/t)=-$2.0M.
Block #j004: +(1Mt x 0.9%Ni x 91% x $9,500/t)-(1Mt x $11.5/t)-(1Mt x $2.1/t)=+$64.2M.
Block #j005: -(1Mt x $2.2/t)=-$2.2M.

Exercise 1.14 Description
Consider the 45-block grade block model (vertical cross-section) shown in Figure 1.14.1 for a zinc deposit whose grades are expressed in percent zinc (% Zn).

0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	Level 1
0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	Level 2
0.0	0.0	1.1	0.0	1.3	0.0	1.2	0.0	0.0	Level 3
0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	Level 4
0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	Level 5

Figure 1.14.1 Zinc (% Zn) block model (vertical cross section)

The following parameters apply to the potential exploitation of this zinc deposit:

Rock within each block: 5Mt
Metallurgical recovery: 86%
Zinc price: $2,400/t Zn
Processing cost: $12.8/t ore
Mining OPEX: $2.3/t level 1 +$0.20/t for each lower level

Value these blocks based on the open pit exploitation of this deposit (generate an open pit mining economic block model)

Exercise 1.14 Solution
The value ($M) of each block is calculated by subtracting the mining cost and processing cost from the revenue. The economic block model is shown in Figure 1.14.2.

#a001 -11.5	#b001 -11.5	#c001 -11.5	#d001 -3.3	#e001 -11.5	#f001 -11.5	#g001 -11.5	#h001 -11.5	#i001 -11.5	Level 1
#a002 -12.5	#b002 -12.5	#c002 +16.4	#d002 -12.5	#e002 -12.5	#f002 -12.5	#g002 -12.5	#h002 -12.5	#i002 -12.5	Level 2
#a003 -13.5	#b003 -13.5	#c003 +36.0	#d003 -13.5	#e003 +56.7	#f003 -13.5	#g003 +46.3	#h003 -13.5	#i003 13.5	Level 3
#a004 -14.5	#b004 -14.5	#c004 -14.5	#d004 -14.5	#e004 -14.5	#f004 +4.1	#g004 -14.5	#h004 -14.5	#i004 -14.5	Level 4
#a005 -15.5	#b005 -15.5	#c005 -15.5	#d005 -15.5	#e005 +75.3	#f005 -15.5	#g005 -15.5	#h005 -15.5	#i005 -15.5	Level 5

Figure 1.14.2. Economic block model ($M) for zinc deposit

Those blocks without zinc mineralisation are only considered for mining (no processing) and therefore only have the mining cost applied to them.

Column e block values are calculated as follows:
Block #j001: -(5Mt x $2.3/t)=-$11.5M.
Block #j002: -(5Mt x $2.5/t)=-$12.5M.
Block #j003: +(5Mt x 1.3%Zn x 86% x $2,400/t)-(5Mt x $12.8/t)-(5Mt x $2.7/t)=+$56.7M.
Block #j004: -(5Mt x $2.9/t)=-$14.5M.
Block #j005: +(5Mt x 1.5%Zn x 86% x $2,400/t)-(5Mt x $12.8/t)-(5Mt x $3.1/t)=+$75.3M.

Exercise 1.15 Description
The following data applies to a mineral block:

- 405 tonnes of contained zinc metal in total
- 15,000 tonnes of rock/ore
- Selling price of zinc $2,300.00 per tonne
- Cost of processing $14.00 per tonne
- Cost of mining $3.00 per tonne
- Block Value = Revenue – Total Costs = $570,000.00

What is the metallurgical recovery associated with this block?

Exercise 1.15 Solution
Total Costs = ($14.00/t + $3.00/t) x 15,000 = $255,000.00

Revenue = Block Value + Total Costs = $570,000.00 + $255,000.00 = $825,000.00

405 t Zn x $2,300.00/t = $931,500.00 x Recovery

Recovery = $825,000.00/$931,500.00 = 0.8857

Recovery = 88.57%

Exercise 1.16 Description
The following data applies to a stope:

- 152 tonnes of contained nickel metal in total
- 9,500 tonnes of rock/ore
- Selling price of nickel $10,800.00 per tonne
- Cost of processing $17.20 per tonne
- Metallurgical recovery of 85%
- Block Value = Revenue – Total Costs = $916,000.00

What is the mining cost ($/t) associated with this block?

Exercise 1.16 Solution
Revenue = 152t Ni x $10,800/t Ni x 0.85 = $1,395,360.00

Total Costs = $1,395,360.00 - $916,000.00= $479,360.00

Total Processing Cost = 9,500t x $17.20/t = $163,400.00

Total Mining Cost = $479,360.00 - $163,400.00 = $315,960.00

Mining Cost per tonne ($/t) = $315,960.00 / 9,500t = $33.26

Exercise 1.17 Description
Consider a nickel laterite deposit with the reported grades and recoveries contained in Table 1.17.1.

Table 1.17.1. Reported grades for nickel laterite deposit

Metal	Grade	Recovery (%)	Price ($)
Nickel	0.81%	91	$11,200.00/t
Cobalt	0.11%	89	$45,000.00/t
Scandium	0.0004%	76	$12,000,000.00/t

What is the Ni-equivalent grade of this deposit?

Exercise 1.17 Solution

The total value of each unit of ore is calculated as shown in Table 1.17.2.

Table 1.17.2. Calculation of equivalent grade

Metal	Grade	Recovery (%)	Price ($)	Value (price x grade)
Nickel	0.81%	91	$11,200.00/t	82.56
Cobalt	0.11%	89	$45,000.00/t	44.06
Scandium	0.0004%	76	$12,000,000.00/t	36.48
Total				**163.09**

By dividing the total value by the nickel price and recovery, the Ni-equivalent grade is calculated:

$$\frac{163.09}{\$11{,}200.00/t \times 0.91} \times 100 = 1.60\%\ Ni$$

The Ni-equivalent grade is thus 1.60% Ni.

Exercise 1.18 Description

Consider a zinc-lead-silver deposit with the reported grades and recoveries contained in Table 1.18.1.

Table 1.18.1. Reported grades for zinc-lead-silver deposit

Metal	Grade	Recovery (%)	Price ($)
Zinc	1.87%	92	$1,700.00/t
Lead	1.41%	90	$1,100.00/t
Silver	19.4g/t	71	$0.50/g

What is the Zn-equivalent grade of this deposit?

Exercise 1.18 Solution

The total value of each unit of ore is calculated as shown in Table 1.18.2.