Who Needs Mine and Mill Constraints ?

Richard Wooller

Qualifications: BSc (Hons) Mining, University of Leeds, UK.
MSc Computer Science, University of Bradford, UK.
Membership: Institution of Mining & Metallurgy, UK.
Experience: Nchanga Consolidated Copper Mines Ltd, Zambia.
Rock Fall Company Ltd, UK.
Irish Base Metals Ltd, Republic of Ireland.
Compower Ltd, UK.
Hamersley Iron Pty Ltd, Australia.
ZC Mines, Australia.
Six years as a Mining Engineer on operations and in mine planning.
Eighteen years developing computer applications in the mining industry for geology and mine planning.
Currently: Senior Consultant Mining Engineer, RTZ Technical Services Ltd, UK.

Abstract

In cut-off grade optimising the capacity limits of the mine, mill and market determine the point at which the cut-off grade is set. There are some situations where the mine and mill capacities are themselves a function of the cut-off grade.

Consider a mine constrained by the size of its truck fleet. Where there is a significant difference between the ore and the waste haul distances a change in the proportion of ore to waste will have an impact on the tonnage capacity. However the ratio of ore to waste is a function of the cut-off grade, which is itself a function of the mine capacity.

Likewise variations in the hardness of ore can affect the capacity of a mill. Hard ore reduces the tonnage throughput by taking longer to grind. The mill capacity changes as zones of differing hardness are encountered. The timing is determined by the cut-off grade policy, which is itself a function of the mill capacity.

In each of these examples the true capacity limits are measured in terms of the available resource; truck-hours in the mine and mill-hours in the process plant.

From the formula for the increment in present value developed by Ken Lane in his book, "The Economic Definition of Ore", it can be shown that both the mine and mill capacity limiting cases can be modelled as market capacity limiting cases. The consumption of mine or mill resources, when modelled as grades, can be used to optimise cut-off grades within the true capacity limits. A study using Opti-Cut demonstrates this.

Introduction

It is not always possible to define a mine's capacity in terms of tonnage. Take the case of a large open pit mine with an in-pit crusher linked to a conveyor system for handling ore. Haul distances for ore are relatively short compared to those for waste rock, which has to be trucked to dumps outside the pit.

Within the capacity of the mine's truck fleet if more material can be treated as ore and less as waste the mine's capacity, expressed in terms of tonnage per period, will be a function of the cut-off grade. This presents a paradox when using cut-off grade optimisers such as Whittle's Opti-Cut system and RTZ Consultants' OGRE (Optimum Grades for Resource Exploitation) program. The optimum cut-off grade policy is a function of the mine capacity, which is itself a function of the cut-off grade.

A similar paradox exists with the mill capacity. Consider a deposit with zones of varying rock hardness. Softer ore takes less time than hard ore to grind. In periods when the ore being mined is predominantly soft, the mill will have a higher throughput. This change in capacity can affect the optimum cut-off grade policy. However, the timing and proportion of soft ore that presents at the mill, hence the mill capacity, will be dependent on the cut-off grade policy selected.

Mine output is a measure of the quantity of the reserve[1] that is depleted during a given period. The mill throughput is the proportion of that reserve that

[1] To avoid confusion with resources that are consumed during mining - such as man-hours, materials and energy - the term reserve is used to describe the rock that is to be mined. For cut-off grade optimising the reserve includes all rock that is to be mined - ore and waste.

is sent for processing. From this it follows that the mine and mill capacity must be defined in the units used to describe the reserve, ie as tonnages.

This paper first presents a mechanism whereby market capacity constraints, ie those that apply to the mineral produced by the mine, can be used to model both mine and mill capacity constraints that are independent of the cut-off grade. The validity of this concept is demonstrated by reference to cut-off grade theory. Finally a practical application and some of the implementation problems encountered are described.

Modelling Mine and Mill Capacities as Market Capacities

A capacity is a measure of the quantity of a resource, such as manpower or machinery, available to perform a task. A mill's throughput capacity is measured in terms of the load and residence time of the ore. The tonnage throughput can be doubled by halving the residence time. Within each period the mill has a finite amount of time available for grinding ore, a resource that is consumed by ore as it passes through the mill. An attribute of each tonne of ore is the mill time needed to grind it.

Likewise a truck fleet is a resource whose capacity can be measured in time. Each tonne of rock has, as one of its attributes, the truck-hours to haul it to a dumping point.

The market is a resource. Its capacity is the amount of a product, such as a mineral or a metal, that it can absorb. Invariably in cut-off grade optimising this is assumed to be infinite in that all mineral produced by the mine can be sold.

There are cases when the market capacity is finite. Mines selling products under fixed quantity contracts or into small local markets, or those selling highly specialised commodities, are examples. A common use of the market constraint in cut-off grade optimising is to model a copper refinery linked to a mine. This effectively limits the amount of copper that can be produced by a mine, mill, smelter and refinery complex to that of the refinery capacity.

Just as a mineral is a product that is consumed by a resource (the market), ore can be interpreted as a product that is consumed by the mill resource and rock a product that is consumed by the mine resource.

Quantities of a product are calculated by multiplying the tonnage of ore by its grade and recovery. When both the grade and recovery are 100% all the ore mined is marketed. This situation can be found in some mines, typically quarries. In this case the market capacity is identical to the mill capacity.

This device can be used when modelling the mill capacity. Ore is defined as an additional product. Its grade and recovery of 100% are applied to all the cut-off intervals of the primary mineral being studied.

The total rock mined can be modelled as a mineral. Its grade would be such that, when multiplied by the tonnage of ore and a recovery of 100%, it generated a quantity of product equivalent to the total tonnage mined. How this is calculated is described later. Just as for the mill capacity, setting the market capacity for rock, modelled as a product, to that of the mine capacity has the same effect as setting the mine capacity.

The above would appear to be of purely academic interest or, perhaps, of limited practical interest to a developer of cut-off grade optimising software. This is not so. Because quantities of a product are calculated from grades they can be measured in units other than tonnage.

Normally grades are defined as proportions by mass such as percentages (tonnes*100 per tonne), ratios (tonnes per tonne), gm per tonne for precious metals and carats per tonne for precious stones. Non-mass units are possible. Energy (kilojoules per tonne) in coal is one such example.

The time taken to process a tonne of ore in a mill can also be thought of as a grade whose units are hours per tonne. Multiplying this by the tonnage of ore gives the total mill time (in hours) to process the ore. Mill-hours can therefore be considered to be a product and, as such, can be constrained within a market capacity limit representing the total available mill-hours in each period.

Likewise the total number of truck-hours required for each tonne of ore can be calculated from a knowledge of the tonnage/grade distribution and haul cycle times. This is also modelled as an additional product and expressed as a grade. The product will be the total truck-hours, which can be constrained within a market capacity limit based on the total operating hours available to the truck fleet.

This presupposes that a model of the mill-hours and truck-hours required for each block is available or that they can be calculated within a mine planning package. These quantities are summarised and averaged in cut-off intervals based on the mineral of interest - the primary mineral. Appendix 2 contains an extract from a sequence text file, Opti-Cut's description of the reserve, as an example.

Theoretical Background

The first part of this section is devoted to a review of the mechanism for determining the optimum cut-off grade for a unit of the reserve. The equations that describe this are then used to demonstrate that both mine and mill capacity constraints can be modelled as market constraints. Finally the use of products or elements to model constraints denominated in units other than tonnage is described.

Table 1 lists the notation used throughout this section. It follows that used by Lane K F (1988, page x).

Table 1 - Notation

Symbol	Usage
v	increment in present value per unit of reserve
p	price per unit of mineral
m	unit cost of mining
h	unit cost of treating
k	unit cost of marketing
x	ore/material ratio
y	yield (recovery) during treatment (100y %)
g'	average grade
f	fixed cost per period
F	opportunity cost
T	time taken per unit of reserve
M	mine capacity (throughput per year)
H	mill capacity (throughput per year)
K	market capacity (throughput per year)
c	cash flow per unit of reserve
δ	cost of capital (discount rate) (100δ %)
V*	maximum present value

Notes:

1. Lane defines the opportunity cost as being ($\delta V^* - dV^*/dT$). These terms are equivalent to Opti-Cut's "delay cost" and "change cost".

2. m, h and k are used as suffixes meaning mine, mill and market respectively.

Determining the Optimum Cut-off Grade

The effective optimum cut-off grade at any moment is that which gives, within the capacity constraints, the greatest increase in present value for each unit of the reserve. This is described in detail by Lane K F (1988, chapter 7).

The increment in present value for each unit of reserve at a given cut-off grade is expressed by the formula:

$v = (p - k)xyg' - xh - m - (f + F)T$ .... (1)

The graph of this function against cut-off grade takes the form of a convex curve with a single maximum. See Figure 1.

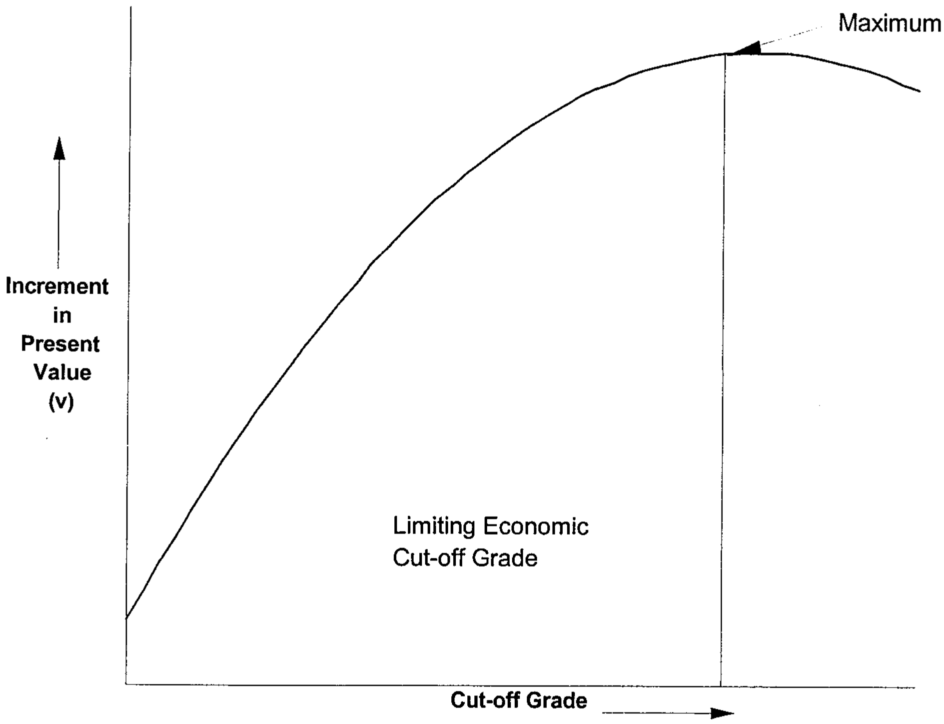

Figure 1

There are three classes of curve depending on which aspect is the limiting capacity - the mine, the mill or the market. Substituting c (the cash flow per unit of reserve) for the term "(p - k)xyg' - xh - m" in (1) these are:

Mine Capacity Limiting

$v_m = c - (f + F)/M$ .... (2)

where the time to process a unit of reserve (T) = 1/M

Mill Capacity Limiting

$v_h = c - (f + F)x/H$ .... (3)

where the time to process a unit of reserve (T) = x/H

Market Capacity Limiting

$v_k = c - (f + F)xyg'/K$ .... (4)

where the time to process a unit of reserve (T) = xyg'/K

The optimum cut-off grade occurs at the point on the cut-off grade axis where the minimum of these functions is at a maximum. This is illustrated in Figure 2.

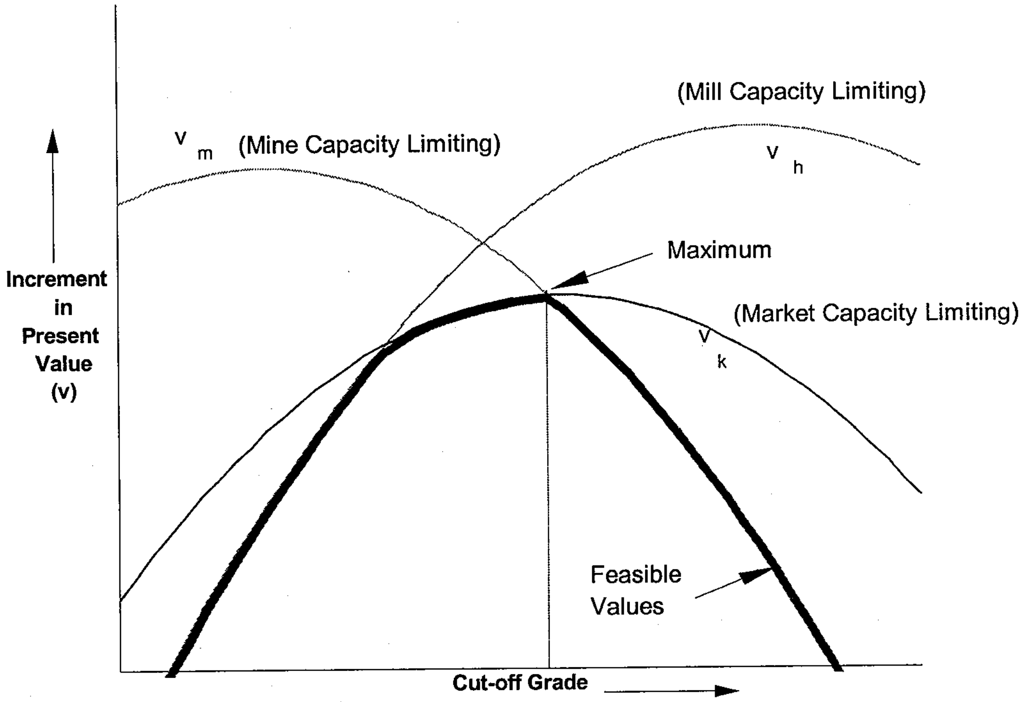

Figure 2

Lane K F (1988, chapter 7) demonstrates cases where a single component is limiting (illustrated here in Figure 1), two components are limiting (not illustrated) and three components are limiting (Figure 2). This is reflected in OGRE, which is restricted to modelling one each of a mine, mill and market constraint.

There is no reason why this should be confined to those three components. The logic can be extended to any number of limiting capacity curves; be they related to the mine, the mill or the market. This is recognised in Opti-Cut, which supports up to 10 capacities (throughput limits) overall for rock types, processing methods and elements.

Modelling Mine and Mill Capacities as Market Capacities

Rock type and method limits can only be expressed in the same units as the reserve, ie tonnages. However the quantity of a mineral produced by a mine is calculated from the product of the ore tonnage, its average grade and recovery. Therefore market capacity constraints, which are expressed in Opti-Cut as element throughput limits, offer the best opportunity to model constraints defined in other units.

The following demonstrate the formulation of the problem to model mine and mill capacities as market capacities.

Mill Capacity

By making the expression for the market limiting case (4), assuming a yield (y) of 1.0 and an average grade (g') of 1.0 - ie all ore is 'marketed' - the expression for the increment in value when the market capacity of ore is limiting (v_{kh}) becomes:

$$v_{kh} = c - (f + F)x/K_h \quad \text{.....................} \quad (5)$$

K_h represents the market capacity of ore, in other words, the mill throughput rate. This is the same form as the expression for the increment in value v_h for the mill limiting case (3) and can be shown to be thus by substituting H (mill throughput rate) for K_h.

$$v_{kh} = c - (f + F)x/H = v_h$$

The significance of this is that the curve modelling the increment in value for the mill limiting case can be generated from a variant of the market limiting curve. All that is required is to create a product that is equivalent to marketing all the ore fed to the mill. The grade of this product in each cut-off interval will be 1.0 (100%).

Mine capacity

Repeating this example but with an average grade (g') of 1/x the expression becomes:

$v_{km} = c - (f + F)/K_m$ .... (6)

which is the same form as the expression for the mine limiting case v_m. This can be seen by substituting M (mine capacity) for K_m.

$v_{km} = c - (f + F)/M = v_m$

In this case the product is the total tonnage that is mined. This is independent of the cut-off grade. The average grade must be 1/x at all cut-off grades. To model this the grade will be set to 0.0 in each cut-off interval except the highest. In that interval it will be calculated from the expression:

total tonnage / tonnage in highest cut-off interval

Modelling Non-Tonnage Denominated Quantities

From the above it follows that, providing the appropriate tonnage/grade distributions are generated, both mine and mill throughputs and capacities can be modelled as market throughputs and capacities.

Just as grades can be used to generate mine output or mill feed quantities measured as tonnages they can also be used to generate quantities measured in other units such as truck-hours or mill-hours. Market capacities (throughput limits) can be applied to each of these elements. They would then effectively function as mine and mill capacity constraints.

Practical Application

To test this concept a set of studies was performed on a dataset based on a large copper deposit. In addition to copper, the deposit also produces significant quantities of other metals. The issues encountered were briefly summarised in the introduction.

The Mine

Ore is hauled to an in-pit crusher from where it is conveyed to the concentrator. The location of this crusher is fixed throughout the life of the mine. Waste is hauled to dumps outside the pit. On average, fewer truck-hours are required to haul a tonne of ore than a tonne of waste.

In order to facilitate blending, the mine operates more ore faces than would be necessary if the only ore target was tonnage. As a consequence, the loading capacity of the mine is not matched by the available trucks. The mine's capacity is limited by the size of the truck fleet. This is measured in terms of the available truck-hours.

The mine passes through a sequence of different rock types with varying hardness. Ore is ground in a set of SAG mills. Hard ore requires a longer residence time to achieve the required recovery of mineral hence it has a lower throughput rate. The mill capacity is given in total available SAG-hours.

The Mine Model

The deposit is modelled using a conventional block model. From the original model and the subsequent design work some twenty attributes were calculated for each block. In addition to the density for each block, those of interest in this study are the:

- net smelter return (NSR),
- truck-hours for hauling material as ore,
- truck-hours for hauling material as waste,
- SAG-hours to achieve the required grind,
- overall recovered copper.

Each attribute is modelled as a grade, hence is able to be used to calculate a quantity of a product or element to which a market constraint can be applied.

Net Smelter Return (NSR)

To model the contribution to revenue from all the products a dollar equivalent - in the form of a net smelter return (NSR) - is used. The technique has been described by Bertinshaw R & Adam R (1995, p34) and Staples M (1995, p136) with respect to Four-D. The NSR is calculated by summing the revenue derived from all the marketable minerals in a block and subtracting all the costs and penalties incurred downstream of the mill.

The NSR is used as the primary mineral. NSR ranges are used to classify each block in the model and the cut-off reported is in terms of an NSR grade.

Truck-Hours for Hauling Material as Ore

Two calculations of truck-hours are performed for each block irrespective of the NSR grade of the block. The first is made on the assumption that the block is to be hauled as ore to the in-pit crusher.

Truck-Hours for Hauling Material as Waste

This is calculated on the assumption that the block is to be hauled to a waste dump outside the pit. It is used with the hours required for hauling as ore to calculate the total truck-hours required at each cut-off. The derivation of this parameter is described in Appendix 1.

SAG-Hours to Achieve the Required Grind

This is derived from the rock type of the block and a model of the metallurgical performance in the mill.

Overall Recovered Copper

Derived from the copper grade, rock type and the metallurgical model of recoveries, it is used to constrain copper production to within the capacity of the refinery.

Each bench within each pushback (bench-increment) was evaluated and its attributes summarised into intervals of NSR value. A schedule was generated from these bench-increments which in turn were summarised by year, still within the NSR cut-off intervals. These annual pit increments were then used to generate the reserve file (Sequence Text File) for cut-off grade optimising studies using Opti-Cut. An extract from the file is listed in Appendix 2.

Capacity Constraints

Three capacity constraints were used for the optimisation study. All were modelled using market (or element) throughput limits. The mine is limited by the available truck-hours, the mill by SAG-hours and the refinery by recovered copper. The following sections describe how each element has been modelled.

Mine Capacity

The total truck-hours for each period are calculated from the total truck-hours per tonne grade for ore. These appear as a product and can be subject to a market capacity constraint. From the equation for the market limiting case (4), the formula for the increment in present value per unit of reserve when the truck fleet is the limiting capacity is:

$$v_{kTruck} = c - (f + F)xy_{Truck}g_{Truck}'/K_{Truck}$$

where

g_{Truck}' is the total truck-hours per tonne of ore,

K_{Truck} is truck fleet capacity in hours

and

y_{Truck} is 1.0

Note that the total truck-hours per tonne grade must include both the truck-hours to haul the ore and the truck-hours to haul the material rejected as waste. In the model these are supplied as two attributes or grades, one each for ore and waste haulage. The derivation of the total truck-hours is described in Appendix 1.

Mill Capacity

Similarly for SAG-hours, from equation (4) the formula for the increment in present value per unit of reserve when the mill is the constraining capacity is:

$$v_{kSAG} = c - (f + F)xy_{SAG}g_{SAG}'/K_{SAG}$$

where

g_{SAG}' is the SAG-hours per tonne,

K_{SAG} is mill capacity in available SAG-hours

and

$y_{SAG} = 1.0$

Refinery Capacity

No capacity constraint is encountered in the smelter. However there is a limit to the refinery throughput. This is modelled as a market constraint.

$$v_{kcu} = c - (f + F)xy_{cu}g_{cu}'/K_{cu}$$

where

g_{cu}' is the recoverable copper per tonne,

K_{cu} is the refinery capacity in tonnes of copper

and

$y_{cu} = 1.0$

Optimisation Runs

To illustrate the use of capacity constraints five optimisations were performed. Table 2 lists the general parameters and capacities used.

Table 2 - Optimisation Parameters

Item	Value	Units	Comments
Fixed Costs	1 000 000	$/y	
Discount Rate	10	%/y	
Price	1.00	$/$	price accounted for in the NSR
Smelting + Refining	0.00	$/$	costs accounted for in the NSR
Cost of disposing of waste	0.20	$/t	
Cost of mining	0.50	$/t	
Cost of processing	6.00	$/t	
Recovery	100	%	accounted for in the NSR.
Mill Capacity (tonnage)	30 000 000	t/y	
Mill Capacity (SAG)	24 000	SAG-hours/y	three mills
Mine Capacity (trucks)	200 000	truck-hours/y	initial capacity
Mine Capacity (trucks)	360 000	truck-hours/y	after expansion
Refinery Capacity (Copper)	180 000	t/y	

Note: No attempt was made to apply unit costs to truck-hours and mill-hours. Although being both feasible and a better model, it was considered to be unnecessary for this study.

Table 3 includes a summary of the results from each test. Present values have been reported relative to Run 1.

Table 3 - Summary of Optimisation Runs

Run	Mine Capacity	Mill Capacity	Refinery Capacity	Relative PV (Run 1 = 1)	Mine Life (Years)
1	-	30 Mt	-	1.000	14
2	-	24 000 h	-	1.012	14
3	200 000 h	24 000 h	-	0.782	20
4	360 000 h	24 000 h	-	0.961	16
5	360 000 h	24 000 h	180 kt (cu)	0.947	16

Figures 4 to 8 - showing the mine, mill, market throughput's and cut-off grade policy for each test - are included in Appendix 3. The salient points for each run are described below.

Run 1 - Mill (Tonnage) Limited (Figure 4)

The first step in a cut-off grade optimising study is to run the program with only the mill capacity limiting. From the results an indication of the mine capacity required to achieve the mill capacity and maximise the project's present value is obtained.

In this case the cut-off grade declines in the expected manner for a mill capacity limiting case.

In terms of tonnage the mill is fully utilised throughout the life of the project. However, in terms of SAG-hours, from years 2 to 7 there is unused capacity as softer ore is mined. Thereafter the mine goes into harder ore and it is unlikely that the expected tonnage throughput would be met.

The curve of truck-hours/ktonne generally follows the cut-off grade curve, reflecting the higher proportion of waste to be trucked out of the pit at high cut-offs. The increase in this curve at the end of the life of the mine is due to the increasing distances for ore haulage. The mine becomes deeper and ore faces move farther away from the location of the in-pit crusher.

Run 2 - Mill (SAG-Hours) Limited (Figure 5)

This run uses a market capacity constraint, based on the SAG-hours grade (element), as the mill capacity constraint or throughput limit. The behaviour is generally similar to that in Run 1.

The tonnage throughput in the mill is increased during years 2 to 7 as softer ore is encountered. There is a marked dip in the cut-off grade in year 5 in order to keep the mill full. From year 8, as expected, the mill tonnage target has not been met.

Run 3 - Mill (SAG-Hours) and Mine (Truck-Hours) Limited (Figure 6)

In addition to the mill capacity constraint a mine capacity constraint (throughput limit) has been applied. The constraint is modelled as a market throughput limit on the total truck-hours.

The effect of the choice of truck fleet size is quite severe. It causes the cut-off grade to drop to around break-even in the early years. In spite of this the mine is still unable to fill the mill. From year 12 the project moves from being mine to mill capacity limited. This is reflected in the cut-off grade, which rises before declining to the end of the life of the mine.

Run 4 - Mine Expansion Case (Figure 7)

An increase in the truck fleet over the first two years sees the project move from being mine constrained to mill constrained in years 4 to 6. This is accompanied by a consequent increase in the optimum cut-off grade during the early years of the project.

In year 7 it briefly moves back to being mine constrained with a consequential dip in the cut-off grade. Thereafter it moves to being mill constrained. The cut-off grade increases and then declines in the expected manner.

Run 5 - Refinery Capacity Limited (Figure 8)

In the final example what could be called a traditional market constraint has been applied. This is used to model the refinery capacity limit.

The limit comes into force during year 5. The program moves to satisfy this by processing lower grade material, dropping the optimum cut-off grade in that year. It still manages to achieve the refinery capacity without filling the mill. Total mining is reduced for years 5 and 6.

Year 7 is constrained by mine and mill, years 8 and 9 by the refinery. In year 10 the mill and refinery are about in balance. From year 11 the mill is the constraining capacity and the declining cut-off grade strategy returns.

This last case is an example where all three of the mine, mill and market constraints come into play. However in this run all three have been implemented by using market constraints.

Conclusions

The title of this paper is 'Who Needs Mine and Mill Constraints?'. The question is posed in the context of cut-off grade optimisation. The answer is that it is possible to model both mine and mill capacity constraints as market capacity constraints. To writers of cut-off grade optimising software this can simplify their task. It is only necessary for them to deal with the market limiting expression, albeit several instances.

More significantly, providing that the appropriate quantity/cut-off grade curves can be generated for the reserve, any capacity that can be visualised as a product can be modelled as a market constraint. Engineers can deal with mine and mill constraints that are expressed in units other than tonnage, enabling the model to closer reflect reality.

Acknowledgments

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Bertinshaw R and Adam R, 1995, Optimization of Multiple Mineral Deposits Using Whittle Four-D, Proceedings of the 1995 Whittle Conference - Optimizing with Whittle, Whittle Programming Pty Ltd, Melbourne.

Staples M, 1995, Whittle and the Muppets, Proceedings of the 1995 Whittle Conference, Optimizing with Whittle, Whittle Programming Pty Ltd, Melbourne.

Appendix 1 - Derivation of Total Truck-Hours

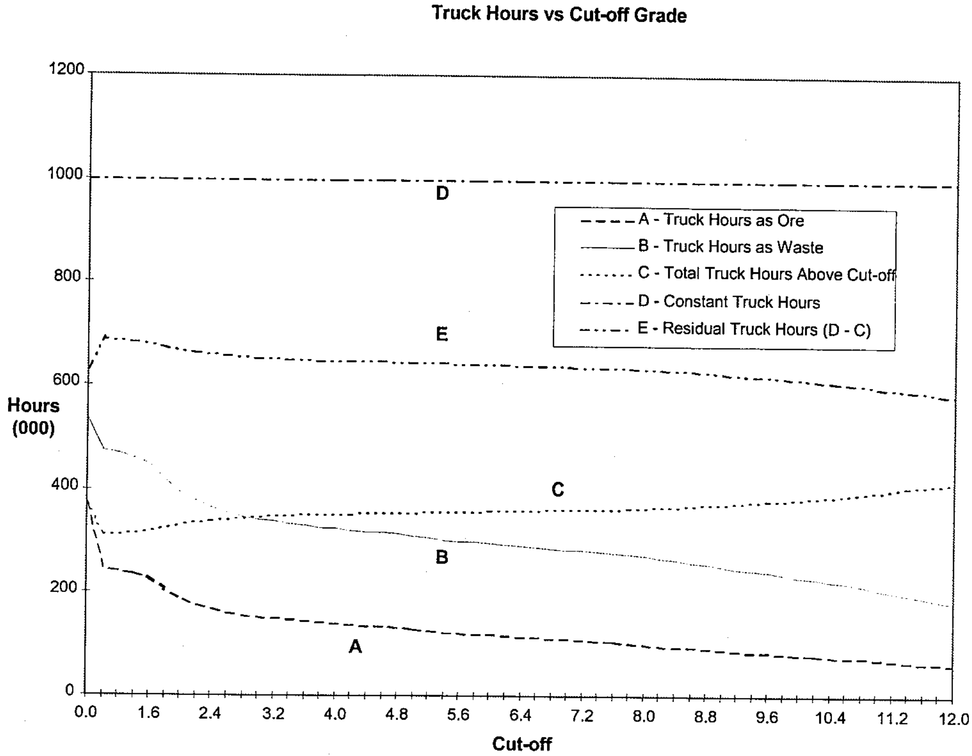


Figure 3

Graph A represents the truck-hours for hauling material above cut-off within an annual increment when that material is delivered as ore to the in-pit crusher. Graph B represents the truck-hours if the same material is trucked as waste out of the pit.

Combining A and B gives C, the total of the ore and waste truck-hours above cut-off. This is calculated from the truck-hours from A for material above the cut-off, added to the truck-hours from B for the material below the cut-off. Note that it increases with increasing cut-off as a greater proportion of material is rejected and has to be hauled over a longer route.

A characteristic of this shape of cumulative curve is that it generates negative interval quantities, hence grades. Because Opti-Cut does not accept negative grades in an interval it is necessary to adopt a device to avoid the problem. This is achieved by generating a curve E, obtained by subtracting C from a constant represented by curve D. The value of 1 million truck-hours was chosen for the constant, this being greater than the maximum of the total truck-hours in any single annual increment.

E is passed to Opti-Cut as element TRK_RES and D as element TRK_MAX. An extract from the Sequence Text File generated is included in Appendix 2.

In the Economics Text File a throughput group (TG) line is used to recreate the total truck-hours quantity TR_HRS to which a throughput limit (TL) is applied as illustrated in the following extract.

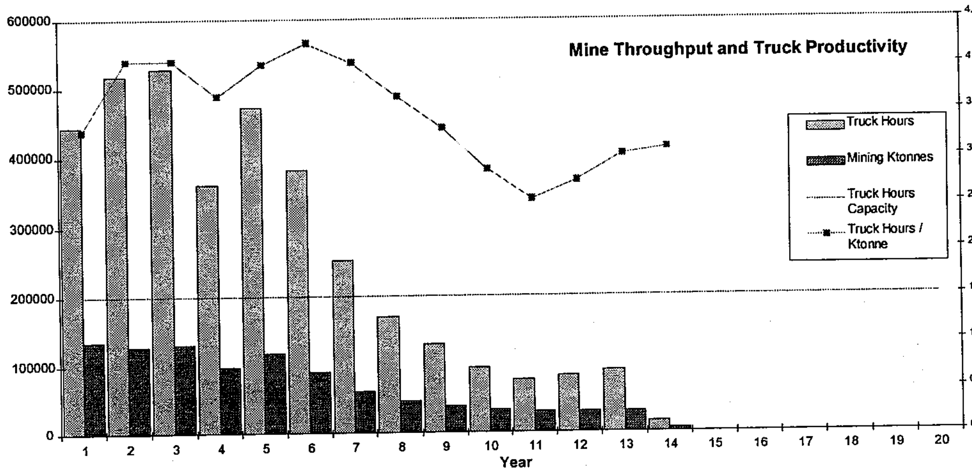
```
MT      MILL      ORE    6.00
  MTP     NSR        R      100
  MTP     TRK_RES    R      100
  MTP     TRK_MAX    R      100
  MTP     SAG_HRS    R      100
  MTP     COPPER     R      100
TG      TRK_HRS          TRK_MAX.Q-TRK_RES.Q
!
!        SAG-hours 24K pa.
!
TL      SAG_HRS  A   24K
!
!        Expansion of truck fleet by +80K hours + additional
!        80K in period 2.
!
TL      TRK_HRS  A     280 P2/360
```

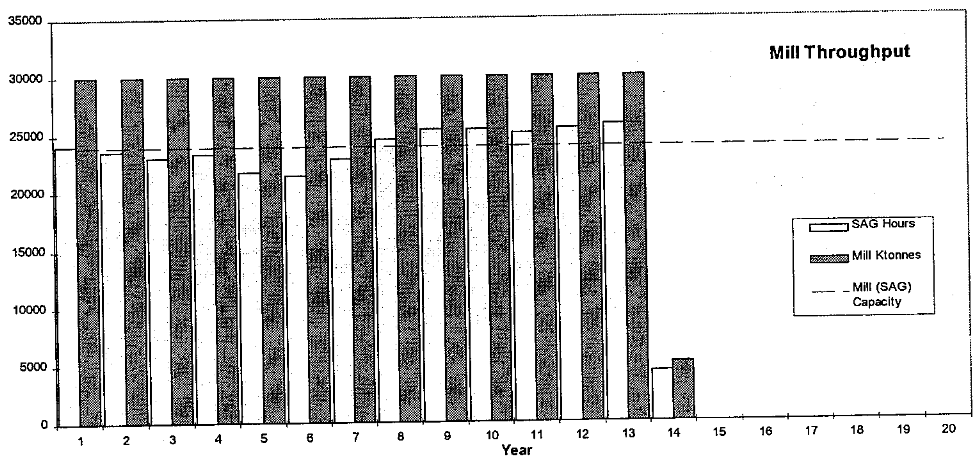
Appendix 2 - Extract from the Sequence Text File

```
SEQ
EL NSR         3
EL SAG_HRS     4
EL TRK_RES     4
EL TRK_MAX     4
EL COPPER      4
RO ORE
ELP NSR
ELP SAG_HRS
ELP TRK_RES
ELP TRK_MAX
ELP COPPER
RO WASTE
IN    1
GR WASTE        9175
GR ORE         590
ELR NSR          1.0000000   1.0918847   1.2000000
ELA SAG_HRS      0.6783000
ELA TRK_RES      0.0004156
ELA TRK_MAX      0.0000000
ELA COPPER       0.0000830
GR ORE         892
ELR NSR          1.2000000   1.2729260   1.4000001
ELA SAG_HRS      0.6213000
ELA TRK_RES      0.0019932
ELA TRK_MAX      0.0000000
ELA COPPER       0.0000405
GR ORE        1267
ELR NSR          1.4000000   1.5125731   1.6000000
ELA SAG_HRS      0.6085000
ELA TRK_RES      0.0006803
ELA TRK_MAX      0.0000000
ELA COPPER       0.0000623
.
.
.
GR ORE         431
ELR NSR         11.8000002  11.8830223  12.0000000
ELA SAG_HRS      0.8330000
ELA TRK_RES      0.0038413
ELA TRK_MAX      0.0000000
ELA COPPER       0.0048476
GR ORE       12450
ELA NSR         21.1573124
ELA SAG_HRS      0.7815000
ELA TRK_RES      0.0663045
ELA TRK_MAX      0.0803191
ELA COPPER       0.0072255
```

Appendix 3 - Figures 4 to 8

Run 1 - Mill (Tonnage) Limited





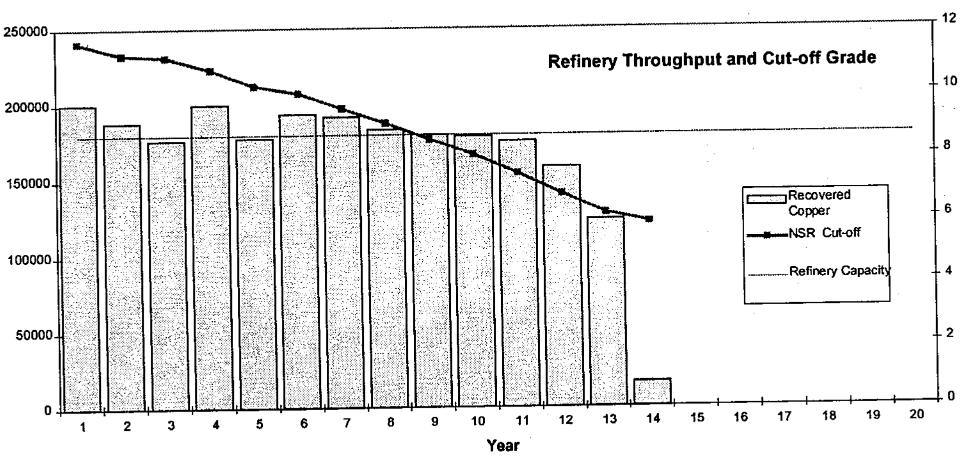
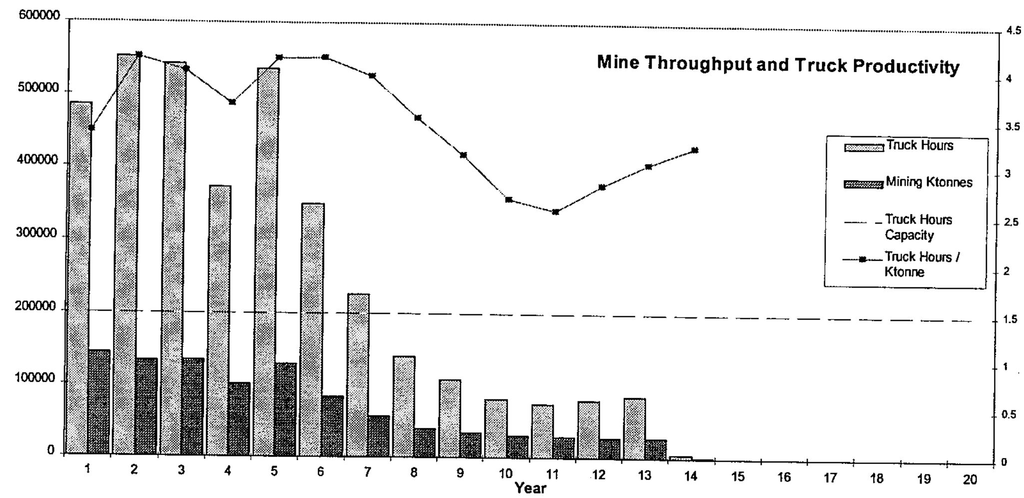
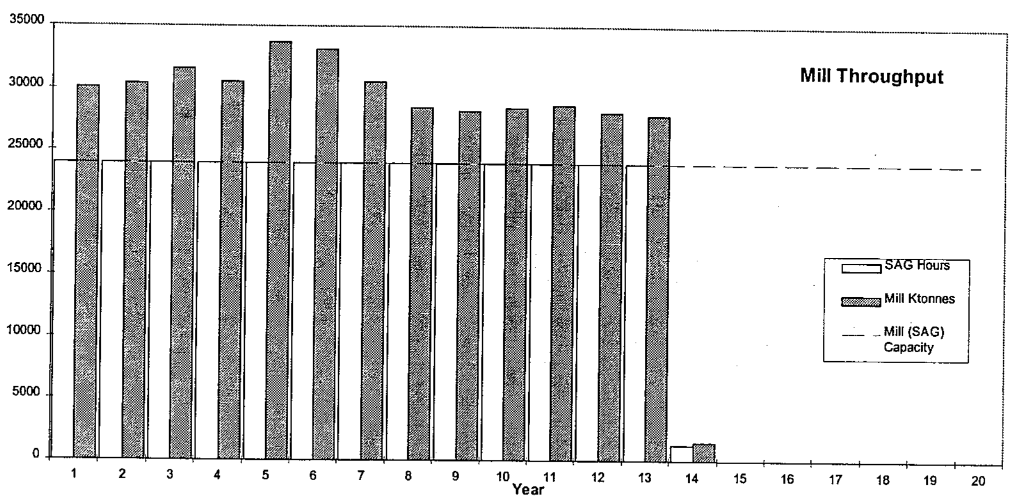


Figure 4

Run 2 - Mill (SAG-Hours) Limited





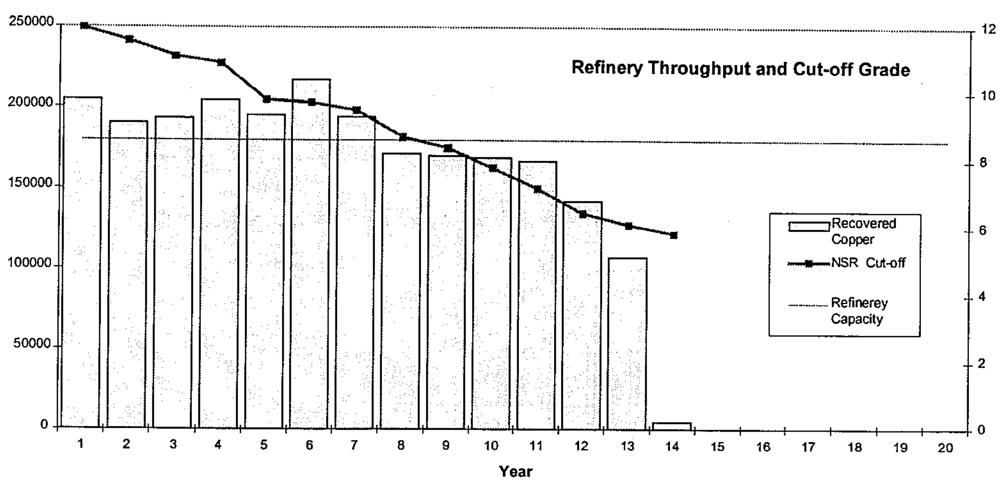


Figure 5

Run 3 - Mill (SAG-Hours) and Mine (Truck-Hours) Limited

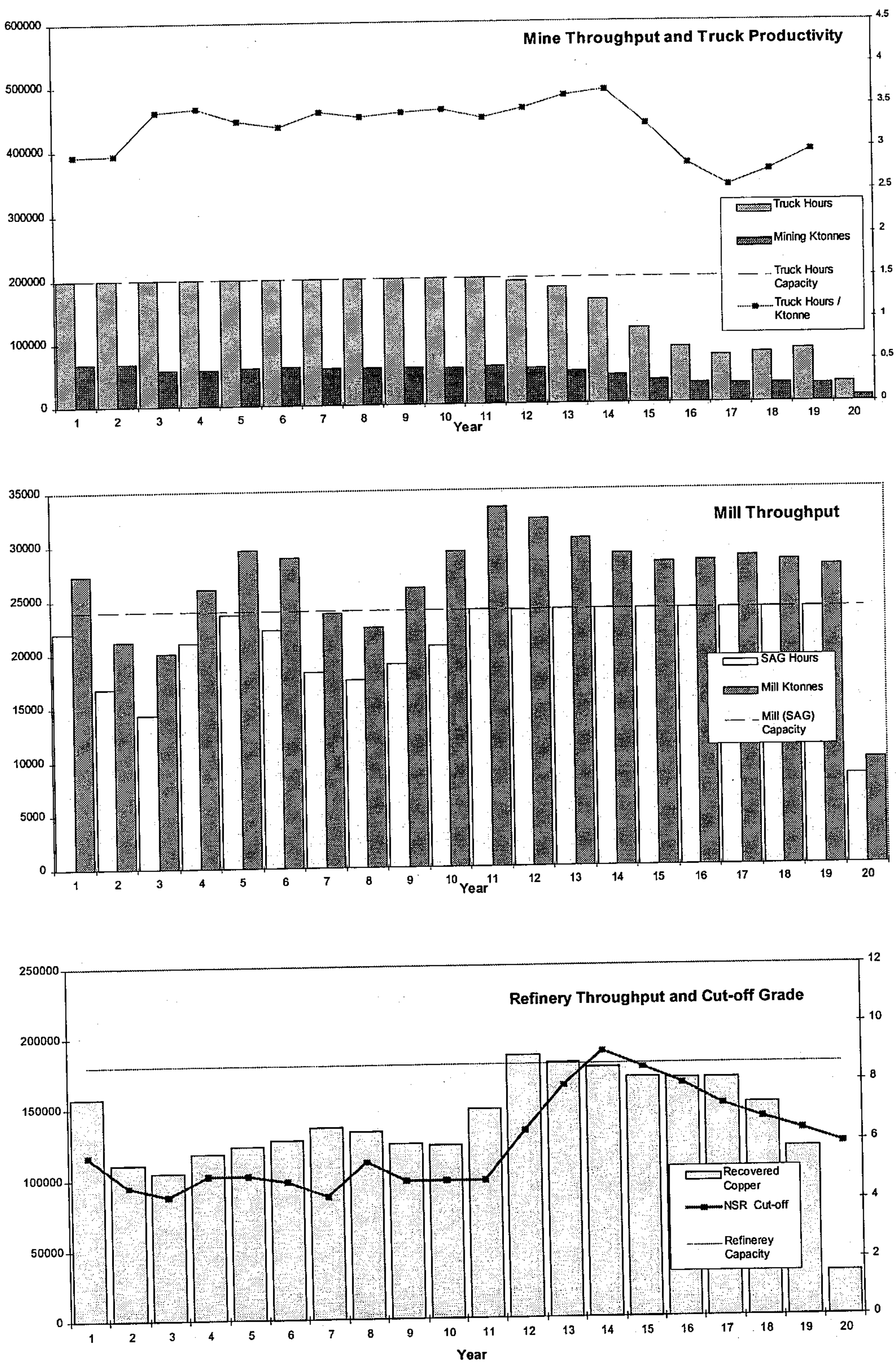


Figure 6

Run 4 - Mine Expansion Case

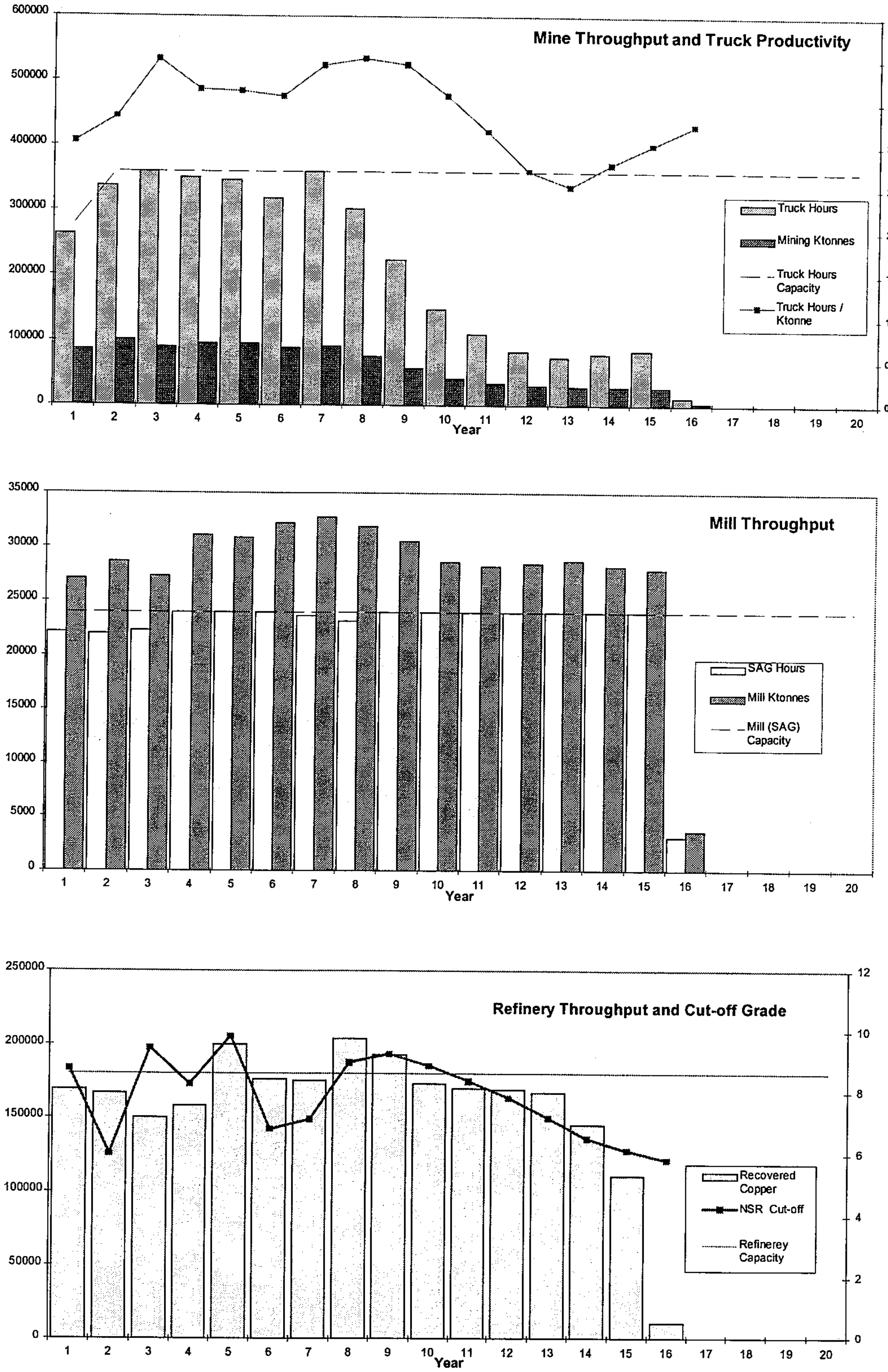
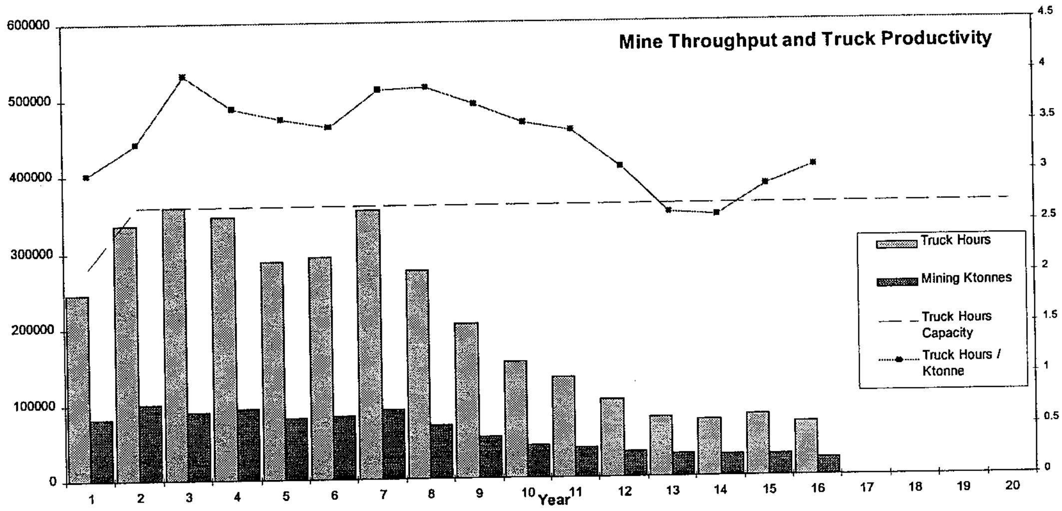
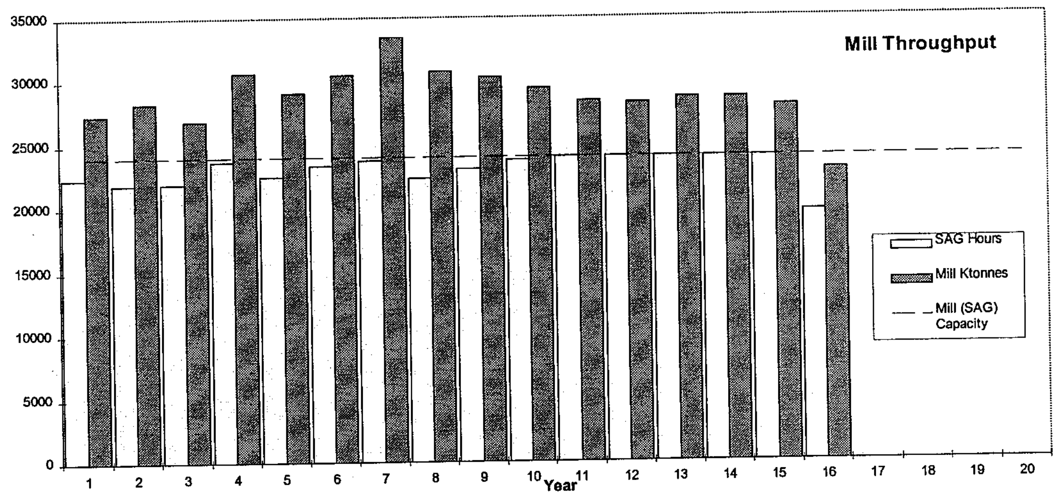


Figure 7

Run 5 - Refinery Capacity Limited





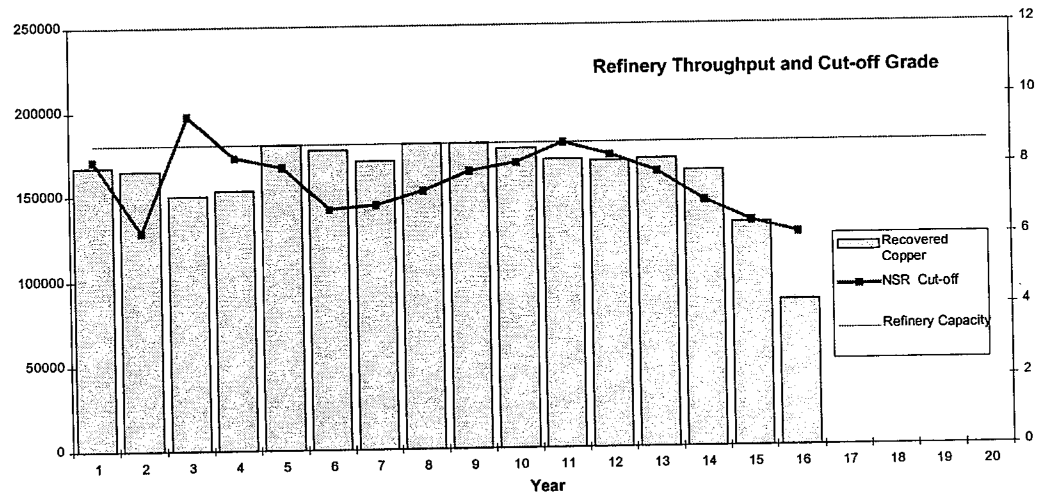


Figure 8

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