"A BENEFIT/COST ANALYSIS OF AVAILABILITY IN OIL SHALE MATERIAL HANDLING SYSTEMS"

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ABSTRACT
The material handling system in an oil shale mining operation is the lifeline of the associated shale oil processing facilities. Due to the continual feed requirements of the process, and the limited storage area typically available, material handling system availability is a critical consideration in overall plant design. Equipment redundancy and adequate storage areas affect system availability by reducing outage time; however, their inclusion requires a greater capital expenditure. This balance between system availability and capital cost can be optimized by an availability analysis. An appropriate methodology is illustrated by an example for handling oil shale from the mine face, through crushing, to the process plant via both mobile equipment and conveyors. The effects of equipment redundancy and storage pile capacity upon system availability are studied to illustrate the use of this methodology in the design of an oil shale materials handling system.

INTRODUCTION
The material handling system design for a complete oil shale facility (mine face through waste disposal) is a complex task. The oil shale retort requires long start-up and re-start times. Because these extensive start-up durations seriously affect the production rate, the equipment supporting the retort must have a high availability. This availability requirement is particularly important for the material handling system, supplying large tonnage rates of raw shale to the retort. Reaching the goal of high availability begins with an effective analysis of the system during the engineering phase of a project.

During the engineering phase, design alternatives are compared and decisions are made to achieve a high tonnage rate for the minimum invested capital and operating cost. Many times these decisions are determined subjectively - relying on previous experience, conventional design or good engineering judgment. RAM (Reliability, Availability, Maintainability) analysis, combined with an economic analysis, allows these decisions to be made on a rational basis by quantitatively assessing the availability aspects of a material handling system. The analysis provides a basis for determining the optimum economic balance between the cost incurred by installing spare or alternate equipment, increasing bin or stockpile capacity, or upgrading maintenance procedures, and the downtime resulting from equipment failures.

During the analysis, components which are critical to the production throughput are established along with their associated cost. After identifying critical equipment, the cost impact of modifications, equipment alternatives, and redundancies to improve availability is determined. The levelized annual capital, operating and maintenance cost (the levelized revenue requirement) is developed for each modification or improvement in the system. These costs are evaluated against the savings derived from the increased oil production due to a more available system. A benefit/cost ratio "goal" or reference is established and used to decide if the modifications are economically warranted. With this approach, the economic impact, in terms of downtime or reduced throughput, is determined and economic optimums achieved.

RAM CONCEPTS
General
Although Reliability is a common label describing all RAM activities, reliability
actually is defined more restrictively by RAM engineers. Reliability is the probability that a device or process has no failures in a given time interval. Availability is the probability that a device or process is in an operational state when required. Maintainability is the probability that a failed device or process is repaired within a specified time interval. If no repair is admissible, such as in some aspects of space missions, then a reliability measure is of most interest—-the probability of no failures. If repairs are possible, as is the case with most industrial processes, then availability may be of greatest interest. Failures occur but repair brings the system back into operation. Reliability and maintainability then become attributes which make the major impacts on availability. Availability is high if there are few failures (high reliability) and quick repairs (high maintainability). Repairs also include replacements or activation of standby devices.

Plant characteristics, such as operating capacity level (i.e., full load as well as reduced load operation) and surge or storage capacity, also influence availability. Reduced capacity outages result from equipment failures which allow the plant to operate at a capacity level between 0 and 100%. These partial outage states, although they have less effect on availability than a full outage, are an important consideration.

Surge capacity is incorporated in a material handling system in the form of storage bins or stockpiles. The impact of surge capacity is usually felt by upstream components in that the failure of one of these components does not affect the downstream system until the storage is depleted. Thus, the effective upstream component availability is made more favorable by the presence of the surge capacity.

Surge capacity can also reduce forced outages of the upstream system due to a failure downstream. The upstream system (such as the mine) can remain in operation even though a downstream system (such as the retort) is shut down, providing the storage is not maintained completely full. Thus, there can be optimum levels of storage. This analysis can help determine optimum storage levels.

**RAM Equations**

The equations describing availability are very simple.

Quantitatively steady-state availability \( A \) is:

\[ A = \frac{MTTF}{MTTF + MTTR} \quad \text{Eq. 1} \]

where MTTF is the mean-time-to-failure (uptime), and MTTR is the mean-time-to-repair (downtime).

Steady-state unavailability \( \bar{A} \) is:

\[ \bar{A} = \frac{MTTR}{MTTF + MTTR} = 1 - A \quad \text{Eq. 2} \]

The frequency of failures is:

\[ f = \frac{1}{MTTF + MTTR} \quad \text{Eq. 3} \]

and the duration of uptime is:

\[ \text{Duration} = A/f = MTTF \quad \text{Eq. 4} \]

Availability models of a system typically consist of groups of equipment items called modules or subsystems. These subsystems are arranged in series or parallel configurations to represent the composite system. The availability of a series of two subsystems is the product of the availabilities of the individual modules.

\[ A_s = A_A \times A_B \quad \text{Eq. 5} \]

Since the individual availability numbers are less than one, their product is a number less than any of its factors. This is intuitively acceptable because the more serial modules in a system, the lower the system availability.
Operation of equipment (each rated 100%) in parallel improves system reliability. If two independent modules operate in parallel the availability of the system is defined as:

\[
A_p = (A_A + A_B) - (A_A \times A_B)
\]  \hspace{1cm} \text{Eq. 6}

In the Venn diagram shown in Figure 1, the probability of modules A and B working are depicted by the circles A and B respectively. Unavailability, or system not working, is shown by the remainder of the rectangle outside the circles. Since the overlap of A and B should be counted only once, the term \(A_A \times A_B\) is subtracted in Equation 6.

**RAM Programs**

Availability calculations for large industrial processes, such as a material handling system, are usually performed by computer programs. The two primary types of RAM computer programs are stochastic and deterministic.

The stochastic approach typically simulates the operating life of a process using a Monte Carlo method. This procedure requires the random sampling of equipment MTTF and MTTR values as well as the calculation of operating status and surge inventory for many time intervals. Usually several thousand time intervals are required to achieve a steady state availability value. As the program proceeds with the calculations, equipment items fail and are repaired, storage contents change, and production flows vary.

Stochastic type programs do not reproduce results exactly. Random number generators are used to select probabilities from distributions for both failure and repair times, leading to non-deterministic results. Thus, to differentiate between small changes in equipment operating rates, storage capacities or MTTF and MTTR values, a large number of time intervals must be used and/or results of several repeat runs averaged. However, stochastic programs are capable of determining, to a reasonable degree of accuracy, the net throughput.

Programs using a deterministic approach assume MTTF and MTTR values are "determined" or fixed (i.e., no random sampling is required). The fact that these values are fixed allows the program to solve for availability without repeated trials. Deterministic programs usually require that the process be characterized by arrangements of elemental blocks called basic subsystems. Basic subsystems consist of single equipment items or groups of equipment items which interconnect with each other only at their end points and (1) have similar throughput capacity and (2) exist only at their maximum throughput capacity level or "zero throughput.

The maximum throughput capacity differs among the basic subsystems. One basic subsystem may operate at a maximum capacity of 25% of the plant overall capacity while another may operate at 33% of the plant capacity. Consequently, the overall plant operating capacity level varies depending upon which basic subsystems are available for operation. However, each basic subsystem's availability is determined by the operating performance or availability of its components. The tie between the basic subsystem's availability and its component availability is made with fault trees. Fault trees incorporate equipment MTTF and MTTR data in a logical arrangement of AND and OR gates. This gate configuration provides a graphical representation of all possible equipment failure combinations causing the basic subsystem to fail.

An AND gate requires that all events feeding into it must fail to obtain a failure indication at the gate output. For example two conveyors (one operating and one back-up) cause a system failure if the operating conveyor or the back-up conveyor fail. An OR gate indicates a failure at its output if any one of the inputs fail. Typically, a subsystem contains many non-redundant components which are vital to the subsystem's operation. The OR gate describes this situation in that the failure of one of these items causes the subsystem to fail.
The fault trees are solved by a computer program to determine the basic subsystem availability. The program builds a plant availability model by configuring the basic subsystems into series and parallel groups. These series and parallel groups are then combined to describe the total plant.

As the plant model is built the unique capacity states associated with each of the series and parallel arrangements are recorded. Consequently, the final combined configuration predicts the availability values of all the unique output capacity states for the overall process. This information is used to determine the equivalent availability - a measure which includes the effects of both full and partial outages.

ECONOMIC CONCEPTS

General

The RAM analysis must be accompanied by an economic analysis to fully evaluate the impact of equipment alternatives, redundancies, and stockpile modifications on a system design. The initial capital cost and the yearly operating and maintenance expense of the alternative or modification to improve availability is a negative factor; whereas the increased yearly revenue resulting from the higher availability is positive. Since these cash flows occur in different time frames, a simple "minus-plus" comparison to determine a modification's profitability is not possible. Techniques incorporating the time value of money, which place all cash flows on the same time base, must be applied to make these decisions.

The comparison method, used in this paper, is a Benefit Cost Ratio (BCR) procedure, based on levelized revenues (benefits) and levelized disbursements (costs). The levelization process puts all cash flows on an equivalent uniform annual basis. This allows a BCR to be developed to ascertain the cost effectiveness of alternative equipment selections or modifications.

A BCR above 1.0 indicates revenues exceed expenditures and the investment is profitable. Conversely, a BCR less than 1.0 shows revenues are less than expenditures and the investment is not advantageous. However, a BCR above 1.0 (indicating profitability) is not sufficient to warrant the implementation of an availability improvement modification. Every investment must include enough profit to offset the risk or uncertainty involved. Usually a BCR goal greater than 1.0 is established to provide a margin covering the risk of project failure or the uncertainty in the cost estimate. A BCR goal of 1.2 is assumed for the example in this paper.

Economic Equations

The equations describing the economic analysis follow:

\[
BCR = \frac{LR}{LRR} \quad \text{Eq. 7}
\]

Where

- \( LR \) = the increase in levelized revenue due to an increase in availability, \$/year
- \( LRR \) = the increase in levelized revenue requirements due to the system added to increase availability, \$/year

It is important to note that, in the example of this paper, the BCR equation applies to incremental values, that is only the increase in revenue, or increase in costs is required. Thus, the base case cost and revenue requirements are not needed, provided the desired or expected profit per cubic meter of oil is known, can be estimated, or is assumed.

The levelized revenue (LR) due to increased availability is calculated as shown in Equation 8.

\[
LR = \Delta A \times AP \times R \times \left[ \frac{1(1 + i)^n}{(1 + i)^n - 1} \right] \sum_{k=1}^{n} \left( \frac{1 + \beta}{1 + i} \right)^k \quad \text{Eq. 8}
\]
Where $\Delta A =$ increase in availability, expressed as a decimal

$AP =$ nominal annual production, cubic meters of oil

$R =$ revenue produced per cubic meter of oil, above and beyond the base case

Levelized revenue requirements ("profit")

$i =$ per period discount rate

$n =$ service life of plant, years

$k =$ period index ($k = 1, 2, 3 \ldots n$)

The levelized revenue requirements for the alternate or modified systems are calculated using the following equation:

$$LRR = (PWRR) \left[ \frac{1}{(1+i)^n} \right] \quad Eq. 9$$

Where $PWRR =$ Present Worth of Revenue Requirements for the entire expected service life of the plant, $\$, 

$i =$ per period discount rate 

$n =$ service life of plant in years.

The PWRR's are converted to levelized revenue requirements (LRR). This conversion is made because the PWRR is typically a large number, and difficult to conceptualize, whereas the LRR is smaller and easier to understand. The levelized costs or revenue requirements do not represent the actual yearly cost of producing shale oil since all the costs incurred are spread out over the plant life.

Present worth of revenue requirements is found using the equation shown below.

$$PWRR = \frac{CI \times FCR \times \sum_{k=1}^{n} \left( \frac{1+e}{1+i} \right)^k}{(1+i)^n} \quad Eq. 10$$

Where $CI =$ Capital Investment, and 

$FCR =$ Fixed Charge Rate, a factor composed of:

- a) cost of capital (without profit)
- b) depreciation annuity to recover capital
- c) factor for insurance and fees
- d) factor for certain taxes

$i =$ per period discount rate

$n =$ service life of plant, years

$FYVC =$ First Year Variable Charges, or the operating and maintenance expense for the first year, $\$

$e =$ a constant escalation rate 

$k =$ period index ($k = 1, 2, 3 \ldots n$)

If the FCR is not available, a more general expression for the PWRR is shown in Equation 11.

$$PWRR = \sum_{k=1}^{n} \frac{RR_k}{(1+i)^k} \quad Eq. 11$$

$$RR_k = O_k + M_k + T_k + \left( \frac{1}{1-t} \right) x (C_k - tC_k - tCiB - K_k)$$

Where $RR_k =$ kth period revenue requirements 

$O_k =$ kth period operating costs 

$M_k =$ kth period maintenance costs 

$T_k =$ kth period property taxes, insurance fees, and miscellaneous fixed costs 

$t =$ composite income tax rate (state and federal) 

$C_k =$ annual recovery on and of capital 

$C =$ capital investment 

$d_k =$ kth period ACRS income tax depreciation factor 

$t =$ composite bond interest (tax deductible) 

$B =$ proportion of debt in capital structure 

$K_k =$ kth period investment tax credit.

The economic analysis included in this paper considers the parameters listed below. Revenue requirements for the alternate systems are calculated using Equation 10, with an assumed FCR. The profit per cubic meter of oil is also assumed.
Capital, operating and maintenance costs are estimated from the data in Ref. 1 and escalated from January 1976 dollars to January 1984 dollars. These costs may not represent current expected costs accurately, but provide a consistent base for all capital, operating and maintenance expenses.

EXAMPLE RAM AND ECONOMIC ANALYSIS
Base Case Model

A simplified flow diagram for a 3180 m³/day oil shale mine and materials handling facility is shown in Figures 2 and 3. This is a simplified facility, and is not intended to represent an engineered system, nor to recommend components. This model is only to illustrate the methodology discussed in this paper and form the base case for analysis. The system consists of the underground mine equipment, the underground materials handling system, the underground surge pocket, and the surface material handling system through the pyrolysis feed bin. The retort system, the waste disposal system, and upgrading system are not discussed in this paper. These systems could, however, be analyzed in a fashion similar to the materials handling system. Each main subsystem, within the materials handling facility, is discussed briefly in the following paragraphs.

Mining operations occur within one or more mine panels (one is assumed in the model). The panel could be analyzed as a separate system, using the methodology presented, however this approach is not adopted. An availability of 90% is assigned to the panel. This assumes the mobile panel equipment includes sufficient spares to provide at least a 90% probability of having enough equipment available to meet production. The panel and all underground equipment, upstream of the 4535 mt (metric ton) underground surge pocket, operate for 6-1/2 hours per shift, 20 shifts per week. The reciprocating plate feeder, the reclaim belt conveyor, and the sloped mine transfer belt operate 8 hours per shift, 20 shifts per week. The reclaim system and mine transfer belt (which transports the shale to the surface) operate 8 hours per shift.

A surface transfer belt conveyor receives the shale from the mine transfer conveyor and transports it to the 27,210 mt surface coarse ore stockpile. The systems downstream of the coarse ore stockpile operate 8 hours per shift, 21 shifts per week. This is necessitated by the retort, which requires a continuous feed 24 hours per day, 7 days a week for many months before a scheduled maintenance shut down.

Typically, the surface coarse ore stockpile contains live storage for at least one day and quite often three days of plant operation. This storage insures feed to the plant, if the mine shuts down. There is, as a result of stockpile geometry, often two weeks or more dead storage in the stockpile that may be reclaimed using mobile equipment. This large amount of storage improves the apparent availability of the system upstream of the surface coarse ore stockpile.

A simple conical storage pile is assumed for this paper. Other storage and reclaim systems, including 100% live storage with separate dead storage, are possible. These alternate systems are normally evaluated before a storage and reclaim system is selected.

The equipment downstream of the surface stockpile through the final screening system consists of a single flow path with all components at 100% capacity, 1085 mtpd (metric tons per hour). The retort feed system is a single flow path of 1000 mtph, assuming 85 mtph of fines are rejected. One stream at 100% capacity is equivalent to two streams at 50% capacity from an availability standpoint. However, the engineering and economic benefits may not be equal, and should be studied before a
FIGURE 3. SURFACE MATERIALS HANDLING SYSTEM
design is finalized. For this paper, one stream at 100% capacity is used to simplify the example and the economic analysis.

The surface material handling system includes a reciprocating plate feeder, the surface reclaim belt conveyor, an open-loop screening and crushing circuit, a final screening circuit (to remove the undersize or fines prior to feeding the pyrolysis system), the pyrolysis feed belt and the small pyrolysis feed bin. A 2,000 mt fine ore bin provides 2 hours of feed to the final screening equipment, permitting the screening/crushing system to be shut down for short maintenance periods. The 500 mt pyrolysis feed bin provides a 30 minute pyrolysis system supply to levelize occasional surges, and provide a small buffer during maintenance and start-up periods.

The pyrolysis system and other systems downstream of the pyrolysis feed are proprietary and are not considered.

**Availability Model**

The first step in developing the availability model is to construct a system availability block diagram (ABD). The dotted lines of Figures 2 and 3 show the partitioning arrangement used to form the modules shown in the availability block diagram of Figure 4. Each rectangle represents an independent subsystem having equipment of like capacity. The triangles denote areas of surge capacity.

This model shows a serial arrangement of subsystems. With this configuration, any subsystem which fails downstream of the fine ore bin immediately causes a loss of production. Any subsystem which fails upstream of a surge point causes a system outage only if all downstream storage inventories are depleted. If the failed subsystem is repaired prior to the depletion of storage then the system is not affected by the outage.

The availability characteristics of each subsystem are described by a fault tree. Figure 5 shows the logical arrangement of AND and OR gates to depict the availability of the underground reclaim subsystem. The fault tree indicates the subsystem is inoperable if reciprocating feeder A and reciprocating feeder B fail or the reclaim conveyor, reclaim conveyor dead bed chute, slope conveyor, slope conveyor dead bed chute, or surface transfer conveyor fails.

Every component shown on the fault tree has an associated MTTF and MTTR. Some of these values are representative only; others were developed from Stearns Catalytic internal database. The MTTF and MTTR values for the material handling equipment are shown in Table 1, Component MTTF and MTTR Values.

**Calculate Base Case Availability**

The ABD and associated fault trees form the availability model. The model is solved by a computer program. A deterministic type computer program was used for this example. (Note: A verification run, using a stochastic program, produced the same results as the deterministic program.)

The base case availability is 0.969568. This availability value corresponds to a MTTF of 522.6 hours (approximately 17 failures/yr) and a mean downtime duration of 16.4 hours. A criticality ranking of each subsystem, using the Fussell-Vesely importance criteria (Ref. 2), is shown in Table 2, Subsystem Criticality Ranking. This table shows the approximate percent influence of each subsystem on the total plant unavailability. Note: the subsystems upstream of the storage pile have no influence on the system unavailability. This is because the large (19 days) capacity storage pile allows all repairs to be completed before the inventory is depleted. This buffer characteristic of the storage pile effectively gives every component upstream of the stockpile an availability value of 1.0. Consequently, only the equipment downstream of the surface stockpile is considered further. A separate study could be performed to determine optimal stockpile size,
FIGURE 4. BASE CASE AVAILABILITY BLOCK FLOW DIAGRAM

FIGURE 5. UNDERGROUND RECLAIM SYSTEM FAULT TREE
## TABLE 1

### COMPONENT MTTF AND MTTR VALUES

<table>
<thead>
<tr>
<th>Subsystem Name</th>
<th>Subsystem No.</th>
<th>Component Name</th>
<th>MTTF Hrs</th>
<th>MTTR Hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine Collection and Transport</td>
<td>01</td>
<td>Mine Panel Equipment</td>
<td>168</td>
<td>4</td>
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<td></td>
<td></td>
<td>Apron Feeder</td>
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<td></td>
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<td>Primary Crusher</td>
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<td>32</td>
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<td></td>
<td></td>
<td>Mine Panel Belt</td>
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<td>18</td>
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<tr>
<td></td>
<td></td>
<td>Gathering Belt</td>
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<td>18</td>
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<td></td>
<td>Gathering Belt Dust Hood</td>
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<td>12</td>
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<td>Tripper Feed Belt</td>
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<td></td>
<td></td>
<td>Tripper Belt</td>
<td>4,380</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tripper Feed Belt Dead Bed Chute</td>
<td>13,140</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tripper Belt Dead Bed Chute</td>
<td>8,760</td>
<td>16</td>
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<td></td>
<td></td>
<td>Underground Surge Pocket</td>
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<td>Underground Reclaim</td>
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<td>Underground Reclaim</td>
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<td></td>
<td></td>
<td>Recip. Plate Feeder A</td>
<td>13,140</td>
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<td></td>
<td></td>
<td>Underground Reclaim</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Recip. Plate Feeder B</td>
<td>13,140</td>
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<tr>
<td></td>
<td></td>
<td>Reclain Conveyor</td>
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<td>Reclain Conveyor Dead Bed Chute</td>
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<td>Slope Conveyor</td>
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<td></td>
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<td>Secondary Crusher</td>
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<td>32</td>
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<td>Scalping Screen Sliding Chute</td>
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<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scalping Screen Belt Feeder Sliding Chute</td>
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<tr>
<td>Fine Ore Product Belt</td>
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<td>Fine Ore Product Belt</td>
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<tr>
<td>Final Screening</td>
<td>06</td>
<td>Fine Ore Bin</td>
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<td></td>
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<td>Vibrating Feeder</td>
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<td></td>
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<td>Vibrating Feeder Sliding Chute</td>
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<tr>
<td></td>
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<td>Final Screen</td>
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<tr>
<td></td>
<td></td>
<td>Final Screen Sliding Chute</td>
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<tr>
<td>Retort Feed</td>
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<td></td>
<td></td>
<td>Retort Feed Bin</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Power Outage</td>
<td>8,760</td>
<td>12</td>
</tr>
</tbody>
</table>

290
and normal operating level, to allow the mine to continue operation in the event of a downstream failure.

**Compare System Design Alternatives**

**General**

After developing the base case model and determining its availability, design alternatives are incorporated to improve system availability. These alternatives must be evaluated from an economic perspective. Each of the subsystems downstream of the stockpile are modified for 100% redundancy, 50% redundancy or both. The incremental capital, operating and maintenance cost to implement each modification along with its associated availability is shown in Table 3, Model Cost Development. The levelized capital, operating and maintenance cost of an improvement are compared to the savings gained from the increased availability (increased product output). This comparison, as discussed previously, is made with a benefit cost ratio, assuming a 20% risk factor. Modifications having a BCR greater than 1.2 are accepted as profitable. Those less than 1.2 are rejected.

Table 3 is ordered with the improvement giving the largest B/C ratio first, followed by modifications giving sequentially lower BCR's. A modification which is economically justified is included in the model. Consequently, the table shows the successive building of a cost effective material handling system as improvements are made. Also shown is the incremental availability improvement, additional revenue, benefit cost ratio (BCR), and acceptability decision for each modification.

Incremental availability increases are developed with respect to the previously accepted modification. The base case availability is provided for reference.

The following discusses each modification made to the material handling system to increase its availability.

**Modification 1 - Coarse Ore Reclaim Subsystem**

A 100% redundant coarse ore reclaim conveyor is added to the base case design, for an availability improvement of 0.003459 percentage points (see Figure 6b). This modification incurs a levelized annual cost of $108,000 and produces added revenues of $250,000. Although this availability increase and corresponding production rise is not significant, the implementation cost is low, resulting in a BCR of 2.32. Since this BCR is well above the reference value of 1.2 the improvement is incorporated in the design. The new availability value, for comparison with succeeding modifications, is 0.973027.

**Modification 2A, 2B - Crushing System**

Two alternatives are considered to improve the availability of the crushing subsystem - three 50% modules and two 100% modules. Three 50% crushing systems (see Figure 6c) added to the design of Modification 2 increases the

<table>
<thead>
<tr>
<th>Subsystem Name</th>
<th>No.</th>
<th>Index</th>
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<tr>
<td>Crushing System</td>
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<td>Fine Ore Belt</td>
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<td>Underground Reclaim</td>
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**TABLE 2**

**SUBSYSTEM CRITICALITY RANKING**

- **Subsystem Name**
- **No.**
- **Index**
<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Incremental Capital</th>
<th>Incremental Oper &amp; Maint</th>
<th>Levelized Revenue Requirement</th>
<th>System Availability Improvement</th>
<th>Additional Revenue Per Year</th>
<th>Benefit/Cost Ratio (BCR)</th>
<th>Accept?</th>
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<tbody>
<tr>
<td>1</td>
<td>Coarse Ore Reclalm - 2 - 100%</td>
<td>465,000</td>
<td>9,000</td>
<td>108,000</td>
<td>0.969568</td>
<td>250,000</td>
<td>2.32</td>
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<td>2A</td>
<td>Crushing System - 3 - 50%</td>
<td>2,877,000</td>
<td>140,000</td>
<td>804,000</td>
<td>0.986483</td>
<td>972,000</td>
<td>1.21</td>
<td>No</td>
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<tr>
<td>2B</td>
<td>Crushing System - 2 - 100%</td>
<td>2,883,000</td>
<td>58,000</td>
<td>672,000</td>
<td>0.986577</td>
<td>979,000</td>
<td>1.46</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>Fine Ore Belt - 2 - 100%</td>
<td>435,000</td>
<td>9,000</td>
<td>102,000</td>
<td>0.988600</td>
<td>146,000</td>
<td>1.44</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>Retort Feed - 2 - 100%</td>
<td>634,000</td>
<td>13,000</td>
<td>148,000</td>
<td>0.991228</td>
<td>190,000</td>
<td>1.28</td>
<td>Yes</td>
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<tr>
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<td>Final Screening - 3 - 50%</td>
<td>2,191,000</td>
<td>68,000</td>
<td>550,000</td>
<td>0.998337</td>
<td>514,000</td>
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<td>No</td>
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<td>5B</td>
<td>Final Screening - 2 - 100%</td>
<td>1,974,000</td>
<td>40,000</td>
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<td>0.998363</td>
<td>516,000</td>
<td>1.12</td>
<td>No</td>
</tr>
</tbody>
</table>

**Note:** All $ values are rounded to the nearest $1,000.
FIGURE 6. AVAILABILITY BLOCK DIAGRAMS
availability by 0.013456 percentage points. The modification cost $804,000/year and provides added revenues of $972,000/year. This is a significant increase in the availability, however the large cost results in a BCR of 1.21.

The second crushing system option, two - 100% modules (Figure 6d), increases the availability by 0.013550 percentage points, an amount only slightly higher than the three - 50% subsystem case. However, the lower implementation cost of $672,000/year results in a BCR of 1.46. This ratio is higher than that for the three 50% module case and is higher than the required 1.2 value. Consequently the two 100% crushing system alternative is incorporated in the design. The new availability value used for comparison with remaining improvements is 0.986577.

Modification 3 - Fine Ore Belt - A 100% redundant fine ore belt is included in the arrangement developed in Modification 2B as shown in Figure 6e. This change results in an availability increase of 0.002023 percentage points. Implementation of this improvement requires a levelized annual cost of $102,000 and generates additional annual revenues of $146,000. This production increase is small; however its low cost results in a BCR of 1.44. This ratio is above the acceptable limit of 1.2 and the modification is included in the design. The new availability value for comparison with succeeding improvements is 0.988600.

Modification 4 - Retort Feed System - A 100% redundant retort feed system is included in the arrangement developed in Modification 3 as shown in Figure 6f. This change results in an availability increase of 0.002627 percentage points. Implementation of this modification requires a levelized annual cost, of $148,000 and generates added annual revenues of $190,000. The BCR of 1.28 is above the reference and the modification is included in the design for an availability value of 0.991228.

Modification 5 - Final Screening - Two alternatives are considered to improve the availability of the final screening subsystem - three 50% modules and two 100% modules. Three 50% final screening subsystems (see Figure 6g) added to the design of Modification 4 results on an availability increase of 0.007109 percentage points. The modification cost $550,000/year and produces added revenues of $514,000/year. The BCR of 0.93 indicates the increased revenue does not justify the cost of the modification. Consequently this availability improvement is rejected.

The second final screening option, two 100% modules (Figure 6h), increases the availability by 0.007135 percentage points. This value is approximately the same as that of the three 50% subsystems, resulting in additional revenues of $516,000/year. Implementation costs are lower that the three 50% module case ($460,000/year) resulting in a higher BCR (1.12). This B/C ratio is still less than the acceptable limit of 1.2. Consequently, this alternative is also rejected.

Final Model - The final configuration, selected by the RAM and C/B analysis, is shown in Figure 7. This configuration is the collection of all accepted modifications as discussed in the previous paragraphs. The availability of the combined model is 0.991228 or 0.021660 percentage points higher than the base case. This arrangement consists of two 100% coarse ore reclaim, retort feed, crushing and fine ore belt subsystems. Redundancy in the final screening area is not warranted according to the economic criteria applicable to this example. Additionally, the analysis demonstrated 3-50% crushing subsystems are not as beneficial as two 100% subsystems.

This analysis assumed no constraints upon the system. However, in practice, there are many restrictions on the system design. Typical constraints include the size limitation on stockpiles due to limited area or size limitations on storage bins due to structural considerations or building size. Engineering
FIGURE 7. FINAL CONFIGURATION AVAILABILITY BLOCK DIAGRAM
judgment may eliminate combinations of subsystems. For example, a single 100% capacity coarse ore reclaim subsystem in combination with three 50% capacity crushing systems is not practical. This arrangement prevents an even distribution of material to each crusher.

Environmental regulations may also influence the design and cost of a system, particularly in the dust collection and suppression areas. These regulations may force the selection of a low BCR alternative, just to meet environmental regulations.

Total available capital will also affect the final system design. The preceding discussion is based on an unlimited capital pool. The effects of a limited capital pool are discussed in the following paragraphs.

It is frequently necessary to determine for a number of independent proposals, which proposal, or which combination of proposals, should be funded providing the available pool of capital is limited, and providing the overall benefit-cost ratio goal is also met. Appendix A carries out calculations in this case for four of the alternatives discussed in this paper. First, Alternatives 2A and 2B are mutually exclusive, and Alternatives 5A and 5B are also mutually exclusive. In each of these two cases 2A and 5A and 5B are eliminated as having low or barely acceptable B/C values, and comparisons are using the four remaining alternatives (1, 2B, 3 and 4).

The analysis method employed in Appendix A is to form all combinations of the four non-mutually exclusive alternatives. The number of combinations is given by $2^N$ or here, $2^4 = 16$ combinations. These are ranked by increasing total capital required, and overall BCR values are computed for each combination. The computer program used also calculated for each combination the present worth of net benefits (PW of revenues - PW of revenue requirements) which was reported at PWBS$, and formed a ratio of PWB dollars to capital dollars. This latter measure may be of some interest, as it gives the present worth dollars of benefits (or profits) per dollar of investment.

See Appendix A for results of these calculations where the capital pool is limited.

Sensitivity Analysis

The above example involved choosing among alternatives with one set of criteria. Presumably, the stated criteria represent the best judgment or forecast of economic conditions and availability data. However, there is always uncertainty about the future; events rarely occur exactly as forecast. Because of this uncertainty, decisions can be made more sensibly if it is known whether the conclusions of the analysis are sensitive to moderate changes in specific criteria.

The conclusions of the above example are sensitive to variations in the revenue (profit) per cubic meter of oil. The results of a sensitivity study performed on this parameter are shown in Figure 8. The lines plotted on this figure show the BCR fluctuations with respect to variations of the profit per cubic meter of oil.

For example, at a $20 profit per cubic meter ($3.20/bbl) and a BCR goal of 1.20, only the coarse ore reclaim system (Modification 1) is economically warranted. However, if the profit per cubic meter were raised to $41 ($6.50/bbl), with a BCR of 1.20, then all of the modifications (except Modification 5A, 3 - 50% Final Screening Systems) would be acceptable. The final system design then would include Modifications 1, 2B, 3, 4, and 5B. Modification 2A (3 - 50% Crushing Systems) would not be incorporated since Modification 2B (2 - 100% Crushing Systems) provides a higher BCR.

If a different BCR goal, say 1.50, were established, higher profits per cubic meter are required. At a $38/cubic meter ($6.00/bbl) profit and a BCR goal of 1.50, only Modification 1 (Coarse Ore Reclaim System) would be
FIGURE 8. SENSITIVITY OF SUBSYSTEM SELECTION TO PROFIT/M³ AND BCR
implemented. A profit of $44/cubic meter ($7.00/bbl) is required at a BCR of 1.50 before the final configuration as shown in Figure 7 is economically justified.

The sensitivity studies are not limited to the above example. Other sensitivity studies applicable to the model include an analysis of:

- The effect of the capital, operating and maintenance cost variations on the BCR.
- The impact of component MTF and MTTR changes on the BCR.
- The influence of alternate equipment performing the same function on the BCR. (i.e., compare the availability and the cost parameters of various feeders - reciprocating plate, apron, vibrating, or screw)
- The effect of stockpile size and location on the BCR.

SUMMARY

RAM analysis combined with an economic analysis can develop a material handling system with a high production rate at a minimum cost, while in the engineering phase. These two techniques help the designer rationally decide which of several alternatives should be added to both improve system availability and meet a specific economic goal. The prior discussion shows an approach to implement this decision process.

A base case system is partitioned into subsystems or modules containing equipment of like capacity. These subsystems are interconnected to form an availability block diagram (ABD) which describes the system from an availability perspective. The availability of each module is characterized by fault trees. The ABD Model and associated fault trees are solved with either a deterministic or stochastic program to calculate the base case availability.

After determining the base case availability alternate schemes to improve availability are investigated. A benefit cost ratio (BCR) analysis, based on levelized revenue and levelized cost, is used during this investigation. Incremental availability, revenue, cost and BCR values are developed (with reference to the previously accepted configuration) for each modification. Only modifications having a BCR above a specified goal are incorporated in the system design. The final design is the economic optimum between the cost incurred to increase system availability and the lost production resulting from equipment failures.

APPENDIX A

As previously noted, the economic analysis of projects which are independent must be treated differently from projects which are mutually exclusive. Mutually exclusive projects are those where several alternatives are considered but only one will be selected. Benefit-Cost ratio (B/C) or rate-of-return (ROR) analyses require not only comparisons to "do nothing," but also require incremental analysis among alternatives such that each increment of added capital is justified. In this paper, Alternatives 2A and 2B and Alternatives 5A and 5B are two sets of mutually exclusive pairs. Based on a minimum B/C value of 1.20, the decision is made to eliminate 2A, 5A, and 5B from further consideration. The remaining alternatives, 1, 2B, 3, and 4, are then non-mutually exclusive alternatives; that is, one, some, or all could be done, depending on meeting two criteria: (a) the combination of capital costs should be less than a specified available pool of capital; and (b) the B/C value for the combination meeting criterion (a) should exceed the goal of 1.2 (or whatever other goal might be decided upon). Management decisions may also be influenced in setting the amount of available capital by how much the B/C ratios exceed the specified goal.

For the independent proposals, 1, 2B, 3 and 4, a computer program is used to create Table 4 which shows the results of all 16 possible combinations of doing the four proposals, from doing none to doing all four. The results are
ordered in ascending total capital involved. The first column indicates a row identifier, followed by four digits indicating the combination of proposals considered. Thus Row 5 includes doing proposals 1 and 3, requiring $899,000 of capital and giving an overall B/C ratio of 1.89. The column labeled PWB$ gives the present worth of added revenues minus added expenses for the combination being considered, over a 30 year period at a discount rate of 15 percent, and the last column ratios PWB$ to Capital$ to obtain the present worth of net benefits (profits) per dollar of capital invested.

For example, if the total capital available for this type of project is $1.6 million, then Row 8 (do 1, 3 and 4) is feasible giving a B/C ratio of 1.64 (>1.2). If management has other places to use the $1.6 million which will produce B/C ratios of 2.00, however, then only proposal 1 would be done for $465,000 in capital giving a B/C ratio of 2.32 (>2.00). The remainder of $1,600,000 - $465,000 = $1,135,000 would then be used for other groups of proposals which have B/C ratios of 2.00 or more. Thus management can use Table 4 to make decisions, based on the economic criteria desired as applied to the group of proposals presented, so long as such proposals are not mutually exclusive.

**REFERENCES**


---

**TABLE 4**

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<th>BCR</th>
<th>PWB$/C$</th>
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**Note:** All $ values are rounded to the nearest $1,000.