7.2.1 Primary Scalper

This element provides the starting point for the model, the point at which the raw material is fed into the plant. Its symbol is shown in Figure 7.1.

The primary scalper is similar to a vibrating screen: the raw material from the quarry is passed over the scalper, which 'scalps' out the fine material. Some plants do in fact have a primary scalper, so that the model directly reflects the physical situation. In this case, a percentage of the raw material, x%, is larger than the scalper mesh-size and is routed to crushers (usually to the primary crusher). The rest of the raw material passes through the scalper mesh (usually bypassing the primary crusher) and is routed wherever desired. The grading of this material is required as input data.
In the case of plants where the raw material is fed directly into the primary crusher(s), it is necessary to create an 'artificial scalper', with 100% of the raw material being considered as larger than the scalper mesh and routed to the primary crusher(s), as shown in Figure 7.2.

### 7.2.2 Crushers

Different symbols are indicated in Figure 7.3 for the various types of crushers found in practice. All crushers are reflected by the same modelling process, however.

![Figure 7.3 Symbols for crushers](image)

Modelling of a crusher is quite straightforward. The crusher setting is not required, but the product-grading and capacity at the applicable setting are. (The Apollo model of a crusher has already been discussed in some detail in Section 3.1.)

As was discussed in Section 3.1, Apollo assumes that the output grading of a crusher is not dependent on the size of the material fed to it. In the physical situation, this assumption is reasonable, as a crusher will produce a fairly constant output-grading even if the feed is altered somewhat.

Nevertheless, this assumption can cause problems when modelling a circuit. In the extreme, a crusher may be fed a maximum size of 13.2 mm, for example, yet it is specified to produce fractions larger than this - the crusher thus becomes a 'boulder producer'. Apollo
prevents this situation from occurring, by using a technique known
as 'crusher physics', a phrase coined by Dr H.J. Tobler (1984), the
developer of the model. Some details of the technique are now given:

**Crusher physics** is a set of constraints that are developed for each
crusher in the circuit; these constraints prevent a crusher from
becoming a 'boulder producer', by ensuring that the curve for the
feed to that crusher is always to the right of the specified curve
for the product (Figure 7.4).

![Figure 7.4 Crusher feed-grading should always be to the right of
the product grading](image)

If Apollo cannot (economically) route a suitable feed-grading to
a crusher to satisfy the specified product-grading, it will prevent
the crusher from being used, and may even prevent production altogether
in the circuit. The modeller must therefore take care that the circuit
allows for a suitable feed to each crusher.

Furthermore, the curve of the feed that Apollo routes to a crusher
may be tangential in places to the product curve, as shown in
Figure 7.5. Although the feed curve is still not to the left of
the product curve, so that production with the crusher is not
prevented, the size-reduction transformation is still questionable,
and the user is accordingly informed.
A numeric example (Table 7.1) is useful in explaining the mathematics of crusher physics. The table shows the feed and product gradings for a crusher, in the form of percent retained in each size interval, and also in cumulative-percent form. Remember that the product grading is specified by the user; the feed grading is calculated by Apollo, depending on how material is routed through the circuit to feed the crusher.

<table>
<thead>
<tr>
<th>Level</th>
<th>Size interval (mm)</th>
<th>% Retained</th>
<th>Cumulative %</th>
<th>Crusher physics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Feed</td>
<td>Product</td>
<td>Feed</td>
</tr>
<tr>
<td>1</td>
<td>19.0 - 26.5</td>
<td>15%</td>
<td>-</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>13.2 - 19.0</td>
<td>5</td>
<td>10%</td>
<td>85</td>
</tr>
<tr>
<td>3</td>
<td>9.5 - 13.2</td>
<td>10</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>4</td>
<td>6.7 - 9.5</td>
<td>35</td>
<td>35</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>4.3 - 6.7</td>
<td>10</td>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>6</td>
<td>0 - 4.8</td>
<td>25</td>
<td>30</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 7.1 Determining 'crusher physics' situations
At each level, if $P_j < 100\%$, a constraint is developed that checks that the cumulative percent in the feed is not greater than in the product (refer to Table 7.1):

- **Level 1** $(P_1 = 100\%)$
- **Level 2** $(P_2 = 100\%)$

\[
\begin{align*}
\text{Level 3} & : f_3 + f_4 + f_5 + f_6 \leq p_3 + p_4 + p_5 + p_6 \\
\text{Level 4} & : f_4 + f_5 + f_6 \leq p_4 + p_5 + p_6 \\
\text{Level 5} & : f_5 + f_6 \leq p_5 + p_6 \\
\text{Level 6} & : f_6 \leq p_6 
\end{align*}
\]

At any level where there is no 'slack' in the constraint, the crusher-physics condition exists (levels 4 and 5 in Table 7.1), and, in the Apollo solution printout, this is indicated as follows:

"CR-PHYS crusher no.1 level no.4 is CRITICAL"
"CR-PHYS crusher no.1 level no.5 is CRITICAL"

### 7.2.3 Screens: Effective Mesh Sizes

There is a small difference between the size of the actual mesh apertures of a screen and the corresponding **effective mesh size**. For example, a screen with physical apertures of 16 mm will tend to pass very little material larger than about 13 mm, so that 13 mm is the effective mesh size. In developing an Apollo model, effective mesh sizes are relevant, real ones are not.

The standard laboratory sieve sizes used for grading in South Africa are (in mm):

4.75, 6.7, 9.5, 13.2, 19.0, 26.5, 37.5, 53.0, 75.0, ...

In setting up a model of a circuit, it is convenient to assign, as the effective mesh size for any screen, one or other of these standard sizes. This makes analysis of material flows more straight-forward.
Also relevant is that screen efficiencies are never 100%. There is always a certain amount of undersize that remains on top of a mesh. Usually, there will be no oversize material passing through the mesh (unless the mesh is faulty). However, since the model is based on effective rather than real mesh sizes, a certain amount of 'oversize' material is allowed for.

For example, consider a screen with physical apertures of 16 mm, and suppose that the gradings of the material that flow over and through (under) the screen are as shown in Figure 7.6. In terms of the physical mesh size, 25% of the material that flows over the screen is undersize, and there is no oversize in the material passing through the screen.

The effective mesh size for this screen (in terms of the standard laboratory sizes) is 13.2 mm, being the standard size closest to, and smaller than, the physical size of 16 mm. In terms of the effective mesh size of 13.2 mm, there is 10% oversize in the material passing through the screen, and 10% undersize in the material passing over the screen.

![Cumulative Percentage Passing](image)

**Figure 7.6** Gradings of products over and through a screen of physical mesh size of 16 mm
In some instances, especially with overloaded screens (which gives rise to inefficient separation), it may be difficult to determine the most appropriate effective mesh size. Here, it is determined as the mesh size where the sum of the oversize and undersize percentages is a minimum. Consider again the example shown in Figure 7.6:

- at 9.5 mm the sum is $50 + 0 = 50\%$
- at 13.2 mm the sum is $10 + 10 = 20\%$ (minimum)
- at 19.0 mm the sum is $0 + 40 = 40\%$

From now on, all mesh sizes in this report are assumed to refer to standard effective mesh sizes, unless otherwise indicated.

It must be noted that Apollo models screens as being 100\% efficient, giving perfect separation of the incoming material at the effective mesh size. In plants that are well designed, screens are usually at least 90-95\% efficient, so that this simplification does not result in serious modelling errors. It does mean, however, that Apollo is a less-effective modelling-tool in plants where screens are overloaded.

Apollo does allow for inclusion of specified amounts of over- and undersize when modelling screens, but this feature should be seen as a 'fine-tuning device' for a model, and not as a basic feature. This facility is discussed in Chapter 8, when more advanced Apollo modelling techniques are described.

### 7.2.4 Screens: Screening Lines

To make the model more size-efficient and easier to handle, screens are modelled as 'screening lines' rather than as individual screens. The symbol for a screening line is shown in Figure 7.7.

The concept of screening lines is best dealt with by means of a number of examples.
Example A

A characteristic of screening lines is that if you have chosen to grade material flows in the plant according to, say, nine specified mesh sizes, each screening line in the plant will have all nine mesh sizes present, even if only some of these mesh sizes are actually used on a particular line. So, for example, a double-deck screen with effective mesh sizes of 26.5 mm and 13.2 mm is modelled as shown in Figure 7.8.
Example A

A characteristic of screening lines is that if you have chosen to grade material flows in the plant according to, say, nine specified mesh sizes, each screening line in the plant will have all nine mesh sizes present, even if only some of these mesh sizes are actually used on a particular line. So, for example, a double-deck screen with effective mesh sizes of 26.5 mm and 13.2 mm is modelled as shown in Figure 7.8.
Example B

Two screens in series can be directly modelled as two screening lines, or as one combined screening line, as shown in Figure 7.9 (but this can lead to problems if the two screens have unequal load capacities and the modeller is using the model to determine screen bottlenecks).

Figure 7.9 Combining two screens into one screening line

One could just as easily combine more than two screens in series into the same screening line. Screens in parallel can also be combined in this manner (but only if they have similar mesh sizes on their decks). Using screening lines, a complex screen-house, consisting of a large number of screens, can be modelled using relatively few screening lines.

Example C

Another characteristic of screening lines is that material can only enter a line at the 'top'. So, for example, two screening lines are needed to satisfactorily model the physical situation shown in Figure 7.10.
Figure 7.10 Two screens that cannot be combined into one screening line

If some of the material from B (in Figure 7.10) was larger than 26.5 mm, some routes shown by the dotted lines would have to be included in the model as well. Of course, if there was no possibility that the material from B contained any fraction larger than 26.5 mm, these dotted-line routes could be left out.

7.2.5 Silos, Stockpiles

Symbols for silos and stockpiles, which are treated in the same manner by the model, are shown in Figure 7.11.
Just as the primary scalper represents the beginning of the system, so do silos represent the final physical destinations of the material flows in the plant.

Note the mass-flow balance at the silos: the difference between demand and production is either a shortfall that must be purchased, or a surplus that must be dumped.

7.2.6 Apollo Flow Diagram

The diagrams overleaf (Figure 7.12) show how the usual flow diagram for an example plant is translated into a suitable Apollo flow diagram. It is necessary to prepare this flow diagram to aid in the preparation of the input-data forms. A careful comparison of the two diagrams shows that some care is required in converting screens to screening lines and in converting conveyors and chutes to 'destinations'.

Another, more complex, Apollo flow diagram is included on the following page (Figure 7.13) to give the reader an idea how these diagrams should look. Of course, each operator can develop his own style and can use whatever symbols he is used to for representing the plant elements.

7.2.7 Model Size

Due to the amount of calculations involved, memory limitations of the IBM PC computer, and the objective that calculations are done in a reasonable time, the number of model components is limited as follows:

- Primary Scalper: 1
- Crushers: 17
- Screening Lines: 20
- Silos/Stockpiles: 40
- Size intervals (levels): 20
Figure 7.12 Typical flow diagram and its Apollo equivalent
Figure 7.13 Apollo flow diagram for Eikenhof (the usual form of the Eikenhof flow diagram is shown in Figure 1.1)
7.3 MODEL STRUCTURE

7.3.1 Constraints

As was discussed in Chapter 5, an aggregate circuit can be considered to be mathematically linear in nature as long as the assumptions of mass conservation and steady-state flow are maintained.

Accordingly, a tableau of linear equations can be developed to model the plant circuit. In essence, each material stream in the plant circuit is represented by a set of variables that describe the size grading of that stream. Mass-balance equations are then developed at various points in the circuit.

The equations that make up the Apollo model are very similar to those in the general mass-flow-analysis model described in Chapter 5. Apollo has additional constraints, (i) to model capacities of machines, and (ii) to ensure that crusher feed-gradings are consistent with their respective product-gradings.

The user of Apollo has no involvement whatsoever in setting up the required tableau of linear equations; this is all done automatically by a 'matrix generator' facility in the Apollo computer program. This matrix generator even has a powerful input-data error-checking facility, so that a large portion of possible input-data errors are eliminated as they are entered.

A typical tableau of equations is shown in Table 7.4. These equations model an example plant, Holderbank Crushers, which is discussed in detail in Sections 7.5 and 7.6. The first part of the table lists the objective function (discussed shortly) and the equations that analyse the mass flows in the circuit; these equations are similar to those contained in the general circuit-model described in Chapter 5. The second part of the table lists the additional constraints that model the screen and crusher capacities, and the conformance of the crusher feed-gradings with their respective product-gradings.
7.3.2 **Objective Function**

The main objective in an aggregate plant is to satisfy market demand in the most economic manner. This objective can be expressed in one of two ways:

- minimisation of costs
- maximisation of marginal income.

The two approaches are not equivalent and may not yield the same optimum solution:

Apollo aims to **minimise overall costs**, while at the same time satisfying total market demand, i.e.

\[
\text{MINIMISE} \quad \text{raw-material costs} + \text{production costs} + \text{costs of dumping superfluous products} + \text{costs of running short of saleable products.}
\]

This formulation requires that the market demand must be completely satisfied, by production and/or by 'purchase' of material from another producer. It is not possible to neglect any part of the given market-demand without incurring what are sometimes 'fictitious' penalties for running short (if the costs of running short are set to zero, Apollo will prefer to run short rather than produce). Sales revenues are not taken into account.

It may be argued that a more realistic optimum would be provided by aiming to **maximise marginal income** (the approach suggested by Fore (1968), discussed in Chapter 6):

\[
\text{MAXIMISE:} \quad \text{revenues} - \text{raw-material costs} - \text{production costs} - \text{costs of dumping superfluous products} - \text{costs of running short (if any).}
\]
This formulation includes sales revenues, and does not require high shortage costs to force production. No penalty is necessarily incurred if market demand is not fully satisfied; the desire to maximise profit ensures that as much market demand is satisfied as is economically wise.

With Apollo, the motivation to minimise costs, rather than maximise profit, stemmed from the environment in which its application was intended. It was assumed that the plant manager has little control over market demand (it is specified by the sales department), nor does he have control over pricing; his task is merely to produce what is required in the most economic manner. Whether this production/sales environment is ideal or not is, needless to say, rather questionable. From a modelling point of view, the cost-minimisation objective does not provide any serious shortcoming, so long as the given market-demand profile is not ridiculously out of line with what the plant can produce, and so long as the shortage costs are reasonably quantified.

7.4 INFORMATION REQUIRED TO SET UP AN APOLLO MODEL

In order to simulate a particular operational period, the following information has to be obtained:

- Plant flow diagram
- Crusher gradings and capacities
- Screen mesh-sizes and screen capacities
- Screen efficiencies
- Raw-material grading and maximum rate of supply
- Production time available
- Costs of crushing and screening
- Costs of disposing of surplus product, and penalties for running short
- Market demand for each product
The list shows that the amount of information required is substantial, demanding the co-operation of various personnel in a plant. The effort and time involved in acquiring this information should not be underestimated.

Some details regarding the acquisition of this information, and how the various data elements influence the model, are now given.

7.4.1 Plant Flow Diagram

This is usually available at the plant, but is often out of date and requires careful checking. It is important that all possible routes of flow are included in the diagram to allow Apollo maximum flexibility in choosing the best flow routes. The plant flow diagram in its usual form requires some modification for Apollo, as was discussed in Section 7.2.6.

7.4.2 Crusher Product-Gradings and Capacities

Obtaining crusher product-gradings and capacities requires that belt cuts are taken in the plant. A belt cut is a sample of material taken off a conveyor belt.

To take a belt cut for a crusher, it is necessary to:

- Run the crusher under choke-load conditions for at least one minute (to ensure smooth operating conditions)

- Stop the feed to the crusher (most crushers cannot be stopped under load)

- Stop the belt onto which the crusher product is deposited, as soon as the crusher empties. It is important that the crusher is empty before the belt is stopped, otherwise the crusher will continue to deposit onto a now stationary belt,
with all-too-obvious results. Also, a fully loaded belt on an incline will sometimes 'run back', again with undesirable results, in which case the belt should only be stopped when most of the length is free of material.

- Remove one metre of material from the belt, including all fines and dust, and place it in a carefully marked plastic bag or other container for laboratory size-analysis.

If the speed of the belt is known, the mass-flow rate, and hence the capacity of the crusher if operating under choke-load conditions, is easily calculated using the sample mass.

At least three samples for each crusher, taken on different occasions, are required in order to get a fair idea about how the crusher performs at a given setting. This of course involves quite a lot of sampling in the plant, which may cause some stoppages of production, as well as much laboratory work.

The size-grading of the feed to each crusher is not essential, but is useful in developing a realistic model. Since many crushers are fed directly from feed bins, it is not possible to take belt cuts, and samples are obtained using a spade at the feed chute.

(It should be noted that the capacities of conveyor belts and chutes are assumed by Apollo to be infinite. The capacities of these 'routing' media can only be restricted in the model by suitably restricting the capacity of the screen or crusher which is fed by the belt or chute.)

7.4.3 Screen Mesh-Sizes and Screen Capacities

The actual mesh aperture-sizes on each deck of each screen must be obtained. Sometimes, more than one aperture-size is used on a deck (for example, three panels of 16 mm holes and one panel of 20 mm holes) and this must also be recorded.
Determining the capacity of a screen is not so straight-forward, because, unlike a crusher, a screen does not have a physical throughput capacity. But, above a certain point, as it starts to overload, its efficiency starts decreasing. The amount of material that a screen can efficiently accommodate depends on a large number of factors, including:

- area of screening surface
- aperture size
- size grading of material approaching screen
- wet (sprays) or dry screening.

Of importance is that the 'capacity' of the screen depends on the grading of the material fed to it. In an Apollo model of a plant, this grading may change, depending on how Apollo routes material through the plant. This indicates a catch-22 situation!

The problem is not so serious, however. A golden rule of aggregate plant operation (which means it is seldom adhered to!) is that the crushers should be the bottlenecks in the circuit, to ensure choke-loading at all times, and the screens should be over-designed, to ensure that they are never overloaded.

With respect to developing a model, it is useful to initially assume that all screens have virtually infinite capacity. The model is then solved, and, using a technique for calculating screen capacities (a description of which is beyond the scope of this report), it is determined whether the actual screens in the circuit could efficiently handle the indicated loads or not. (Apollo may provide the first indication that screens in a circuit are being overloaded.)

7.4.4 Screen Efficiencies

As was discussed in Section 7.2.3, Apollo models screens as being 100% efficient at size separation. However, it does have a facility to include oversize and undersize material which results from screening inefficiency (see Chapter 8).
Where possible, belt cuts should be taken of material that is the product of screening, to gauge the efficiency of screens. If belt cuts are not possible, it is even sufficient that one places a spade in the material stream at the end of the screen deck and examines it visually to gauge the amount of undersize retained on top of the deck.

7.4.5 Raw-Material Grading and Maximum Rate of Supply

The raw material is the broken rock fed into the plant, usually from a quarry. In practice, it is very difficult to obtain a grading of this material, because the rock-sizes are large, and sampling is not possible as conveyor belts are used only after the primary crusher.

All that is required for Apollo is the grading of the 'bypass' material, i.e. the fines in the raw material that fall through the scalper mesh. Also required is the percent of the raw material that remains on the scalper mesh and is fed to the primary crusher.

Obtaining this information is not too difficult if the bypass material and the primary crusher product are routed onto two different conveyor belts, as shown in Figure 7.14.

Figure 7.14 Determining the grading and proportion of the bypass material
If there is no scalper, or if the bypass material is routed to the same conveyor belt as the primary crusher product (Figure 7.15), then it is extremely difficult to determine the size grading of the bypass material. In this case, it is assumed in the model that 100% of the raw material is larger than the scalper mesh, so that there is no bypass material, and all the raw material is fed to the primary crusher. The grading of the material after the primary crusher, which in reality includes the bypass material, is assumed in the model to be due to the crusher only.

**Figure 7.15** Bypass material and primary-crusher product routed to same conveyor belt

These concepts are made clearer in Section 7.5 which deals with preparing the data for input into the computer.

Also required is the scalper capacity. This could be an apt reference, but more usefully indicates the maximum rate at which the quarry can supply the plant with raw material.
7.4.6 Production Hours Available and Production Rate

The number of production hours available in the period (usually the period is one year) is not difficult to determine.

This variable has an important bearing on the model. It must be remembered that Apollo is an optimisation model that minimises costs. If allowed a generous amount of time in which to satisfy the given demand, Apollo will stretch production over the whole period, indicating an unrealistically low throughput rate for the plant, in order to avoid using more expensive machines and crushers with unfavourable product gradings. Restricting the allowed hours forces the model to increase the plant throughput-rate in line with the near-capacity levels that are evident in practice. The time allowed therefore directly influences the plant throughput-rate in the model.

An estimate of the actual production-rate for a plant is almost always available.

7.4.7 Costs

The reason that costs are required is to enable Apollo to choose the best routing of material through the plant. Also, the costs allow Apollo to develop a realistic trade-off between producing costly surpluses of some sizes and running short of others.

Experience has shown that these costs do not have to be specified too accurately. However, it is important that the magnitudes of the various costs, relative to each other, are reasonable.

The following costs are required:

- Raw-material cost. This is the cost of bringing material to the primary crusher, and is mainly the cost of quarrying and transport. This cost is typically R1.00 to R3.00 per ton.
Operating costs for each crusher and screen. These are quite difficult to determine, as the cost records in a plant are seldom subdivided the way you want them. Suffice it to say that crushing costs typically range between R0.10 and R0.50 per ton per crusher, primary crushing being the cheapest and the later stages progressively more expensive.

Screening costs are relatively low, typically about R0.05 per ton per screen.

Cost of dumping or stockpiling of surplus product sizes. This reflects the cost of disposal of surplus material to a dump site. Typical values range between R1.00 and R5.00 per ton. If it is desired that excess production of a particular product is to be prevented at all costs, the cost of dumping for that product could be set at an artificially high level, say at R99.00 per ton.

Penalty for running short. As discussed in Section 7.3, this is a rather fictitious element. If it did not exist, Apollo would find it cheaper to run short rather than incur the costs of producing. Suggested values for this cost range between R15.00 and R40.00 per ton, the main criterion being that the cost of running short should be higher than the cost of producing. To ensure maximum production of a particular product, its penalty for shortage can be set at an artificially high level, say at R99.00 per ton.

7.4.8 Market Demand for Each Product

Sales forecasts are usually available for a plant, but they suffer from a limitation in that they are often drawn up taking into account the plant's ability to produce. What is required is the overall market demand, regardless of whether the plant in its present form can satisfy it or not.