Some aspects of quarrying economics

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SYNOPSIS

Quarrying is a comparatively simple process which is open to certain economic pitfalls. One of these is the appropriate size of the equipment needed to meet demand.

This is most evident when considering plants making stone aggregates, or plants which market the product with minimum processing.

This paper deals with the optimum sizing of plant and its difficulties and then illustrates how similar methods can be used in deciding on two other aspects, viz. timing of machine replacements and control of fragmentation. All of these can be integrated into a single model for the optimization of earnings.

1.0 INTRODUCTION

In an operation where quarrying is followed by a minimum of processing, certain rough principles emerge which may show where the major problems lie. This study refers to an ordinary stone quarry making crusher aggregate stone.

A breakeven chart (Fig. 1) is perhaps the clearest means of demonstrating the features of this particular type of business.

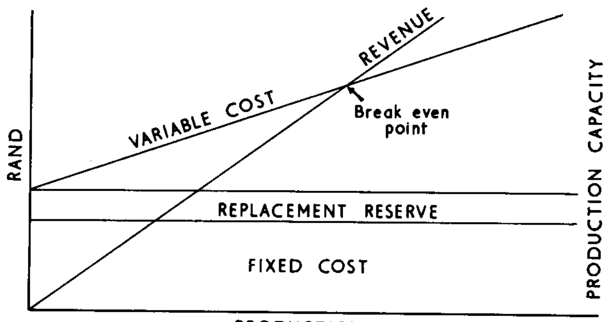

Fig. 1—Breakeven chart

1.1 In a very large quarry the breakeven point is often at about one-third of the productive capacity of the plant. In smaller quarries, however, the ratio of fixed to variable costs increases so that the breakeven point may be as much as two-thirds of the total capacity of the plant.

It follows, therefore, that small crusher plants are particularly vulnerable to fluctuations in the market.

1.2 The marginal income is small. Thus, in both large and small quarries, it is difficult to market products at any great distance from the quarry.

1.3 The size of a quarry establishment is therefore dependent on the size of the market to a much greater degree than other similar type enterprises. If a quarry is too large for its market it is uneconomic. Alternatively, if a quarry is too small for its market it not only falls short of its optimum profits but also invites competition.

1.4 Quarry machinery has a short economic service life. Operating costs of large units increase at a rate sufficient to justify their replacement in comparatively few years. A one-and-a-half yard excavator may last six and a two-yard shovel eight years.

Technical progress in earth moving equipment is quite rapid and obsolescence factors further shorten the economic lives of the machines.

2.0 SIZE OF HAUL TRUCKS

2.1 Factors to consider

To develop the argument a perhaps deceptively simple calculation on the sizing of haul trucks will be examined. At the risk of being excessively trite a picture of the process is given (Fig. 2):

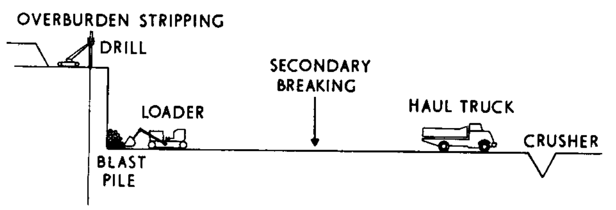

Fig. 2—The quarry process

It is proposed to deal with the process depicted up to the primary crusher stage and no consideration is given to what happens to the rock thereafter.

As will be apparent from the calculation below, the methods used are rather laborious and seem to need integration into a more concise model.

In practice, however, there is seldom need to complete the whole calculation process and, to date, no attempt has been made to do so.

After a size range has been indicated, final choice of equipment must be left to a mechanical engineer who would take into consideration such facts as spares availability, mechanical suitability and after sales service.

2.2 Truck size and cycle time

In outline the calculation follows these steps.

STEP 1: The initial selection of truck size is based on previous experience or knowledge of similar operations elsewhere.

STEP 2: Cycle time can be determined using maker's specifications and handbooks.

This process would require the following data:

(*a*) Length of the haul road.
(*b*) Conditions of the surface of the haul road.
(*c*) Gradient of the haul road.
(*d*) Maximum safe speed on curves.

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STEP 3: Confirm that the capacity of the truck is adequate for the required production.

STEP 4: Estimate the time lost in waiting in the queue.

STEP 5: Allow for vehicle availability.

STEP 6: Determine the optimum fleet number based on the size.

STEP 7: Determine the optimum size.

To exclude the effect of irrelevant factors it is advisable to confirm the decision by an illustrative calculation.

2.3 Specimen calculation

Assume that in Step 1 it was decided to use a 35 ton truck which takes 2.4 minutes to load and needs 1.0 minutes to dump into the crusher with a total travelling time of 3.2 minutes. The total cycle time is therefore 6.6 minutes. The number of cycle times per hour is therefore 9.06 and one truck will deliver 35 × 9.06 tons per hour, i.e. 317 tons per hour.

Assume crusher requirement is 400 tons per hour (the requirement is equivalent to 1.26 trucks—hence two trucks are required).

Waiting time

A method of estimating queue waiting time is given in Appendix I. The effect of increasing numbers of haul trucks is shown below.

No. of trucks in line	Total waiting time
1	0
2	0.44
3	1.469
4	4.313

To these times must be added the initial cycle time of 6.6 minutes.

Availability

Seventy per cent availability of trucks is assumed. The binomial distribution gives the probable availability of various numbers of trucks. The full complement of trucks, when present, may be able to deliver more than the crusher capacity.

(Probabilities are obtained from binomial tables.)

Two-Truck fleet

Trucks available	Cycle Time	Production tons/hr	Probability	Probable Production tons/hour
2	7.04	596 (400)*	0.49	196
1	6.60	317	0.42	136
0	—	0	0.09	0
				332 t/hr

*Crusher capacity constrains truck production.

It will be seen from the above, that a preliminary calculation indicates that two trucks could easily satisfy a demand of 400 tons per hour. Consideration of the two factors of queue waiting and availability however reduces this duty to 332 tons/hour.

It does not look as though another truck would be economical, but a calculation based on a three truck fleet shows an increase in capacity from 332 tons per hour to 373; and four trucks have a capacity of 390 tons per hour.

This illustrates a diminishing return process, i.e.:—

The first truck delivers 222 tons per hour.

A second truck increases deliveries by 110 tons per hour.

A third truck increases deliveries by 41 tons per hour, and

A fourth truck increases deliveries by only another 17 tons per hour.

2.4 Economic optimization

Using the principle of diminishing returns it follows that a point must be reached when an additional truck is unpayable.

The first item to consider is capital expenditure. This is a more complex figure than appears at first sight. It is the capital amount less tax allowances and salvage value all brought to present value (see Appendix II).

A truck costing R50 000 for example has a net value of R30 022, and is equivalent to an annual expenditure of R7 920.

Assume that an extra ton of rock is worth a nett 20c per ton. After tax this is worth 12.5c per ton.

To make operation of this truck a payable proposition, it would have to transport 63 360 tons in a year or 32 tons per hour in a 2 000 hour year.

The incremental tonnages of the third truck at 41 tons/hour and the fourth truck at 17 tons/hour can now be assessed. The third truck is obviously payable and the fourth is not.

Payability of three trucks is assessed by taking the annual after tax marginal income and subtracting the annual capital cost:

(tons per hour) × (cents/ton) × (tax factor) × (working hours) − (number of trucks) × (annual expenditure) e.g.

(373) × (.20) × (.625) × (2 000) − (3) × (7 920) = R69 490.

This is the equivalent annual profit of the investment. All that has been accomplished is that the haul fleet size has been optimized for 35 ton trucks. It is now necessary to repeat this exercise with different size trucks to find the optimum size of truck. It is advisable, in order to confirm the finding, to continue the calculations to the point where a larger and a smaller truck both give inferior profits.

3.0 OTHER CONSIDERATIONS

3.1 Increased crusher capacity

Consideration of haul truck capacity was reviewed in some detail because it contained all the elements necessary for subsequent calculations. The effect of an increase in crusher capacity also bears consideration.

Let us assume that the capacity of the primary crusher plant, which operates at 400 tons per hour, is increased to 600 tons per hour. The effect on the operation of the haul fleet is considerable, for example:

Trucks available	Cycle time	Production tons/hr	Proba-bility	Probable Production tons/hr
2	7.04	596	.49	292
1	6.60	317	.42	136
0	—	0	.09	0
				428 t/hr

It is seen by comparison with the tabulation in paragraph 2.3 that an increase in crusher capacity will increase output, using two 35 ton trucks, from 332 to 428 tons per hour or about 96 tons per hour, which is useful if a tonnage of that kind is required. Further increases in production are then possible by increasing or optimizing the number of trucks.

Calculation of the feasibility of a project for increasing crusher capacity is based on:

(*a*) Determining the net capital value of the investment less salvage values, at present value.

(*b*) Dividing by the present value factor to give equivalent annual cost.

(*c*) Subtracting the marginal income of the excess tonnage after tax.

The profit figure thus obtained is directly comparable with that obtained for haul trucks.

3.2 Increased loader capacity

In a situation such as the one we are describing the loader does not play a great role in increasing the output. Addition of another loader would simply reduce the queue waiting time, with no increase in production, as follows:

Trucks available	Cycle time	Production tons/hr	Proba-bility	Probable Production tons/hr
2	6.82	614 (400)*	.49	196
1	6.60	317	.42	136
0	—	0	.09	0
				332 t/hr†

*Crusher capacity constrains truck production.
†Compare with tabulation in paragraph 2.3.

On increased crusher capacity there would be an increase of about nine tons per hour. This will not generate enough income to justify a new loader.

The reason for this insensitiveness to loader capacity is the underutilization of the loaders: in this particular situation a loader takes 2.4 minutes to fill a truck, and in each hour only works $\frac{332}{35} \times 2.4$ minutes or 38 per cent of the time. Yet in the rough and tumble of quarry operations it is quite possible that a demand as high as this may be unrealistic.

Loader production may be slowed down by maintenance requirements and activities not directly connected with loading such as crowding rock, putting boulders on one side, moving into position, trouble with toes, etc. Some of these activities can be postponed to fit in with loading requirements and some of them cannot.

One way or another there will be occasions when a haul truck will arrive at the loader and the loader will not be able to deal with it. In this particular case the loader has to be available 0.38 of the time; if for 0.01 of the time it is not available then a further 0.04 of the time will be lost. This is usually added to the estimate of the loading time in the first place. This same consideration applies to crusher availability.

3.3 General model of the haul fleet

We can now draw a generalized picture of the economic sizing of a haul fleet whereby any unit added will add a progressively smaller increment to the productive capacity. Due to various factors the output of the fleet is much smaller than the sum of its units. A true optimum is found by trial and error; however the amount of money involved is usually large enough to justify the effort.

The practical situation is complicated by two further difficulties, *viz.* that of economic replacements and variable output requirements.

4.0 EQUIPMENT REPLACEMENT

4.1 Cost of operation as machine ages

According to authorities, the cost of operation of any machine will increase as it ages. This increase is to all intents and purposes linear. (Fig. 3). A small tendency towards flattening of the curve takes place, but this is usually well past the economic life of the unit.

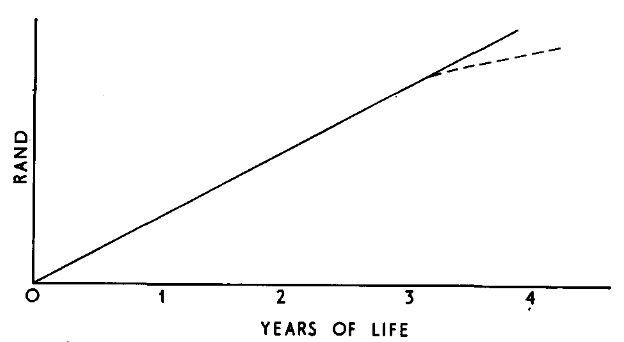

Fig. 3—Increase in cost of operation of a machine with age

Because this 'cost deterioration' in a quarry is disturbingly rapid, it is usually advisable to record individual costs of each unit to keep track of the position. Over a period of time the sceptical observer will probably have some doubt about the above statement about increasing costs. Costs do not appear to increase and this might be due to the fact that the machine has an increasing down time, or that it is handling less material.

Cost per ton of rock handled will make this tendency clearer. Another factor which has an important bearing is the long term overhaul. Over a period of time, overhauls tend to increase in frequency and cost.

A good time to review the possibility of replacement of a machine is when a major overhaul is contemplated. If the cost of a pending overhaul can be estimated, this represents the first contribution to the cost of a new machine.

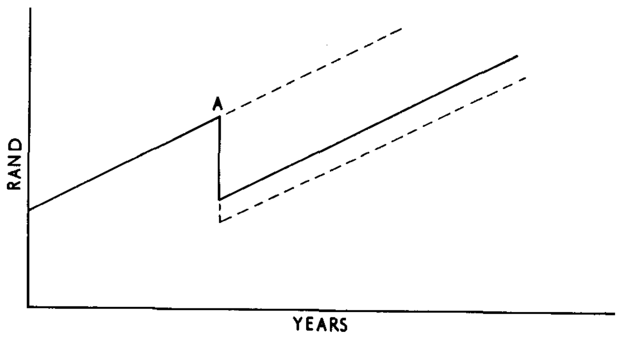

Fig. 4—Level of operating costs if a machine is replaced

At point A in Fig. 4 a replacement would return the cost level to its initial level, or if, in the meantime, a new and improved model has become available, to lower than the first year costs. Assuming that this cost advantage is R500 and the service life of the new machine is five years, a realistic pattern of savings is:

Year	Cost of Savings
	R
1	500
2	400
3	300
4	200
5	100

True annual earnings are computed by adding the value of the overhaul (say R1 000) to the cost savings and subtracting tax, which at present is about 37.5 per cent of profits, and discounting at an appropriate rate:

Year	Cost saving	Avoided overhaul	After tax earnings	Discounted earnings
1	500	1 000	938	853
2	400	—	250	207
3	300	—	188	141
4	200	—	125	85
5	100	—	63	39
				1 325

In a mining operation the entire capital amount required to buy a new machine may be available for tax relief in the first year. Assuming a machine costs R2 000, this means that the effective amount to be spent is R1 250. Salvage value of the old machine should be deducted, say R100, which after tax is worth R63. This leaves R1 187. In effect the proposal means that an effective R1 187 is to be spent in order to earn R1 325. The replacement of the machine is therefore justified, if not slightly overdue.

There are many variations of this calculation; most of them give similar answers, but the reason for giving it here is to show that under certain circumstances this calculation requires modifying. In turn the preceding calculations may be affected by these considerations of machine economics.

4.2 Variable output

The output requirements of a quarry operation are seldom static. Assume that in, say three years' time, an increased production rate is forecast. Going through the optimization exercise it is quite possible that the ideal fleet will consist of 50-ton trucks instead of 35-tonners, the crusher may need replacement and a larger loader required.

It can be quite ruinous to dispose blindly of the present fleet and replace it by the ideal one. A strategy must be worked out. In the process it may happen that an ideally economic fleet may never be achieved. Diagrammatically the process of expansion is depicted in Fig. 5.

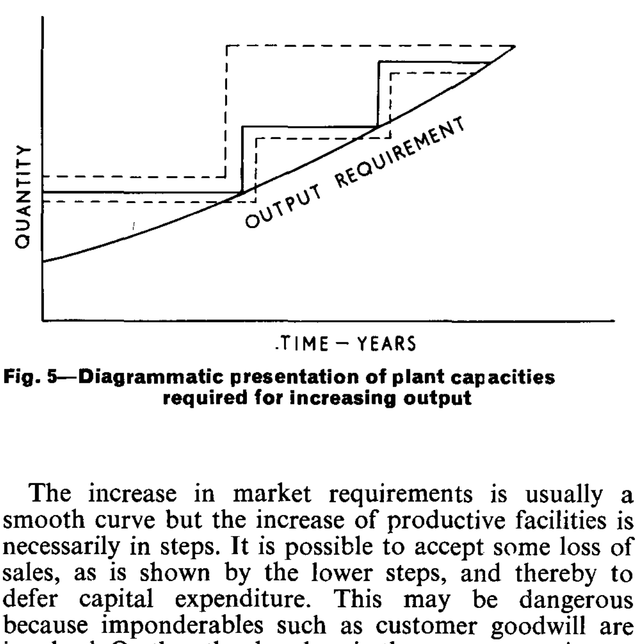

Fig. 5—Diagrammatic presentation of plant capacities required for increasing output

The increase in market requirements is usually a smooth curve but the increase of productive facilities is necessarily in steps. It is possible to accept some loss of sales, as is shown by the lower steps, and thereby to defer capital expenditure. This may be dangerous because imponderables such as customer goodwill are involved. On the other hand, as in the upper curve, it may be possible to expand in larger steps, spending large sums of money less frequently. In all cases it may happen that the composition of the haul fleet is not at the optimum but tends to approach that condition.

The final criterion is that, allowing for the effect of tax and discounting what is spent against what is earned, the excess should be as large as possible. The best result is found by trial and error.

5.0 QUARRY FRAGMENTATION CONTROL

A higher degree of rock fragmentation can be achieved by increasing the amount of explosive used. This can be done by increasing the charge or decreasing the burden and spacing.

The net effect of such a change on various cost factors would in theory be:—

(*a*) An increase in drilling costs—or increase in footage drilled.

(*b*) An increase in explosives cost.

(*c*) A decrease in loader costs, or increase in loading rate.

(*d*) A decrease in secondary breaking costs, or a decrease in the amount of work done.

(*e*) No real effect on the transport costs, although decreased loading time could have an observable effect.

(*f*) A decrease in crusher costs, or increase of crusher throughput rate. (This usually does not show up as an increase in actual tons per hour on the running crusher. It is usually shown by a decrease in the incidence and severity of boulder stoppages and sometimes by an increase in liner life. Crusher performance may show no change if secondary breaking is proportionately decreased.)

The situation is depicted graphically in Fig. 6.

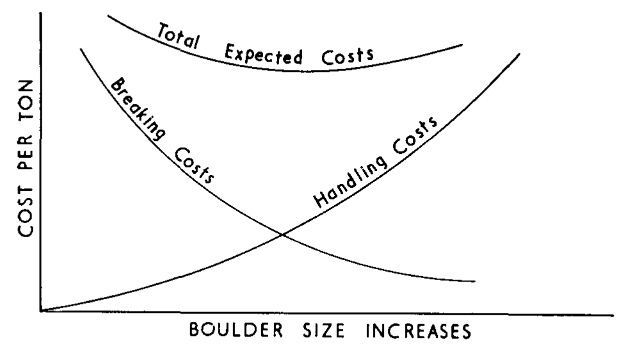

Fig. 6—Effect of fragmentation on costs

This is rather a theoretical model. In practice, the only solution is to change the degree of fragmentation at the primary breaking stage and see what happens.

It is necessary to obtain standard costs for the various units of equipment to relate to the physical performance data, as nothing can be gained from the collection and analysis of actual costs.

A loader's costs per ton decreases with increasing loading rate (Fig. 7).

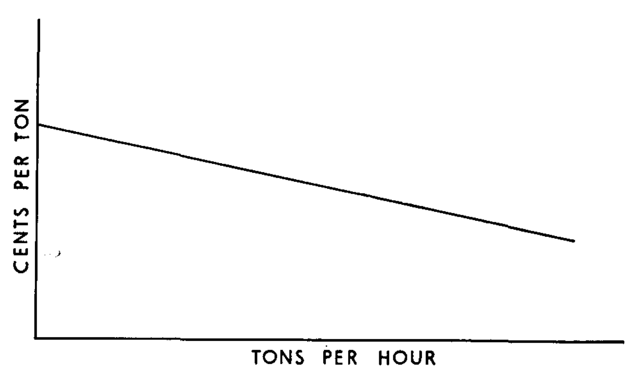

Fig. 7—Decreasing loader costs with increasing loading rate

This means that, whereas the cost per ton of variable items such as fuel, maintenance, materials, etc. remains constant, at least to the point where the machine is being damaged, the fixed costs (i.e. wages, insurance, etc.) are divided by a larger and larger amount of tons per hour.

A curve is obtained by recording the costs of a loader or crusher at various levels of throughput and plotting the best fitting line by the method of least squares. Alternatively, the costs could be classified into fixed and variable and the curve computed. It is advisable to use both methods.

The sub-optimum, which is how much secondary breaking is required so that the crusher costs and secondary breaking result in the best combined costs, should be attended to first. This is done by passing rock under controlled conditions through the crusher with various maximum boulder sizes, i.e. various degrees of secondary breaking. This is much easier than it looks. The optimization curve shows a crusher being fed with quite small maximum size rock results in lowest costs.

At this stage it is possible to try changing the fragmentation to see what happens to the costs. As previously mentioned, standard costs, which may have little relation to actual costs, are used in the calculations. The parameters from which the costs are calculated are: pounds of explosives per ton of rock, number of boulders broken, tons per hour of rock loaded, and tons per hour through the secondary crusher, all on a full shift basis.

The problem is one of degree—how far to go when increasing or decreasing the fragmentation. If the change is too abrupt, the optimum condition may be passed. If the increase in fragmentation is too small, it may not be possible to see the effect. (Refer to Fig. 6.)

A mean and sample variance calculation on the parameters listed will show how small a change in fragmentation will actually be visible at, say, the five per cent significance level; and this amount, calculated as money, can be justifiably spent on explosives.

Before an investigation of this kind is initiated, it is advisable to examine the standard of blasting, the measurement and alignment of drill holes etc. This is, needless to say, a precaution to make sure that unnecessary boulders are not caused by careless practices.

It must be borne in mind that experimenting actively with production units is not good practice, and should be severely controlled to prevent disorganisation of production.

Having obtained a picture of the real operating conditions in a quarry, it may happen that the changing outputs of the units can completely upset previous ideas of what constitutes economic sizes and numbers of equipment. Careful calculations based on the real conditions are required to ensure maximum profitability. The various stages to be considered in equipment selection, taking into account the factors described in previous paragraphs, are set out diagrammatically in Fig. 8.

It may of course not always be necessary to work through the entire calculation, but the diagram shows the interaction of the various factors in the economics of quarrying.

ACKNOWLEDGEMENTS

The authors wish to acknowledge their indebtedness to L. Greenberg for his work on fragmentation, written up in an unpublished Advanced Laboratory Thesis of

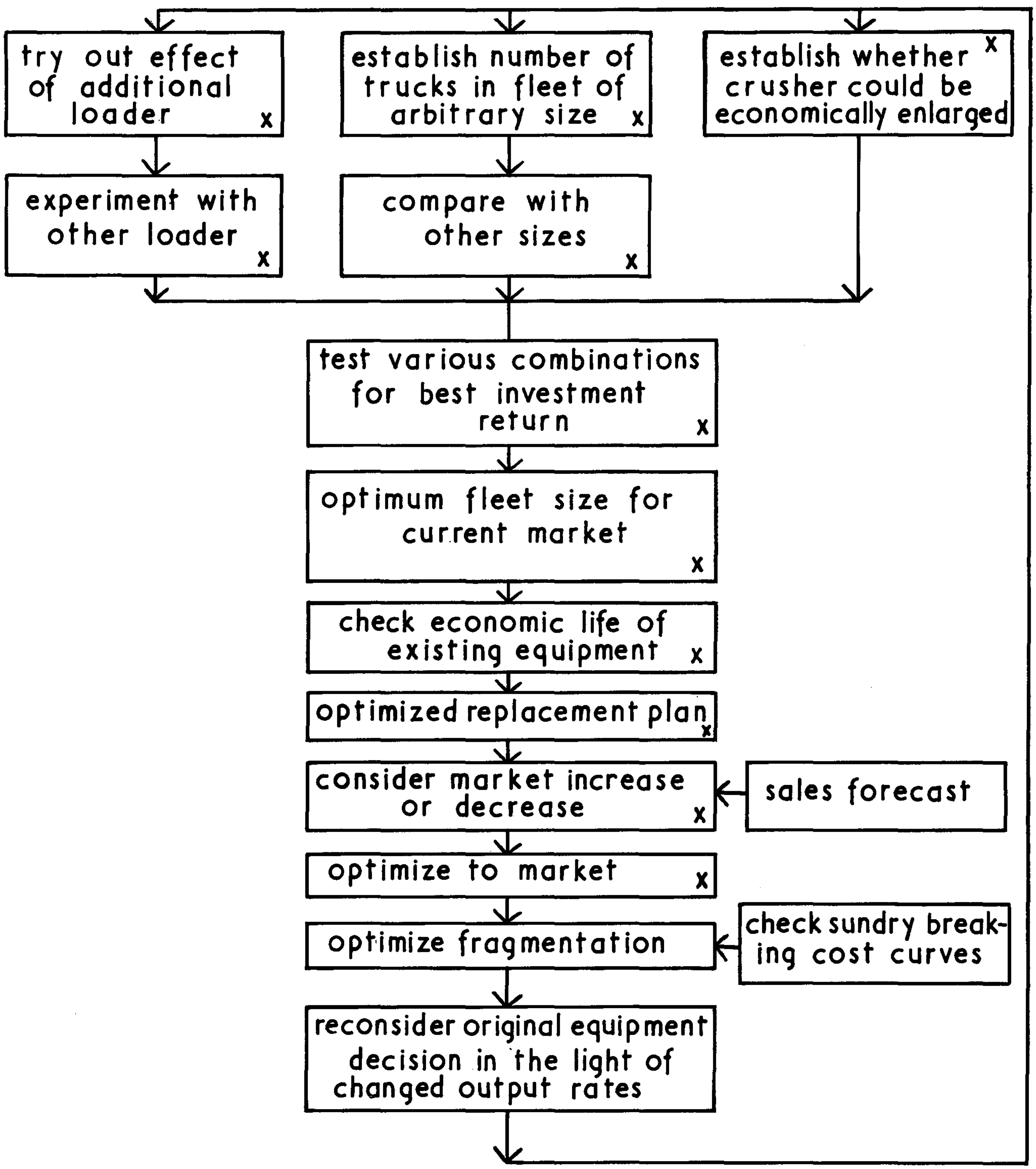

Fig. 8—Logic diagram of stages in equipment selection

Note: In stages marked X after tax expenditure is compared with earnings, whether revenue or cost savings, reduced to present value.

the University of the Witwatersrand, and Dr H. Sichel for some ideas on circular queueing given in an address to the Johannesburg O.R. Group, and to various Earth-moving Plant Manufacturers for the data extracted from their handbooks and used in the calculations for the paper.

APPENDIX I

Queueing

The formulation of an exact model to give Haul Truck waiting time is difficult due to the complexity of the actual situation. A semi-empirical approach which permits the variable conditions existing in a quarry to be taken into account, is presented here.

Two basic conditions exist; either the loading time or the truck cycle time sets a limit on the quantity hauled. The first case can be written as

$$(N - 1)S < C$$

and the second as

$$(N - 1)S \geqslant C$$

where C is the cycle time

S the time to load a truck

N is the number of trucks.

In both cases the waiting time at the start of operations is different to the waiting time after a period of operation when equilibrium or stable conditions have been established. Under normal quarry conditions, 'stable' operation is frequently interrupted by the presence of boulders or bad distribution of the rock, resulting in a delay in loading. This can be regarded as a return or a partial return to the starting condition. Thus the average waiting time may be written as:—

$$W = C_T W_T + C_S W_S$$

where the subscript $_T$ denotes the starting or transient condition and the subscript $_S$ denotes the stable condition.

The coefficients, C_T and C_S, are the proportions of the time that the transient and stable conditions exist in the system and are determined by observation of the system.

Consider an ordinary haul fleet starting in the morning.

1. The trucks stand in a line at the loader. Assuming that there are four trucks and each needs four minutes loading time, the second waits four minutes, the third eight minutes, and so on. Taking N as the number of trucks and S the loading or service time, the average time per truck spent waiting is

$$\frac{S(N-1)}{2}$$

This can be called *first cycle queueing*.

2. When the total cycle time is exceeded by the time required to load the remaining trucks, ($(N-1)S > C$), the average waiting time under non-random conditions is

$$(N-1)S-C.$$

This can be called *non-random queueing*.

The average waiting time per cycle is thus

$$W = C_T \frac{S(N-1)}{2} + C_S[(N-1)S - C]. \quad \ldots.(1)$$

3. When the total cycle time is greater than the time required to service the remaining trucks, ($(N-1)S \leqslant C$), there will be no further queueing under non-random conditions. If, however, random effects are permitted and a simple model is used which allows a truck to be early, on time, or late with equal probability, then an expression can be obtained which relates the waiting time in terms of average deviations, V, of the cycle time, to the number of vehicles N.

The waiting times under these conditions are shown in the following table.

Number of trucks	Average waiting time per truck
2	2V
3	8V
4	38.5V
5	137.6V
6	462.7V
7	1499.7V

The average waiting time per cycle is then

$$W = C_T \frac{S(N-1)}{2} + C_S W_S \quad \ldots\ldots..(2)$$

Where W_S is given in the above table.

To establish the average queueing time per truck it is necessary to observe and time the system in operation to determine.

1. The cycle time and loading time and thus whether equation 1 or 2 is applicable.
2. The proportions C_T and C_S that transient or stable conditions exist in the system.
3. The average deviation (V) from the mean cycle time if equation (2) is to be used.

These values are then inserted in the relevant equation to calculate the average waiting time per truck.

APPENDIX II

Nett capital value of a truck

The cost of a 35 ton truck is, say, R50 000; assuming a five year service life, a R10 000 terminal salvage and 20 per cent declining balance tax allowance, then the nett capital value of the truck is arrived at as follows:

Year	Capital	Tax allow.	Tax saving	Total	Discount factors at 10%	Discounted capital
0	50 000	—	—	50 000	1.0	50 000
1		10 000	(3 750)	(3 750)	.909	(3 408)
2		8 000	(3 000)	(3 000)	.826	(2 478)
3		6 400	(2 400)	(2 400)	.751	(1 802)
4		5 120	(1 920)	(1 920)	.683	(1 311)
5	(10 000)	20 480	(7 680)	(17 680)	.621	(10 979)
						30 022

The nett capital value of a truck is, therefore, R30 022 equivalent to an annual expenditure of $\frac{30\,022}{3.791} = \text{R}7\,920$, where 3.791 is the sum of the discount factors for years 1 to 5.