A Procedure for the Calculation of Surge Bin Sizes

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Summary

A surge bin between two machines in series has the effect of increasing the total capacity of the system. In the present paper this effect is related to the machines' rates, average production and interruption periods and internal availabilities. A procedure has been developed which calculates the total capacity as a function of these parameters and of the live volume of the intermediate surge bin. This procedure substitutes the rule of thumb of "so and so many hours of surge" and provides the engineer with a tool for finding appropriate dimensions of surge bins.

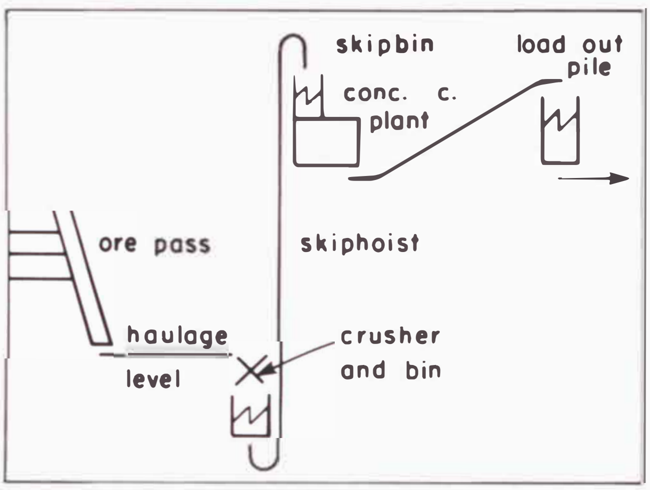
1. Introduction

The transporting machinery in the mineral industry is characterized by a rather high degree of variability. The machines' physical availabilities are low compared with those of other industries. This is due to the impact of the ore, which causes high wear and frequent breakdowns. The flow rate of the ore is variable due to its physical properties in combination with the capability of the machinery to deliver and to receive the ore as it moves from one machine to the next.

Surge bins and piles in an ore production and transportation system have the function of separating machines in series by means of volumes, which are filled and emptied, and which thus protect the machines in series from each others' breakdowns and flow rate variations.

In an ore production and transportation system there are typically 3—5 locations where surge bins or piles are installed between machines or machine systems from the mining front through to the expedition of the final product to the customer. In an underground operation there are orepasses between the production levels and the haulage level (Fig. 1). These orepasses, apart from conducting the ore, also act as surge bins. If the ore is hoisted by skip it would be crushed and held in a surge bin waiting to be fed into the measuring bin before the skip. At the top of the skip hoist a surge bin would hold the ore before it is fed to the further processing. If the ore is hoisted in cars, the tracks on the haulage level ahead of the hoist and the cars would together act as a surge. On the surface the cars would be dumped into bins holding the ore before further processing. In an open pit mine operated by shovels and trucks there might be a surge pile ahead of the crusher and a bin under the crusher holding the ore which is then fed to screening and secondary crushing and possibly to further screening and tertiary crushing (Fig. 2). Between these steps there would be surge bins. The ore then moves to further processing. If it has to undergo important beneficiation steps before a final product has been attained, there will be surge bins between these steps, some of them possibly holding the ore in slurry form. The final product — the concentrate — would be stored in bins for bulk delivery or packed in sacks or barrels in a warehouse before delivery. If the ore is moved forward by rail to a port

Fig. 1: The flow of ore from an underground operation



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there would be a load out pile for rail car loading and at the port end piles for loading the ore into the arriving vessels (Figs. 1 and 2).

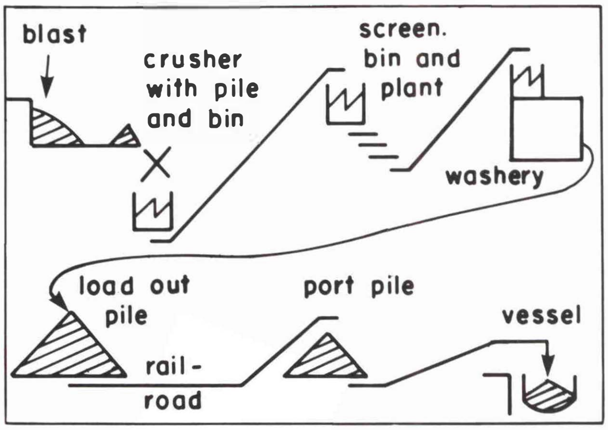


Fig. 2: The flow of ore from an open pit operation

Bins and piles have other functions such as blending and homogenization. In this paper, however, only the functions of surge capacity is considered.

In the technical literature on bins and silos the problems of materials flow appear more prominently than the problems related to the effect of the size of internal storage volume. In the list of references, which is far from being complete, [1] and [4] describe various analytical approaches to the problem of the effect of storage volume. The present author used a simulation approach [2] developed into an adjusted analytical approach [3] and [5], which has been further developed into the complete procedure described in this paper.

2. The Effect of a Surge Bin

A surge bin between two machines (Fig. 3) has the effect of permitting the first machine to continue to operate (and deliver ore to the bin), while the second machine is broken down. Eventually the bin would become full and the first machine would have to stop if the second machine did not start up again in the mean time. And vice versa, the second machine can continue to operate and receive ore, while the first machine is broken down, until the bin is empty. For the purpose of this reasoning it has been assumed that the first machine in Fig. 3 receives ore from a very large (never empty) bin and that the second machine delivers ore to a very large (never full) bin.

The loss of production is a function of the live volume of the bin. When there is no bin volume between the two machines the ore is moving ahead only when the two machines are operating simultaneously and only at the rate of the machine with the lower rate. When either of them is broken down no ore would come through. Installing a surge bin would have the effect of increasing the total production. At the limit, if a very large bin volume were installed between the two machines the total capacity of the system would approach the capacity of the machine with the smallest capacity. Intuitively one would expect that adding a certain bin volume to a small bin would create a larger capacity increase than adding the same bin volume to an already large volume. In other words the marginal benefit of adding volume decreases with increasing bin volume.

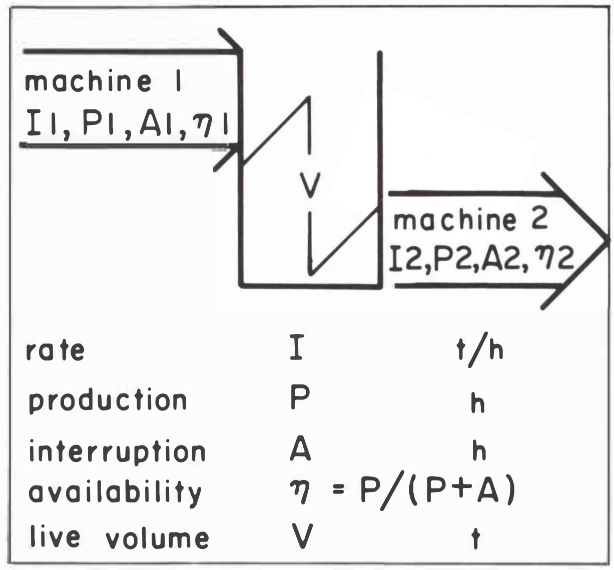


Fig. 3: The "machine 1 — bin — machine 2" system

This is illustrated in Fig. 4, which shows total capacity as a function of bin volume. It is precisely the establishment of this function and its possible uses, which is the purpose of this paper.

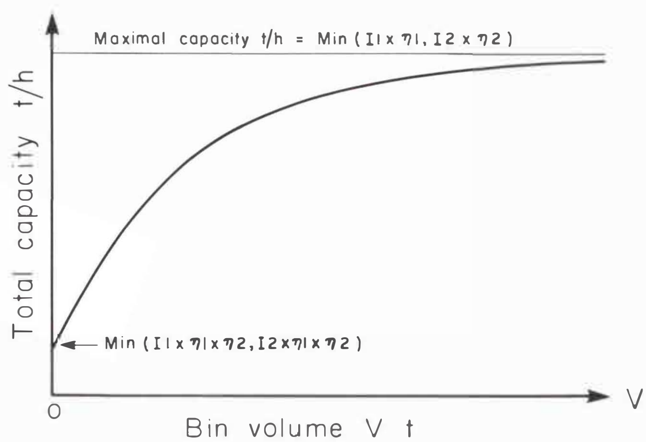


Fig. 4: Total capacity as a function of live bin volume

Apart from being a function of the bin volume the total capacity of the system shown in Fig. 3 is of course also a function of the machines' installed internal capacities as well as of their internal production variations.

3. A Machine's Rate, Internal Availability and Capacity

A machine's chronology is composed of production periods and periods of interruption some of which are caused by the upstream and downstream machinery in the form of bins empty and full and some of which are caused by the machine itself in the form of breakdowns and periods of preventive maintenance. The pattern of production periods and internal interruptions — their average lengths and standard deviations — is an important characteristic of a machine and its state of availability. (It should be observed that the lengths of production periods can be established only after weeding out the interruptions of external causes.) A machine's rate is the average production per time unit when not interrupted. For the purpose of the present development a machine's availability is defined as the ratio of the average length of production to the sum of the average length of production and the average length of interruption. When a machine is operating without external interruptions, which would be the case when there are very large bins at both ends, the availability figure becomes its internal availability. A machine's internal capacity is defined as the product of its rate and its internal availability.

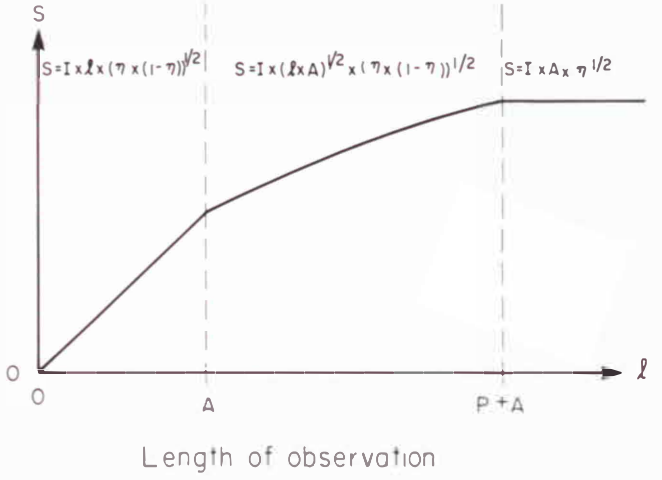


Fig. 5: Standard deviation of production, *S*

4. A Machine's Production Variation

The output of an isolated machine, as the one considered in the preceding paragraph, expressed in production per unit of time regardless of whether the machine is producing or halted, varies from time to time. If the machine is producing continuously during the observed unit of time it obtains the highest production per time unit equal to the rate. If it is broken down or stopped for preventive maintenance during the whole observed time unit the production is nil. If production is interrupted or recommences during the observed unit of time, the production during that unit of time is somewhat between the rate and nil. The variation will be higher for longer average lengths of interruption than for shorter while considering equal rates and equal internal availabilities. The variation will also be higher for higher values of the internal availability than for lower while considering equal rates and equal average lengths of interruption. The variation will be higher for higher rates than for lower while considering equal internal variabilities and equal lengths of interruptions.

A useful description of variation is the standard deviation, which is the root of the average of the squares of deviation of the observations from the average production.

When considering an industrial process, operating under stationary circumstances, one would intuitively expect that the standard deviation would increase somewhat when observing more consecutive time units together. However, it would not continue to increase. Instead there is reason to assume that it attains a maximum level and remains there in spite of increasing number of time units of observation. The author has not found a strict proof for this, but it is supported by simultations, which also showed that a rather simple model of the standard deviation of production as a function of rate, average length of interruption and internal availability could be established. This is shown in Fig. 5. The standard deviation increases linearly with the length of observation from 0 to the average length of interruption and parabolically from there until the sum of the average lengths of production and interruption. And from this point the standard deviation attains its maximal level and remains there even when the length of observation increases. It is this maximal level which is used in the following consideration leading to the formulation of the loss function.

5. A Bin's Content Variation

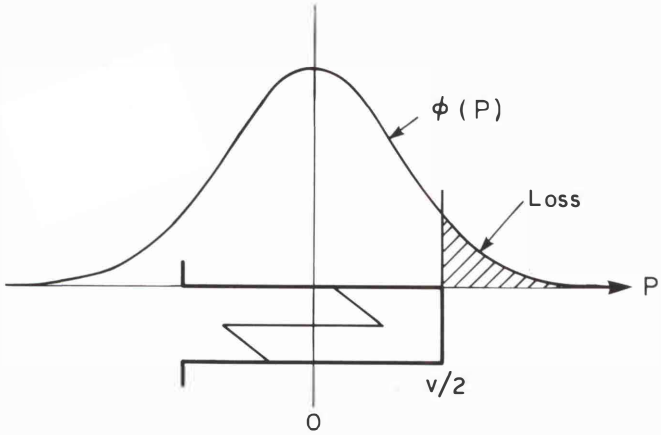
The content of a bin varies with time because of the production variations of the input and of the output machines. Obviously the content variation is obtained by substracting the output production from the input production. For the purpose of the immediate development it is assumed that the input and output machines have equal internal capacities. The difference between their productions is thus equal to zero, which also means that the average bin content is at a constant level. However, due to the variations of input and output the content has a variation, which under the assumption of independency in the statistical sense between the two machines, can be expressed as the root of the sum of the two machines' squared production standard deviations.

6. A Bin's Content Frequency Function

When observing the bin content repeatedly one would find that the bin at an average is half full (under the assumption of equal internal input and output capacities) and that the frequency function of its content is symmetrical. In the case of a very large bin the content frequency function would tend towards zero both above and below the half point. However, with smaller bins, i.e., such which give rise to a loss of production, one would observe deformations of the frequency function both at bin full and at bin empty.

7. The Loss

When a bin content variation tends to pass beyond the volume of the bin or below a zero bin content, then a loss occurs. The calculation of the loss is in principle carried out by multiplying the bin content frequency function with the amounts by which the bin content variation would pass over or pass under the limits of the bin. This involves a double integral of which one part — the bin content frequency function — is non-analytical. It has been found that a sufficiently correct result is obtained by assuming a rectangular or a triangular frequency function and carry out the integrations at selected points (Fig. 6).



$$\text{Loss} = \int_{V/2}^{\infty} (P - V/2) \times \phi(P) \times dP$$

Fig. 6: Production loss

8. The Capacity of the System Assuming Equal Internal Machine Capacities

The loss calculated following the development in the former paragraph is a normalized figure which takes the value 1 when the bin's volume is equal to 0 and the value 0 when the bin is very large.

The calculation of the capacity assumes first that in addition to the assumption of equal internal machine capacities the rates of the two machines are also equal. In that case the capacity is the product of the rate with both machines' internal availabilities and with the loss factor plus the internal machine capacity multiplyed by 1 minus the loss factor. Mathematically expressed using the notations in the Appendix: $C(1-2) = I1 \times \eta 1 \times \eta 2 \times F + I2 \times \eta 2 \times (1\text{-}F)$. If the rates are different but the internal machine capacities still equal, the capacity becomes: $C(1-2) = \mathrm{Min}(I1, I2 \times \eta 1 \times \eta 2 \times F + I2 \times \eta 2 \times (1\text{-}F)$

9. System's Capacity with Unequal Internal Machine Capacities

This is obviously the most common case, which unfortunately is difficult to treat directly with the straightforward approach used in the development described in the former paragraphs, which has the advantage of using the parameters of rate and variation generation directly. It has therefore been chosen to use this basic method in combination with an adjustment.

Let us assume a system of two machines with an intermediary bin. Both machines have certain internal availabilities and average lengths of interruption and the second machine has a certain rate. All of these parameters are kept constant while the rate of the first machine is allowed to increase from 0. If the bin is very large the capacity of the system would increase linearly from 0 to the capacity of the second machine while increasing the rate of the first machine. The maximal capacity which is the internal capacity of the second machine is obtained when the two internal capacities are equal. If the bin volume is equal to 0 the capacity of the system would increase linearly from 0 to a maximal capacity, while the rate of the first machine increases from 0. This maximal capacity would be obtained when the rate of the first machine reaches the rate of the second machine and would be equal to the product of this rate with the two internal machine availabilities.

With a certain bin volume the solution — the total system's capacity — would be between these two boundaries and is found by forcing the total capacity of a system consisting of machines with equal internal capacities (the rate of the first machine having been adjusted to abtain equal internal capacities) along a certain type of function by readjusting the rate of the first machine to its initial value. The types of function which have been selected are derived from Erlangian and hyperexponential functions, which have shapes suited for the adjustment. They do not represent models of the object. The adjustment is illustrated in Fig. 12 in the Appendix.

Further to the adjustment along a function an additional adjustment has occasionally to be applied in order to assure that the solution lies above the lower boundary.

The resulting output rate from the second machine is equal to its initial output rate if the rate of the first machine is larger than that of the second machine. It is a weighted average between the two initial rates when the rate of the second machine is larger than the rate of the first machine.

The resulting availability of the system is the total capacity divided by the system's resulting rate.

10. Summary of the Evaluation and Calculation Procedure

The calculation procedure by itself is shown in detailed steps in the Appendix. The total procedure includes data evaluation and can be summarized as follows:

A. Determine the parameters: rate, average length of production (uninterrupted from external causes) and average length of internal interruption and from these two lengths of time the internal availability for the considered machines (or machine systems) in series.

B. Determine the live volume of the intermediary surge bin or pile.

C. Calculate the maximal production standard deviations of the two machines or machine systems from the basic parameters or determine them from observations of similar machines.

D. Calculate the maximal standard deviation of a bin content variation.

E. Calculate the total capacity of the system, where the rate of the first machine or machine system is adjusted so that the two machines have equal internal capacities.

F. Readjust this calculated total capacity to the searched capacity by forcing it along specified functions to the interception with the initial rate of the first machine.

G. Undertake the minor boundary corrections if any.

H. Calculate the resulting average rate of the system (equal the new rate of machine 2).

I. Calculate the resulting internal availability of the system.

11. Use of the Procedure and Calculation Results

The uses of the procedure are best demonstrated by some calculations of which the results are shown in Figs. 7 to 11. In Fig. 7 the total capacities of two almost identical 2 machine systems are shown as a function of the intermediary surge bin. The only difference between the two systems is that the machines in system 1 have an average interruption length of 2 hours whereas in system 2 it is 5 hours, which causes the lower capacity of system 2.

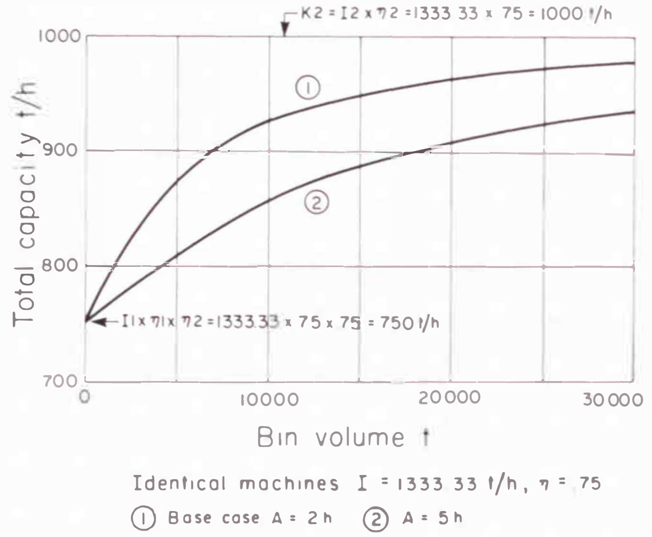


Fig. 7 Total capacity ~ bin volume

In Fig. 8 the base case of Fig. 7 is compared with a system (3) of which the first machine has a lower internal capacity than the second which depresses its capacity curve although its rate is somewhat higher.

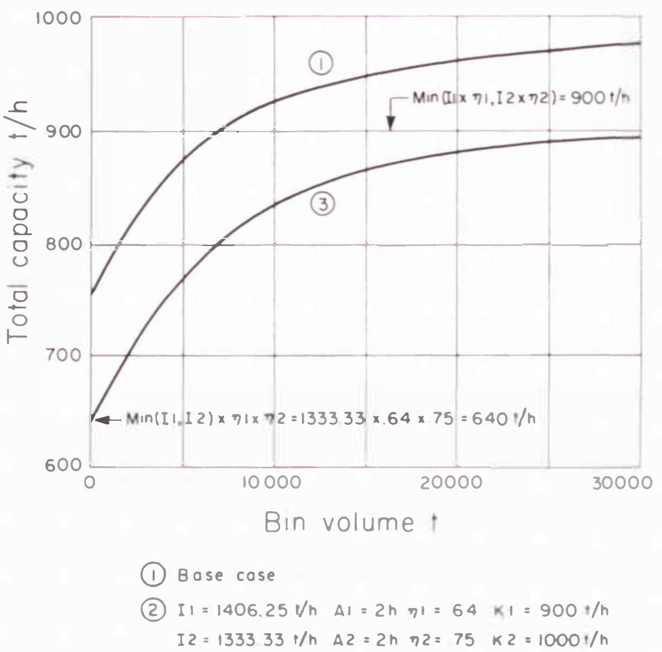


Fig. 8: Total capacity ~ bin volume

In Fig. 9 the base case of Fig. 7 is compared with a system (4) where the second machine has the same internal capacity as the first machine, higher rate, but lower internal availability which results in a lower initial capacity.

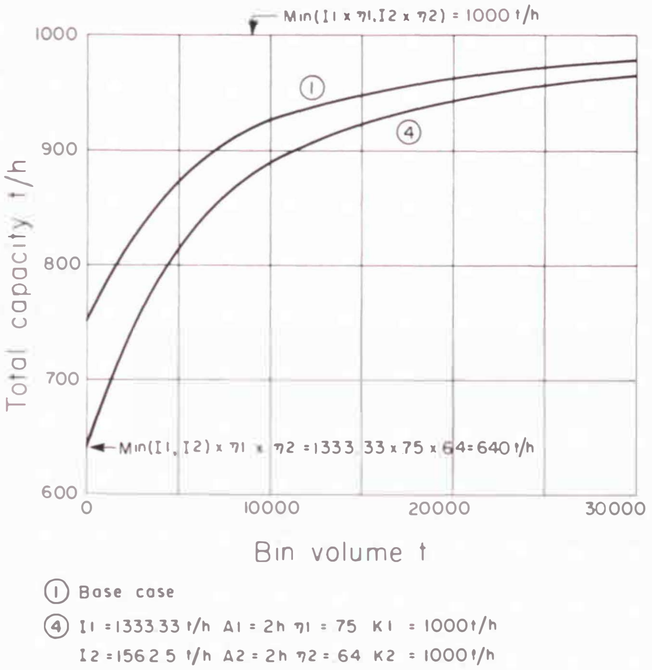


Fig. 9: Total capacity ~ bin volume

In Fig. 10 a sensitivity analysis is carried out from a base case by changing the rate of the first or of the second machine or the volume of the surge bin. Further analysis of the parameters interruption and internal availability and of all combinations are of course also possible.

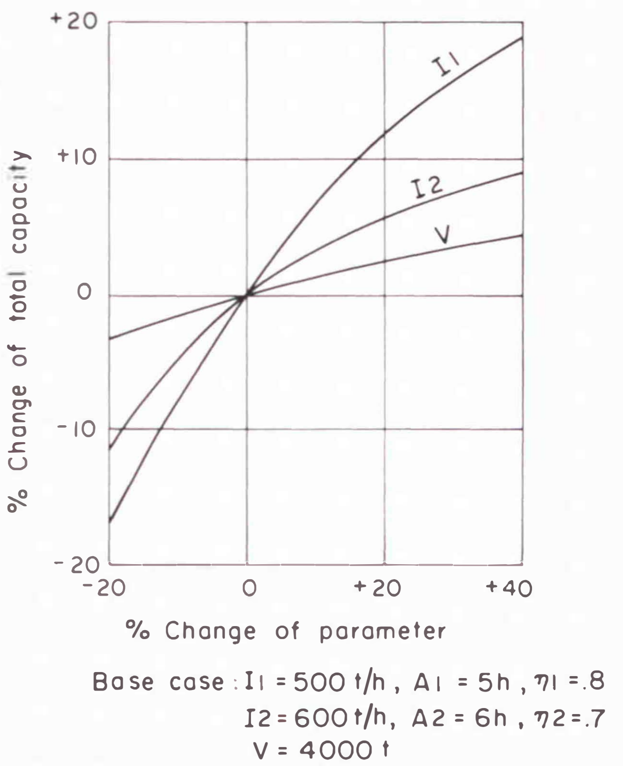


Fig. 10: Sensitivity analysis

In Fig. 11 the effect of a chain of machines is shown. By some simulation experiments it was earlier found that the resulting average length of interruption in a two machine system was close to the initial average length of interruption of the second machine. The output of the first two machines from the calculation procedure is then used as the input to the third machine, the output of which is then used as input to the forth machine and an estimate of the total capacity of the four-machine system has been obtained. This approach does seem to generate acceptable results, when considering systems with relatively large surge bins. Some minor modifications and adjustments might be required when considering systems with smaller bins.

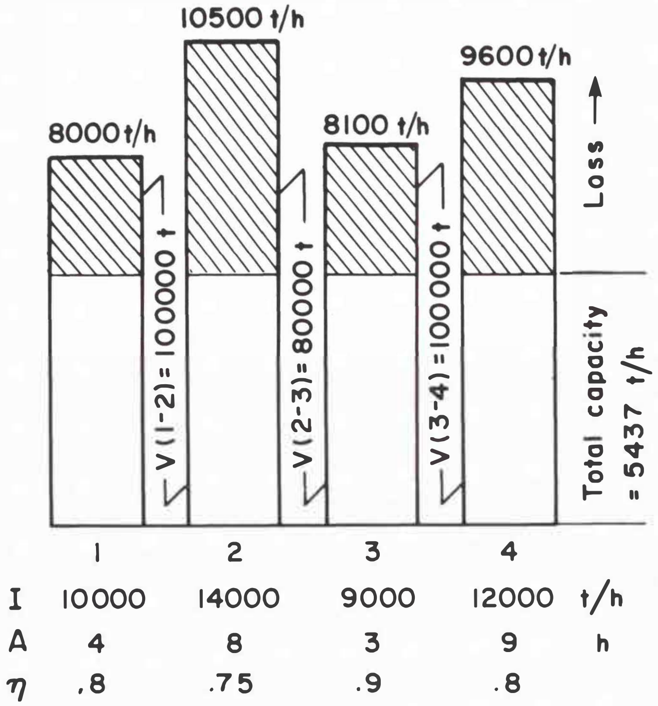


Fig. 11: Total capacity of a series of 4 machines with intermediary bins

12. Verification and Adjustment

The use of a model for estimates requires, whenever practical, verification by comparing observed figures with calculation results. In the case of capacity estimates this can become a rather complicated task since real operations often are non-stationary. However, the simplicity and flexibility of the procedure described here should make this work easier than, say, simulations. The observed period could be broken down into periods, which seem to be closer to stationarity.

Adjustments to local conditions might be required as, for example, the standard deviations of production and interruption lengths, which in the present procedure are near those normally observed in this type machinery. Standard deviation of production length equals approximately half this length. Standard deviation of interruption equals approximately this length. The flexibility of the procedure should be helpful in forcing calculation results to coincide with observations and in explaining the reason why.

13. Computational Aspects

The described procedure is easily programmable even for a desktop calculator. However, the adjustment procedure does require multiple iterations, which for large bin volumes become time consuming on desktop calculators. This is almost completely avoided by using a minicomputer. The obvious advantage is that the procedure can be used directly in the discussion of required surge bin sizes and in experimentation with various assumptions about machine rate, interruption length and internal availability.

14. Conclusion

The described procedure although possibly requiring local adjustments does provide the design engineer of machine series systems with a quick tool, which substitutes the rule of thumb of "so and so many hours or production as surge" in that it brings into calculation the main causes of the production variation: length of interruption and internal non-availability. The appropriate surge bin volumes are very different from case to case as a function of these parameters.

Acknowledgements

The procedure was initially developed and used while the author was employed by the Swedish Iron Ore Company, LUOSSAVAARA-KIIRUNAVAARA AB. Further developments benefitted widely from discussions with the staff of MOUNT NEWMAN MINING CO, Western Australia. Simulation experiments were supported by a grant from the Department of Energy, Mines and Resources, Ottawa.

Appendix

Procedure for the calculation of the total capacity, resulting output rate and internal availability of the machine 1 — bin — machine 2 system.

Notations

Machine parameters:

I	t/h	rate
P	h	average length of production
A	h	average length of interruption
η	—	internal availability, $\eta = P/(P+A)$
K	t/h	isolated capacity, $K = I \times \eta$

Bin parameter:

V	t	live volume

Calculation results:

$C\,(1—2)$	t/h	total system's capacity
IN	t/h	output rate of system
ηN	—	system's internal availability

Calculations

1. Adjustment of $I1$ so that $I'1 \times \eta 1 = I2 \times \eta 2$;
$I'1 = I2 \times \eta 2 / \eta 1$

2. Calculation of maximal production standard deviations of machines 1 and 2
$S1 = I'1 \times A1 \times (\eta 1)^{1/2}$
$S2 = I2 \times A2 \times (\eta 2)^{1/2}$

3. Calculation of the bin content change's standard deviation.
$S\,(1-2) = ((S1)^2 + (S2)^2)^{1/2}$

4. Normalization of bin volume
$k = 1/2 \times V / S\,(1-2)$

5. Loss calculation departing from bin 1/2 full
$F = (2\pi)^{1/2} \times [\phi(k) - k \times (1 - \Phi(k))]$
$\phi(k) = (2\pi)^{-1/2} \times e^{-k^2/2}$; $\Phi(k) = (2\pi)^{-1/2} \times \int_{\infty}^{k} e^{-t^2/2} \times dt$

6. Loss calculation departing from
f. ex. bin 1/4 full with frequency 0.25
bin 1/2 full with frequency 0.50 and
bin 3/4 full with frequency 0.25
$F = 0.25 \times F(1/2 \times k) + 0.50 \times F(k) + 0.25 \times F(3/2 \times k)$

7. Capacity of the system:
$[I'1, \eta 1]$, V, $[I2, \eta 2]$:
$C'\,(1-2) = \mathrm{Min}\,(I'1, I2) \times \eta 2 \times \eta 1 \times F + I2 \times \eta 2 \times (1-F)$

8. Adjustment of $C'\,(1-2)$ to $C\,(1-2)$ by changing $I'1$ to $I1$ and forcing $C'\,(1-2)$ along a function ((1 — Erlangian) or (1 — hyperexponential)), which starts at 0 with a tangent of 45° and goes asymmtotically towards horizontal 1 in the coordinate system of Fig. 12.

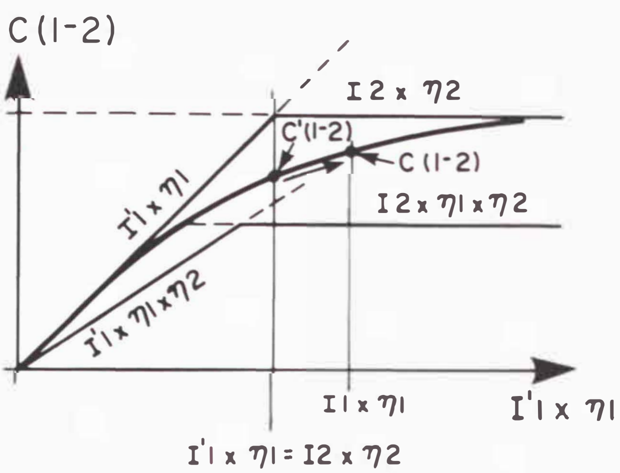


Fig. 12: Adjustment to C (1—2)

8.1 IF $C'\,(1-2)/(I2 \times \eta 2) > (1 - e^{-1})$ then find l of equation $E\,(l, p)$,
where $E\,(l, p)$

$$= 1 - e^{l \times p} \times \sum_{n=0}^{l-1} [(1 - n/l \times (l \times p)^n / n!] \text{ and } p = 1$$

so that $E\,(l, p) \leq C'\,(1-2)/(I2 \times \eta 2) \leq E\,(l+1, p)$

8.1.1 Calculation of capacity $C\,(1-2)$, $p = I1 \times \eta 2/(I2 \times \eta 2)$

$C\,(1-2) = [E\,(l, p) \times [E\,(l+1, 1) - C'\,(1-2)/(I2 \times \eta 2)] / E\,(l+1, 1) - E\,(l, 1)] + E\,(l+1, p) \times [C'\,(1-2)/(I2 \times \eta 2) - E\,(l, 1)]/[E\,(l+1, 1) - E\,(l, 1)]] \times I2 \times \eta 2$

8.2 If $C'\,(1-2)/(I2 \times \eta 2) \leq (1 - e^{-1})$ then find α of equation $H\,(\alpha, p)$ where
$H = 1 - 1/2 \times (e^{-2 \times \alpha \times p} \times e^{-2 \times (1-\alpha) \times p})$ and $p = 1$ so that
$H\,(\alpha, 1) \geq C'\,(1-2)/(I2 \times \eta 2) \geq H\,(\alpha + 0.1, 1)$

8.2.1 Calculation of capacity $C\,(1-2)$, $p = I1 \times \eta 1/(I2 \times \eta 2)$
$C\,(1-2) = [H\,(\alpha, p) \times [C'\,(1-2)/(I2 \times \eta 2) -$
$H\,(\alpha + 0.1, 1)]/[H\,(\alpha, 1) -$
$H\,(\alpha + 0.1, 1)] + H\,(\alpha + 0.1, 1) \times [H\,(\alpha, 1) -$
$C'\,(1-2)/(I2 \times \eta 2)]/[H\,(\alpha, 1) -$
$H\,(\alpha + 0.1, 1)]] \times I2 \times \eta 2$

9. If $C\,(1-2) \leq A$, where
$A = [\mathrm{Min}\,(I1 \times \eta 1, I2 \times \eta 2) \times [C'\,(1-2) -$
$\mathrm{Min}\,(I'1 \times \eta 1 \times \eta 2, I2 \times \eta 1 \times \eta 2)] +$
$\mathrm{Min}\,(I1 \times \eta 1 \times \eta 2, I2 \times \eta 1 \times \eta 2) \times [I2 \times \eta 2 -$
$C'\,(1-2)]]/[I2 \times \eta 2 -$
$\mathrm{Min}\,(I'1 \times \eta 1 \times \eta 2, I2 \times \eta 1 \times \eta 2)] \times (I2 \times \eta 2)$
set $C\,(1-2) = A$

10. IF $I2 \leq I1$
set $IN = I2$
IF $I2 > I1$
set $IN = [C\,(1-2) - I1 \times \eta 1 \times \eta 2]/[\mathrm{Min}\,(I1 \times \eta 1, I2 \times \eta 2) - I1 \times \eta 1 \times \eta 2] \times (I2 - I1) + I1$

11. $\eta N = C\,(1-2)/IN$

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