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Improving Productivity with Installed Spares

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It is often desirable to increase plant productivity by installing spare equipment or by using multiple trains. It is apparent that there is an increase in reliability with an installed spare, but evaluating the expected improvement in production is not always straightforward. This paper describes and demonstrates methods to predict the relative cost and change in productivity with various configurations of trains or installed spares.

This paper considers only the reliability of machines, not total plant reliability, which involves utilities, raw material, and labor. Many operating plants track the "available time", which is the percent of time the equipment is running divided by the time it was scheduled to run. Reliability as used in this paper is defined as the hours the equipment operates divided by the hours the equipment operates plus the down time. If the equipment operated for 96 hours out of 168 hours and was down for 4 hours, the reliability would be 96 / (96 + 4) = 96%.

There are at least three methods of improving equipment productivity that should be considered.

1. In looking at the definition of reliability, it is apparent that the reliability of individual pieces of equipment is greatly influenced by the availability of spares and skilled maintenance personnel. This option has a minimal effect on capital cost and does not increase operating costs.
2. Another option is to oversize the equipment and store an intermediate product. This option increases capital cost and inventory, but has a minimal effect on operating cost.
3. The third choice is to install spares with an increase in capital and operating cost, but with the advantage of immediate resumption of production in the event of an equipment failure.

If the option of installing spares is chosen, the following table shows the results of several configurations assuming that all trains are 98% reliable and that the entire quantity of the product is used.

Configuration	Capital Cost as % of a Single Train	% Lost Production	Operating Effort as % of a Single Train	Maintenance as % of a Single Train Capital Cost
Single 100% Train	100	2.00	100	6.0
Two 100% Trains	200	0.02	100	9.0
Three 50% Trains	198	0.04	200	9.6
One 67% & One 33% Train	130	2.00	200	7.8
Four 33% Trains	207	0.06	300	10.6

The capital cost was calculated using the six tenths power rule which states, "if the cost of a given unit at one capacity is known, the cost of a similar unit with X times the capacity of the first is approximately $(X)^{0.6}$ times the cost of the initial unit".[1] This is a simplification of the actual costs and should be used with the realization that it will understate cost when instrumentation is a large portion of the capital cost, or for smaller trains, and when there are interconnecting trains. Using the "One 67% & One 33% Train" as an example, the calculation is $(67\% / 100\%)^{0.6} + (33\% / 100\%)^{0.6} = 130.05\%$.

The "% Lost Production" is based on all trains having a reliability of 98% and by a difference of 2% downtime. In the following example, it is assumed that all trains have the same capacity and same reliability, a good assumption in most applications. However, the same calculations can be made with different sizes and reliabilities by evaluating each possible combination individually.

The downtime must be corrected for the percent of the time that the unit is operating as opposed to chronological time. As an example, in the "Three 50% Trains" case, each train in the long term will only be operating for 2/3s of the time, so the net loss is multiplied by 0.67 to correct for the lower operating rate--and therefore a lower down time--compared to a continuously operating unit.

Lost production is based on a statistical prediction. The probability of each possible combination of operating units is calculated and multiplied by the percent of total production lost from that combination. If all trains are alike, then the unique combinations can be determined and multiplied by the number of times that combination occurs. To verify that all combinations have been considered, the time should total 100%. The table at the end of this paper lists the number of combinations for different numbers of trains when all trains are alike.

[1] Peters & Timmerhaus, Plant Design and Economics for Chemical Engineers, Page 107

Using the "Three 50% Trains" as an example, a table showing all possible combinations and the calculations are as follows:

Train Number	**A**	**B**	**C**
All Down	D	D	D
Two Trains Down	D	D	U
	D	U	D
	U	D	D
One Train Down	D	U	U
	U	D	U
	U	U	D
No Trains Down	U	U	U

The probability that a train will be Up is 0.98 and the probability it will be Down is 0.02.

All trains down, 0.02 x 0.02 x 0.02 = 0.0008%

Two trains down, 0.02 x 0.02 x 0.98 = 0.0392 x 3 combinations = 0.1176%

One train down, 0.02 x 0.98 x 0.98 = 1.9208% x 3 combinations = 5.7624%

No trains down, 0.98 x 0.98 x 0.98 = 94.1192%

Total time accounted for = 100.0000%

There is no loss of production for the time that "no trains" are down or when "one train" is down since there would be two or more trains available. When two trains are down, 50% of the production is lost and when all trains are down, 100% of the production is lost. So the lost production is (0.0008% x 100%) + (0.1176% x 50%) = 0.0596%, but since the trains only have to operate for 2/3 of the time, then the net loss is 0.0596 x 0.67 = 0.039932%.

When the assumption that "the entire quantity of the product is used" is invalid, then the amount of down time should be adjusted. Using the "Three 50% Trains" example, if the demand is 67% of the system rated capacity, then the down time with two trains down would be multiplied by (17% / 67%) = 25% instead of 50%, and the calculation is (0.0008% x 100%) + (0.1176% x 25%) = 0.0302% lost production. An extreme case would be if the trains where 100% over sized(in other words, when there are in reality three 100% trains), then the % lost production column in the table would be 0.0008%. It would appear that considerably more was spent in capital cost than was justifiable.

Reliability has a large effect on the improvement in lost production. In the first table, it was assumed that the reliability was 98%. Comparing a single 100% Train to Two 100% Trains, the reliability improved by a factor of 100 (2.00% / 0.02%). The following table lists the % Lost Production assuming a reliability of 90%. In this case, Two 100% Trains improve by 20 times compared to a Single 100% Train. One of the advantages of multiple trains is that preventive maintenance can be performed while the spare is idle, increasing the reliability of the system exponentially.

Configuration	% Lost Production
Single 100% Train	10.00
Two 100% Trains	0.50
Three 50% Trains	0.97
One 67% & One 33% Trains	10.00
Four 33% Trains	1.40

The Operating Effort column is a reminder that more operating equipment requires more attention from the operating crew. A simple spare piece of equipment may only add a mater of minutes to an operator's day, but in complex trains, it can mean the addition of several operators along with an increase in support operations such as quality control.

The maintenance and repair cost is calculated based on 6% of the capital cost per year at 100% of operating capacity, 75% of the capital cost times 6% when operating at 50% of capacity, and 85% of the capital cost times 6% when operating at 75% of capacity.[2] By extrapolation, the maintenance and repair cost is 81% of 6% at 2/3 of the operating rate.

[2] Peters & Timmerhaus, Plant Design and Economics for Chemical Engineers, Page 133

The following table lists the number of combinations for like trains.

Number of Trains	Number Operating	Number of Combinations		Number of Trains	Number Operating	Number of Combinations
1	0	1		7	0	1
	1	1			1	7
					2	21
2	0	1			3	35
	1	2			4	35
	2	1			5	21
					6	7
3	0	1			7	1
	1	3				
	2	3		8	0	1
	3	1			1	8
					2	28
4	0	1			3	56
	1	4			4	70
	2	6			5	56
	3	4			6	28
	4	1			7	8
					8	1
5	0	1				
	1	5		9	0	1
	2	10			1	9
	3	10			2	36
	4	5			3	84
	5	1			4	126
					5	126
6	0	1			6	84
	1	6			7	36
	2	15			8	9
	3	20			9	1
	4	15				
	5	6				
	6	1				