"AN INTEGRATED AND STRUCTURED APPROACH TO IMPROVE MAINTENANCE"

Part II: Application

by

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An integrated and structured approach to improve maintenance. Part II: Application

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To test our ideas in practice, we implemented the concepts of Part I of this paper at three industrial sites. In one of them, there was a very clear need for improving reliability and availability since demand exceeded capacity. At this plant, the eight phases approach was fully implemented. In this paper, we report on our experiences with this implementation and illustrate how our concepts can be applied. Experiences with the other sites are only mentioned in case of notable differences. The paper starts with a description of the plant. The application of our concepts is discussed in Section 2.

1 PLANT DESCRIPTION

Our plant, called Betodal, is a small factory producing concrete stones. The following list summarizes the main characteristics of this plant:

- size: 10 workmen; 5 machines; 5 stages of production process; 500.000 stones a week; annual turnover of 8 million Dfl. (50% of which is raw materials)
- maintenance budget Dfl. 360.000; book value of equipment Dfl. 600.000
- production process relatively simple and old fashioned
- flow shop production line; one class of products (clinker stones)
- integrated production and maintenance
- 1 shift
- throughput time: ± 2 days

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Figure 1

The production process is briefly sketched as follows. Raw materials, such as sand, water etc., are put together and mixed. A mould is filled with this mix, which is then condensed by a press and a vibration mechanism (block machine). The resulting stones are transported to the drying rooms where they remain for one day. From there they are transported to the packing machine and finally they are stored on the grounds (Figure 1 and 2). As the buffers between the process phases are very small, there is a high level of interdependency. Consequently, a major breakdown of a machine often leads to a shutdown of the whole line.

The maintenance administration is done by the head of production. From his own experience as well as from comparisons with another concrete plant, owned by the same company, the production head forms an idea of how to maintain a given piece of equipment (which components to replace, on what basis and how often). It was clear however that the number of failures and the associated downtime were far too high. This could be observed from the irregular flow pattern of the production process (high variability) and the job satisfaction of the personnel (if there are many failures people tend to become frustrated).

For the general administrative business functions like bookkeeping and inventory control, a structured way of data gathering and information storage was started only recently. For reliability, quality and maintenance only very little (written) information was available. The goals of maintenance were not clearly stated and no targets were set.

During the period just before we started the study, Betodal suffered from availability problems causing for lost demand. As a consequence, the management had a positive attitude towards improving and structuring the maintenance.

We visited two other plants, which were bigger in size: the other concrete plant, belonging to the same company, and a large electronics firm. The larger scale of production in these plants resulted in three main differences. Firstly, the interest of management was more on budgets and people rather than on performance (availability) of the machines (as in the Betodal case). Secondly, the production and maintenance departments were separated and thirdly the level of automation was higher.

Figure 2

The tendency of larger firms to separate the production and maintenance departments causes some managerial difficulties since the aims of the two departments may be different. In contrast with production, maintenance people are often not so much inclined to do routine preventive replacements since this is not a very challenging job. They'd rather be troubleshooting in case of breakdowns. Also, it may be difficult to trace the causes of certain problems since both groups try to blame one another. The Japanese Total Productive Maintenance concept recommends to integrate maintenance and production as much as possible (Nakajima (1986)).

The two larger plants had put much more effort in automation than Betodal. In the technologically advanced electronic plant a factory-wide production management information system had been implemented, with terminals near the machines and employees entering data. Although this system gathers a tremendous amount of data, the maintenance executives did not use information from this system to substantiate their decision making partly because they could not access the information they wanted, or in a format they liked. In fact, like in the other plants they hardly used any factual information to substantiate their maintenance decisions.

2 APPLICATION OF CONCEPTS

We fully implemented the eight-phase approach in Betodal. To illustrate how the concepts can be applied in practice, we discuss the application of three main steps, viz. getting a picture of the quality and downtime problems, prioritize actions (effectiveness), and improve the efficiency of maintenance procedures. Other matters, such as the choice of performance indicators and the set up of information procedures are not discussed here. This section is an abstract of a report which was carried out for, and in collaboration with, Betodal's management.

2.1 Quality and downtime problems

The fishbone diagram in Figure 3 shows the possible causes of downtime in general terms.

Figure 3

Each time a new production run is started, a set-up takes place. During the set-up phase many problems occur and it takes a while before production is running smoothly, partly due to failures. If the product variety is large, as is more and more the case, the large number of set-ups associated with this can cause much downtime. It is therefore important to streamline the set-up phase and choose a smart variety of products that does not lay too heavy a burden on the set-up.

Errors in technical design can be solved by modification. Some errors directly come forward but others only become apparent after some time, for example if the production rate is increased.

Downtime problems can also be caused by quality problems at previous stages, by service or adjustments, which relate to the motivation and training of the personnel, and accelerated wear, which relate to quality of equipment and effectiveness of maintenance procedures.

This general picture was further analyzed to more specific causes and problem fields. Two machines were particularly vulnerable to downtime problems: the block machine and the packing machine. Causes are located in all of the above-mentioned fields, with an emphasis on maintenance procedures and quality of the mix for the block machine (previous stage), and on design problems and wear for the packing machine. In the next subsection we will go further into detail on the causes and solutions.

The second step is to rank the occurrence of downtime and quality problems according to importance (e.g. frequency). Both expert opinion as well as some real data obtained by failure lists or production reports were used to obtain estimates. It is important to have more than one source of information because a single source is often unreliable. For example, an expert may tend to exaggerate a problem which is of great concern to him or her. On the other hand, if a machine is causing much trouble, people get tired of filling in forms denoting every failure. Especially if many short interruptions occur, one cannot expect the employee to run to a desk each time to fill out forms. In this case, a different way of accounting is needed.

From manually filled out failure lists, estimates from the workmen and some additional measurements we got the following picture of the reliability and quality problems. The amount of downtime is approximately 6 hours a week on average. In percentage this stems from the problem fields listed below:

- set-up (25%)
- block machine (20%)
- packing machine (40%)
- transportation problems (10%)
- other (5%)

Since set-up problems occur mainly at the early stages of production, this is essentially a classification according to production stage.

Besides downtime due to failures production time is also lost because of cleaning and greasing (including minor maintenance). This amounts to about 6 hours a week as well.

It is interesting to note that these problems extend beyond the maintenance department and cannot be solved solely by technical measures on the equipment. Some problems, e.g. set-up problems, relate to marketing and others to the design of equipment.

2.2 Effectiveness of solutions

To illustrate the method of effectiveness analysis we consider the problems at the bottleneck machine. The major bottleneck appeared to be the packing machine, in contrast with the normal situation in this type of industry where the block machine is the bottleneck. Based on production data, failure records and additional measurements we concluded that both the speed during operation as well as the proportion of time the machine was operating (availability) were less than normal (w.r.t. the benchmark in this type of industry). It was investigated what caused the problems and what could be done about them.

Several problems contributed to the poor functioning of the machine. First, the machine was rather old (7 years) and slower than new equipment, which was e.g. installed at the other concrete plant, and which had clearly benefitted from technical improvements. Also, it had been quite some time since the last overhaul. An overhaul was carried out only during the year-end production stop. From comparisons with the other plant and analysing failure data (not only for the packing machine), which clearly exhibited an increasing trend towards the end of the year, it was concluded that the frequency of production stops should be increased. A third cause of downtime was that just before the packing machine, the stones were inspected and bad ones were replaced by good ones, thus causing for delays.

Another problem was that the binding machine, which forms the back-end of the packing department (see Figure 2), functioned very badly. This machine puts a wire along the stones. It failed very frequently and caused the packing machine to halt when the downtime was too long (short interruptions could be recovered since the binding machine operated relatively fast).

The total amount of downtime of the packing machine (excluding the binding part) was approximately 1,5 hours a week. The binding machine was approximately 5 hours a week down, 2 hours of which led to production loss. If the packing machine was operating well it was known to be about as fast as the block machine. The block machine has a cycletime of approximately 17 sec., i.e. it produces a full board of stones every 17 sec. on average.

To estimate the production loss per hour (PLH) we reason as follows. The annual turnover is about Dfl. 7.500.000. The variable cost (mainly raw materials) accounts for Dfl. 3.400.000. The cumulative number of effective production hours is about 1200 hours per year (excluding maintenance, cleaning, downtime etc.). If the production is stopped one (effective) hour, then the total production as well as the variable cost are affected. Hence, we obtain a PLH of (7.500.000 - 3.400.000)/1.200 ≈ 3.400. We note that this calculation depends on certain assumptions. For example, we assumed that time saved is evenly spread among the product types. If there is reason to assume that time saved can be used completely for the most profitable product then the calculation has to be done on the base of cycletimes (how many products are made per time unit).

Let us first analyze the binding machine. For this old machine (18 years) the only option is to replace it by a new one. A new machine costs about Dfl. 75.000. It is expected that a new machine will reduce the production loss from 80 hours a year to about 20 hours (75% reduction), thus saving Dfl. 204.000 per year. This estimate is based on a comparison with the binding machine in the other plant. Hence, it is clearly profitable to replace the machine and furthermore this decision is not sensitive to changes in the cost parameters.

Next we turn to the packing machine. Based on the PLH the cumulative failures at the packing department lead to an annual production loss of 204.000. There are three solution alternatives:

Option 1) Renew the entire packing machine.

This is the most drastic solution alternative. The total cost of replacement including installation, additive investments and production losses (2 days) amount to Dfl. 800.000, or, when depreciated in 8 years, about Dfl. 100.000 a year. The estimated savings amount to 50 - 80% of the downtime or Dfl. 100.000 - 160.000 per year. The benefits can be larger than the costs, but given the magnitude and uncertainty of the amounts, it is not clear that this option is a profitable one. It is noted that a new machine is also much faster (the cycletime is about 13 seconds) but this is only of interest if the block machine can be made faster. We do not further consider this option.

Option 2) Perform a few technical modifications on the packing machine.

It is expected that part of the failures can be prevented by a few technical modifications. For example it was experienced in other factories that the electrical engines work much better under direct than under alternate current. The costs of these modifications amount to Dfl. 250.000 while the expected savings range from 60.000 to 140.000 a year. At a depreciation of 8 years this is certainly a profitable investment.

Option 3) Increase the frequency of maintenance and overhauls.

A number of critical components such as layers, clamps etc. could be replaced more frequently. Currently, the annual (direct) maintenance cost amounts to Dfl. 10.000. (Notice that the hidden costs relating to maintenance are a multitude of the tangible cost). Suppose the frequency would be doubled, then the amount of savings is, roughly estimated, Dfl. 20.000 to 60.000. Additional production losses yield approximately Dfl. 10.000. Given the uncertainty of this estimate and the low marginal profit in absolute terms this does not seem to be very effective (at least not if this option is taken as a single alternative).

The estimates concerning the reduction of failures are based on an analysis of the type of failures, information from the equipment manufacturer and experiences in the other concrete plant.

Summarizing, the most attractive option is Option 2, and this one was indeed chosen by the management.

It is interesting to discuss some further aspects of Option 1. The reason that the expected downtime after renewal is much lower is partly due to the fact that the machine has been technically improved, but also because a new machine in general leads to fewer problems than an older one (except if the machine is based on very new technology which is not yet fully tested). In the calculations of the costs and benefits of Option 1 we assumed a constant amount of 80 hours downtime a year for the old machine, and 20 for a new. It is more realistic, but also more complicated, to assume that the amount of downtime as well as the maintenance costs gradually increase with the age of the machine. From experienced people in the field it was learned that the maintenance costs indeed show an increasing trend. This is due to the fact that as the machine gets older more and more components are subject to overhaul and renewal.

If the maintenance costs are increasing with age and are substantial compared to the cost of a new machine, then at a certain age it may be worthwhile to replace the machine with an entirely new one. If we denote the maintenance cost in the i-th year of operation by c_i and the replacement costs by A then the average cost per period in the long run if we replace every T periods is given by (see e.g. Nahmias, 1989):

$$g(T) = \frac{1}{T} [A + \sum_{i=1}^{T} c_i]$$

This model was introduced in Part I of this paper as the deterministic age-replacement model. In this model the probability of failure of the components is subsumed in the expected maintenance costs per year. Based on estimates of c_i and the value A = 800.000 (see Option 1) we computed the formula for several values of T. The maintenance costs in the i-th period of operation are a combination of the tangible costs t_i (material, new components) and the production loss h_i, which is obtained by combining the unavailability u_i, the PLH, and the total number of effective hours per period. The estimates for t_i and u_i are based on expert judgement and supported by data. The resulting average costs are shown in Table 1 and we see that the optimal replacement age is 6 years with an average cost per year of Dfl. 216.000. We note that this model is actually an efficiency model which is used here to judge the effectiveness of the solution of replacement.

Table 1
Results for the deterministic age-replacement model

i	t_i	u_i	h_i	$g(i)$
1	1.000	0 %	0	801.000
2	3.000	1 %	51.000	427.500
3	3.000	1 %	51.000	303.000
4	10.000	2 %	102.000	255.250
5	10.000	2 %	102.000	226.600
6	10.000	3 %	153.000	216.000
7	20.000	4 %	204.000	217.143
8	20.000	5 %	255.000	224.375
9	15.000	5 %	255.000	229.444
10	15.000	6 %	306.000	238.600

The effectiveness analysis has been applied to a number of situations at Betodal. Although each situation has its specific requirements, the general approach is very similar in each case.

2.3 Maintenance efficiency

Anticipating on the modifications on the packing machine, we did some further analyses on the block machine, which is the heart of the production process. A preliminary study suggested that for this machine, improvement of the maintenance procedures could be effective. To study the maintenance efficiency of certain tasks we applied some models. Two successful applications are presented in this section.

We consider two components of the block machine and assume now that this machine is the bottleneck machine. The most critical component is the so-called mould clamp holder (MCH). For this component we analyze the optimal replacement frequency. The other object of maintenance is a series of bolts (SOB) which fixes a press beam. We refer to this group of bolts as a component. The SOB is not very critical, but the routine maintenance tasks on this unit are very time consuming. Here we investigate whether the bolts have to be maintained individually or as a group in order to minimize the amount of time spent on the unit.

Mould clamp holder

The MCH is replaced after it has been in use for 4 months (preventively) and upon failure. Despite the frequent preventive replacements the unit still fails from time to time. When it fails, some other parts are damaged and it takes 5 hours to replace them. A preventive replacement takes 2 hours. We gathered estimates of costs and failure characteristics together with the head of production. Under the present replacement policy it was estimated that approximately 1 out of 5 MCHs fails. If the replacement frequency would be doubled, that is replacement after 2 months, almost no failure would occur (say 1 in 20, or approximately 1 in 3 years) and if it would be done after 6 months 1 out of the 2 would fail. Let c_p be the cost of a preventive replacement and c_f the cost of corrective replacement. Using the PLH of 3400 and the fact that a repair upon failure takes 5 hours of downtime, we conclude that c_f = 17.000 (the tangible costs are negligible). Preventive maintenance takes 2 hours, and the costs of an hour preventive maintenance are, as we will see below, Dfl. 1000. Hence c_p= 2.000. It is now easily verified that it costs approximately Dfl. 17.100 per year if replacement is done after two months, 16.200 after 4 months and 21.000 after 6 months.

These calculations provide a check on the estimates of the production head, and at the same time a check for the results of the model. It is very important for the acceptance of the results of a model, that the people from the shop-floor can obtain an idea of whether the results are in accordance with their experiences, since they usually cannot easily understand the model. The simplicity of a model is not so much important for explanatory purposes, but rather for the ability to check special cases with relatively simple calculations or rough estimates.

The cost of preventive maintenance is not easy to establish. On one hand, preventive maintenance has an impact on production because the time devoted to maintenance could have been used for production. On the other hand, maintenance can be planned on moments that the equipment is not required for production, like during shutdowns or at moments at which the machine is halted. For example, for some products, the drying rooms are full at the end of the day, and so the block machine cannot continue to work. Here we applied the following reasoning: There are certain time intervals used for preventive maintenance, but since these time-intervals could also have been used for production, they mean production loss. However, a careful planning of these time-intervals makes it possible to maintain 3 to 4 installations simultaneously. Hence, we can spread the cost among the machines and conclude that preventive maintenance on the block machine costs about 1000 guilders per hour. Note that a failure occurs usually unexpectedly and therefore in such a case no other preventive maintenance can be carried out simultaneously.

We applied the probabilistic age-replacement model, which was briefly introduced in Section 3.2 of Part I, to find the optimal replacement age. This model balances the probability that the component fails against the cost of preventive replacement. The input parameters are the cost of preventive and corrective maintenance and the probability distribution of the lifetime. In the appendix we show how we estimated the lifetime distribution from the data. The formula for the average cost now yields (see e.g. Nahmias, 1989):

$$g(T) = \frac{c_p + (c_f - c_p)F(T)}{\sum_{k=0}^{T-1} (1 - F(k))}$$

where $F(t)$ is the probability that the machine fails before time t. The optimal replacement age is 3 months (see Figure 4) with an average cost per year of Dfl. 15.000. This result supported the feeling of the head of production that the current frequency was perhaps too low, although the expected savings are not high.

Figure 4

Series of bolts

Next we turn to the problem of the bolts. The front beam of the block machine is fixed with 12 bolts. If a bolt cracks, the machine continues operating, but if several bolts have failed and some are loose, then the machine can break down, with severe damage as a result. Therefore, the bolts are checked at the end of each workday and if a bolt turns out to have failed, it is immediately replaced, while the loosened bolts are fixed again. At the moment of our study, a bolt cracked practically each day. The present maintenance policy was to replace a bolt if it turns out to have failed at the end of the day (hence no preventive replacement). Fixing a single cracked bolt takes on average 1.5 hours time. Preventive replacement of the whole group of bolts takes only 2 hours (the reason that it takes so long to replace a failed bolt is that it often gets stuck and has to be drilled out).

The fact that it takes relatively little time to replace the whole group makes it interesting to investigate whether preventive group replacement is useful. The group-replacement model, mentioned in Section 3.2 of Part I, is used to analyze this situation. The following class of policies is analyzed: replace individual components upon failure and the entire group of components at multiples of a time period T (this policy is also known as a block-replacement policy). Thereby, we assume that the intensity of failures increases with age. Under this assumption it is to be expected that after a certain period of time with relatively few failures, a number of failures will occur relatively short after one another, and time-savings are incurred by performing joint-replacements. We note that the increasing failure rate assumption could not be tested because data on individual bolts were not available. However, in principle, the model could be validated afterwards with the results.

From the fact that there are 12 bolts and practically each day one of them fails we conclude that the mean lifetime is approximately 12 days. We made some further assumptions on the distribution (see Appendix) and applied the group replacement model. It appeared that a block replacement every five days is most efficient. Under this policy the expected number of failures between two consecutive group replacements equals one, so that the total time for maintenance is $(1{\cdot}2 + 1{\cdot}1.5)= 3.5$ hours a week. Comparing this with the failure based policy where one looses 1.5 hours per day or 7.5 hours a week, we conclude that the total amount of time needed for maintenance can be reduced by 50%. Costs associated with the additional number of bolts are negligible.

A drawback of the block replacement policy is that it does not use any information regarding the state of the components. For example, it may happen that at time T many components have already been replaced once (upon failure) and are almost new or that one component fails just before T while the others are still functioning (and almost reached age T). In the first case it seems more efficient to defer the group replacement while in the latter case, the moment of failure provides a nice opportunity to replace the entire system. A model that takes information about the components into account on an aggregate level is the group replacement model developed by van der Duyn Schouten and Vanneste (1993). We applied this model to the SOB problem. The input parameters are again the lifetime distribution and the cost of individual failure replacement as well as the costs of group replacement (we note that all components can be replaced in two hours, regardless of the fact that one failed or not). An efficient group maintenance policy is paraphrased as follows: replace an individual component as soon as it fails or reaches the age of 7 days and take this opportunity to replace the entire group if 9 components or more have reached the age of 3 days. According to the group replacement model, this policy leads to 2.5 hours a week for maintenance, that is, a further reduction of 15%, compared to no preventive replacements at all. For a further discussion of this type of policy we refer to article just mentioned.

Unfortunately for us, neither of the two group replacement models could be validated because a new type of bolt was introduced and the problem did not occur as frequently anymore. In other words, a more effective solution was found!

APPENDIX

Estimating the lifetime distribution

In this appendix we discuss the derivation of the lifetime distribution for the age replacement model and the group replacement model. We denote the lifetime distribution by $F(t)$.

A widely known lifetime distribution in reliability is the Weibull distribution. Several techniques, based on least squares or maximum likelihood, are available to estimate the two parameters of a Weibull distribution on base of (censored) failure data. For a discussion of these methods and references we refer to Gertsbakh (1989). Next to failure data, one can also use expert judgment to estimate a lifetime distribution. A general methodology is given in Van Noortwijk et al. (1992).

Here, we use a very simple and straightforward approach to obtain a preliminary estimate of the lifetime distribution based on a few estimates of the expected number of failures under certain policies. Recall from Section 2 that the present policy of replacing after four months resulted in 20% failures. Hence, $F(4)$ is estimated to be 0.2. In the same way, we obtain from the other estimates reported in that section that $F(2) \approx 0.05$ and $F(6) \approx 0.5$. Note that the estimates for $F(4)$ and $F(2)$ are based on actual experience (they could be verified with data), but the estimate for F(6) is only a subjective extrapolation. On the other hand, the estimate of $F(2)$ is inaccurate (could be 0.08 or 0.02 as well). Therefore we used the estimates for $F(4)$ and $F(6)$ to obtain the scale parameter λ and the shape parameter β. Note that two estimates of a Weibull distribution suffice to solve the parameters from the data (this results in two equations in two unknowns, which can be easily solved). It is easily verified that $\lambda=0.15$ and $\beta=2.8$. The third data point appeared to be in accordance with these values, and the general statistical methods, based on least squares, also led to approximately the same results.

For the group replacement model we took a Weibull distribution with parameters $\lambda=0.075$ and $\beta=2.5$ (the mean of this distribution is indeed 12 days).

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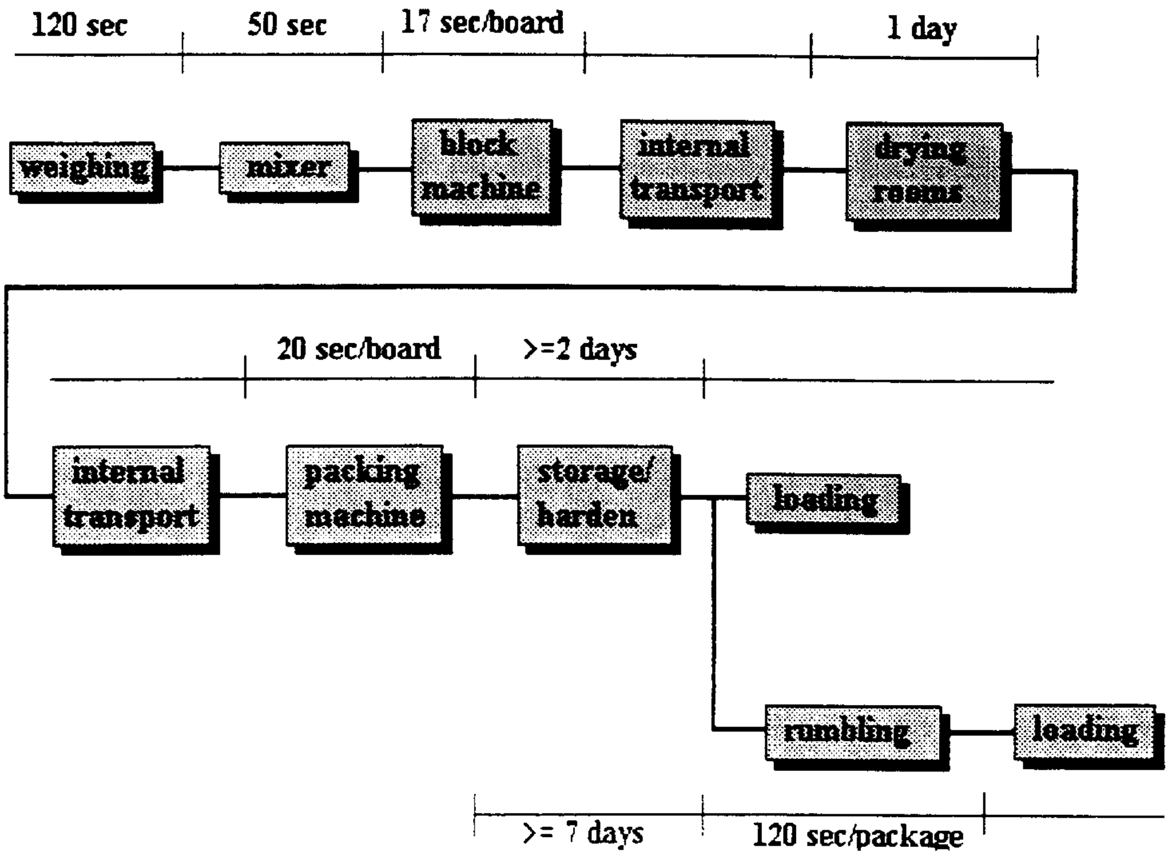

Figure 1 Flow chart of production process

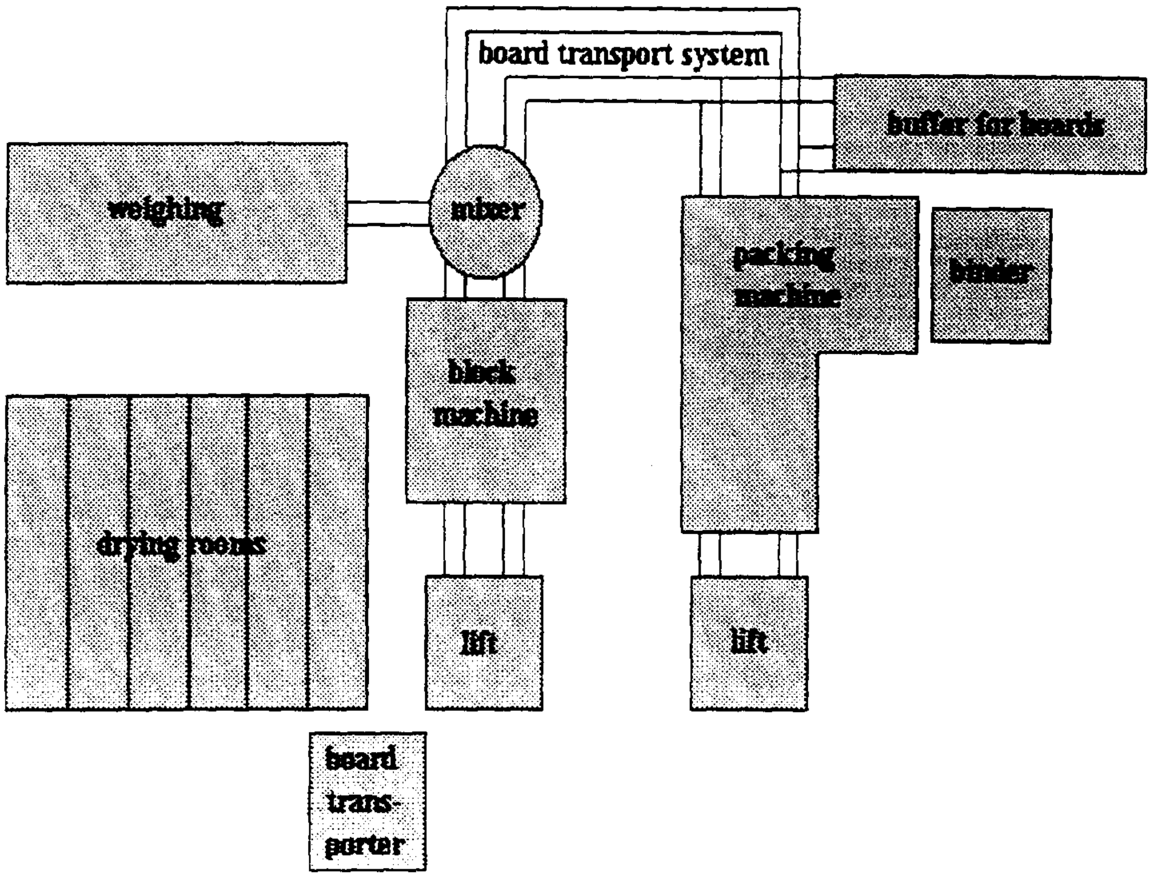

Figure 2 Plant lay-out

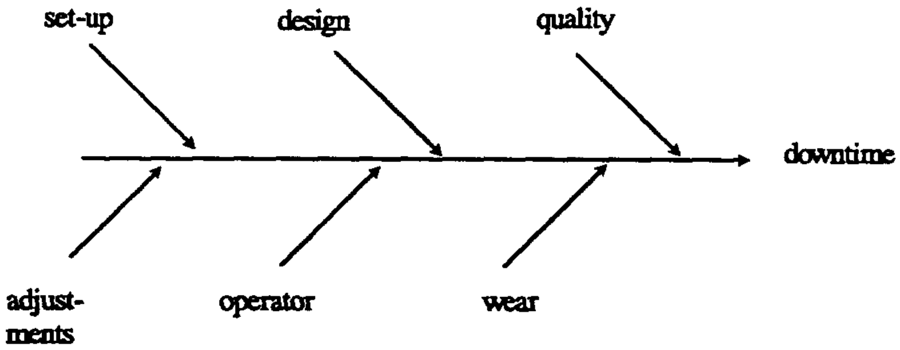

Figure 3 Causes of downtime

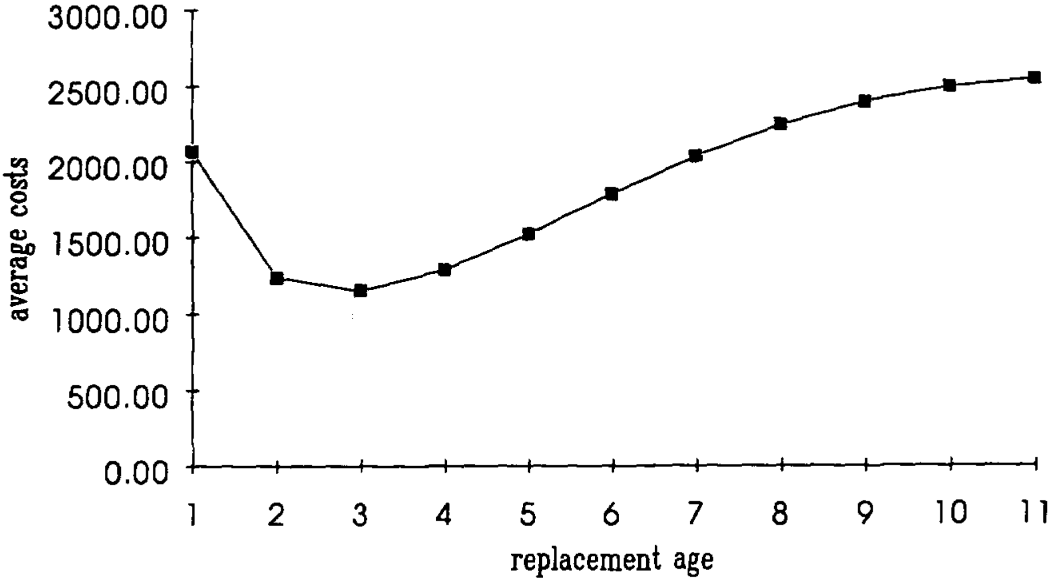

Figure 4 Results for probabilistic age-replacement model