Reliability and Maintenance Based Design of Machine Tools

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Abstract: In this paper a methodology for selection of optimal machine tool configuration by simultaneously considering reliability and maintenance is developed. Methodology is based on measures like Life Cycle Cost (LCC), Availability (A) and Overall Equipment Effectiveness (OEE). These measures explicitly consider the user’s cost structure and shop floor level policy parameters. A simulation based Genetic Algorithm (GA) is used to solve the simultaneous optimization problem. Case example using operations and maintenance data of a CNC grinding machine is presented.

Keywords: Reliability design, availability, maintenance, overall equipment effectiveness, life cycle cost, machine tools

1. Introduction

Historically, machine tool designers have done a good job of evaluating the functions and form of products at the design phase. Once the functional design of the machine tool is done, designers generally have multiple alternatives for most of the components/subassemblies that can satisfy the functional requirements of the system. Such alternatives, apart from their cost, also differ in their inherent failure and repair characteristics, like time-to-failure distribution, time-to-repair distribution, failure consequences, etc. For example, a designer may have two alternatives for spindle, viz., motorized and belted spindle. Even though both these alternatives may satisfy the functional requirements of the machine, they will have different failure and repair characteristics. Similarly, inherent failure and repair characteristics also vary among alternatives of different make. Therefore, each of these alternatives will contribute differently to the reliability performance of the system. Further, Preventive Maintenance (PM) can also be used to improve the reliability performance of the system. However, preventive maintenance again consumes resources and time which could otherwise be used for production, thereby affecting profit. Therefore, in the view of machine tool designer, the problem of reliability and maintenance based design of machine tool finally boils down to selecting the optimal machine tool configuration from the available alternatives for different components/subassemblies by simultaneously considering reliability and maintenance parameters such that it meets user’s reliability requirements and budget constraints.

From the literature perspective, this problem broadly falls under the category of optimal reliability design of repairable system (also called optimal availability design). Many researchers have addressed this problem in literature. The works of [1-6] deserve attention in this regard. In general, optimal reliability design of repairable systems (or availability design) aims at obtaining the optimal allocation of reliability/redundancy and/or maintainability. It considers the effect of repair or some fixed preventive maintenance policy. However, as mentioned earlier, the user’s reliability requirements can also be met by incorporating an appropriate maintenance policy. In such situations,
optimizing reliability and maintenance parameters simultaneously will be more significant for repairable systems.

The complexity in optimal reliability and maintenance schedule design arises when users are unable to express their reliability requirements explicitly in quantitative terms. It was observed during the research work that only a few corporate customers express their reliability requirements explicitly in terms of Mean Time Between Failures (MTBF). But, even these users are more concerned about their shop floor level performance and they judge the reliability of a machine tool based on how well it performs in terms of performance measures like Overall Equipment Effectiveness (OEE), Life Cycle Cost (LCC), operational availability, etc. These performance measures are closer to the heart of the users and are also affected by inherent failure and repair characteristics and maintenance of the machine tool components/subassemblies. The link of such performance measures with machine reliability and maintenance parameters area also highlighted in the work of [7-11]. However, the impact have not duly considered in literature while designing the machine tool from reliability and maintenance point of view. Moreover, the extent to which the inherent failure and repair characteristics and preventive maintenance of machine components/subassemblies affect a user’s performance measures also depends on the user’s cost structure and shop floor level policies. For example, if a user has alternative machines available to bear the load of a failed machine, then the down time cost of that machine may not be as significant as in the case where there is no alternative machine available to bear the load of the failed machine [12]. Similarly, if a machine is being used as a stand-alone machine, its down time cost will be different than that in the case when the same machine is being used in a production line. As can be seen from the examples, the cost structures will be different for each of the cases. Similarly, a tighter quality control policy at user’s end will detect process shifts due to failure of machine components/subassemblies much earlier, thereby reducing the rejection rate. Thus, the effect of machine failures and maintenances on LCC, OEE, and other performance measures, may be different for different users. This essentially says that different users may require different reliability configuration and maintenance schedule. Thus, a user oriented, reliability and maintenance based design of the machine tool is required.

The objective of the present paper is to develop a methodology for selection of optimal machine tool configuration by simultaneously considering reliability and maintenance parameters. The methodology is based on measures like Life Cycle Cost (LCC), Availability (A) and Overall Equipment Effectiveness (OEE). These measures explicitly consider the user’s cost structure and shop floor level policy parameters. Methodology is illustrated using a case example of operations and maintenance data of grinding machine tool.

2. Machine Tool Failures

In the present research, failures of a machine tool are divided into three consequences. These consequences express the users’ view of failure under the mutually agreed operating conditions between the users and the manufacturers. Whenever failure occurs, it leads to one of the following Failure Consequences (FC) [13].

FC1: failure detected immediately and machine has to be totally stopped.

FC2: machine runs but at a lower production rate than designed (i.e., with increased cycle time) due to failure of any of the machine components.

FC3: machine runs but produces more rejections than the normal rejection rate due to failure of any of the machine components.
Failure consequences 2 and 3 are detected by the users after a time lag, during which the machine tool runs at a reduced performance level. Figure 1 depicts these failure consequences on a time-performance curve. It clearly indicates the relation of a machine tool failure with the user’s shop floor performance measures like, Availability (A), Performance Rate (PR), Quality Rate (QR) and failure costs.

It was observed during the present research that most of the failure events of machine tools lead to failure consequences 2 and 3. Thus, such failure consequences must be considered explicitly while designing the machine tool from reliability and maintenance point of view. Table 1 provides examples of all the three types of failure consequences for a CNC grinding machine.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>FC</th>
<th>Observed effect</th>
<th>Affected performance</th>
<th>Component(s) involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>#2</td>
<td>Tailstock does not move properly</td>
<td>Production</td>
<td>Quil</td>
</tr>
<tr>
<td>2</td>
<td>#2</td>
<td>Work head RPM reduced</td>
<td>Production</td>
<td>Work head belt and pulley</td>
</tr>
<tr>
<td>3</td>
<td>#3</td>
<td>Chatter marks on jobs</td>
<td>Quality</td>
<td>Wheel</td>
</tr>
<tr>
<td>4</td>
<td>#3</td>
<td>Ovality on jobs</td>
<td>Quality</td>
<td>Ball screw</td>
</tr>
<tr>
<td>5</td>
<td>#1</td>
<td>Machine stopped</td>
<td>Availability</td>
<td>Work head belt</td>
</tr>
<tr>
<td>6</td>
<td>#1</td>
<td>Machine stopped</td>
<td>Availability</td>
<td>Wheel head belt</td>
</tr>
</tbody>
</table>

3. Models for Performance Measures

Let there be ‘n’ components/subassemblies in a machine tool. Every time a system fails due to failure of ith component/subassembly, let $P_{FC1i}$, $P_{FC2i}$ and $P_{FC3i}$ be the probabilities with which it leads to FC1, FC2 and FC3, respectively. Consider the following assumptions:

a) Occurrence of FC1, FC2 and FC3, are independent
b) FC1, FC2 and FC3, don’t occur simultaneously
c) The failures of components/subassemblies are independent

Whenever FC1 occurs, the machine is immediately down, or has to stop (for example due to detection of excessive noise, heat, etc.). Thus it can be assumed that detection of FC1 is immediate. However, there is a time lag between occurrence and detection of FC2 and FC3 as shown in Figure 1. Let $RPR_i$ be the reduction in production rate
attributed to the failure consequence $FC_i$ and $IRR_i$ be the increase in rejection rate due to failure consequence $FC_i$ of the $i^{th}$ component/subassembly. For example, if Designed Production Rate be $DPR$ and percentage reduction in production rate due to $FC_i$ of $i^{th}$ component/subassembly is $r'$ then $RPR_i$ is $(\frac{r}{100})$ and production rate during this period will be $(1 - \frac{r}{100}) \cdot DPR$. Similarly, if failure of $i^{th}$ component/subassembly due to $FC_i$ increases the rejection rate by 1% then $IRR$ will be equal to $(\frac{1}{100})$. This rejection rate is over and above the Normal Rejection Rate (NRR).

The total rejection rate during the failed state will be $(NRR + \frac{1}{100})$. Let $t_{FC_i}$ and $t_{FCi}$ be the time to detect the occurrence of $FC_i$ and $FC_i$, respectively. Values of these parameters can be obtained from the production records and quality control mechanisms (e.g., control chart) of the user.

Using the above general description, models for linking availability, overall equipment effectiveness, and life cycle cost, with the reliability and maintenance parameters have been developed. These models explicitly consider user’s cost structure and shop floor level policy parameters. Thus, it helps in capturing user’s reliability and maintenance requirements. The details are presented in the following subsections.

3.1 Availability

Availability is the ratio of actual operating time to the planned production time. Mathematically,

$$A = \frac{Actual\ Operating\ Time}{Planned\ Production\ Time}$$

Let the planned production time in any investigation period be $T$ hours. For example, if investigation period is one year and if it is planned to operate the machine in two shifts of eight hours each and there are 300 working days in a calendar year, then $T = 2 \times 8 \times 300 = 4800$ hours. It does not include any planned maintenance time.

In any investigation period, let, $E(T_{idle})$ be the average time for which the machine tool is not operating due to unavailability of raw materials, set up changes, operator breaks, etc., and $E(T_{DT})$ be the expected time for which the machine tool is down or not available due to failure or maintenance in any investigation period. Thus, actual operating time, $T_{opr}$, in any investigation period can be calculated as follows;

$$T_{opr} = T - E(T_{idle}) - E(T_{DT})$$

Thus,

$$A = \frac{Actual\ Operating\ Time}{Planned\ Production\ Time} = \frac{T_{opr}}{T} = \frac{T - E(T_{idle}) - E(T_{DT})}{T}$$

In above equation, $E(T_{DT})$ also includes all maintenance delays, due to unavailability of maintenance personnel, spare parts, equipment, etc. Thus the availability in equation (3) can also be called as the operational availability [14].

In general, machine tool components/subassemblies receive one or more of the following maintenance actions during the useful life of the machine.

- Corrective actions (repair/replacement)
- Preventive repair
- Preventive replacement
- Preventive major overhauling

Expected down time $E(T_{DT})$ in any investigation period can thus be calculated as:

$$E(T_{DT}) = \sum_{i=1}^{n}[E[N_{CA}] \cdot MTTC_{A_i} + E[N_{PA}] \cdot MTTP_{A_i}]$$


where, \( E[N_{CAi}] \) and \( E[N_{PAi}] \) are the expected number of corrective and preventive actions respectively, during the investigation period. Preventive actions may be repair, overhauling or replacement. Thus, equation (4) can be further elaborated as,

\[
E(T_{DT}) = \sum_{i=1}^{n} \left[ E[N_{CAi}] \cdot MTTCA_i + E[N_{PR Repa{i}}] \cdot MTTPR_{Repairi} + E[N_{PReplacei}] \cdot MTTPR_{Replacei} \right]
\]

where, suffix ‘i’ indicates the \( i^{th} \) component/subassembly in the machine tool.

\( E[N_{PR Repa{i}}] \), \( E[N_{OHi}] \) and \( E[N_{PReplacei}] \) are the expected number of preventive repairs, overhauling, and preventive replacements respectively, in the investigation period. \( MTTCA_i \) and \( MTTPA_i \) are the average time for which machine is down in each of the corrective and preventive actions respectively. It includes the actual time spent in repair as well as the time for which machine is waiting due to unavailability of maintenance personnel, spare parts, etc.

It can further be expressed as:

\[
MTTCA_i = MACAT_i + MCADT_i
\]

\[
MTTPA_i = MAPAT_i + MPADT_i
\]

where, \( MACMT_i \) and \( MAPMT_i \) are the mean active time per corrective and preventive maintenance respectively, and \( MCMDT_i \) and \( MPMDT_i \) are the mean delay time per corrective and preventive maintenance respectively.

Similarly,

\[
MTTP_{Repairi} = MAP_{RepairTi} + MP_{RepairDTi}
\]

\[
MTTOH_i = MAOHT_i + MOHDT_i
\]

\[
MTTP_{Replacei} = MAP_{ReplaceTi} + MP_{ReplaceDTi}
\]

Mean active maintenance time depends on the inherent maintainability of the components/subassemblies in the system. Mean delay time in maintenance can be reduced by providing proper maintenance support in the form of maintenance personnel, spares parts, logistic supports, etc.

Thus the availability can now be expressed as,

\[
A = \frac{T - E(T_{idle}) - \sum_{i=1}^{n} \left[ E[N_{CAi}] \cdot MTTCA_i + E[N_{PR Repai}i] \cdot MTTPR_{Repairi} + E[N_{PReplacei}] \cdot MTTPR_{Replacei} \right]}{T}
\]

The machine tool designer is not responsible for \( E(T_{idle}) \), thus, in order to use above equation for reliability and maintenance based design, designer needs to obtain estimates of \( E(T_{idle}) \) from the users. Alternatively, designer can assign a zero value to it. In this situation, availability becomes the maximum achievable availability or designed availability.

### 3.2 Overall Equipment Effectiveness Model

The Overall Equipment Effectiveness (OEE) as defined earlier is the product of Availability (A), Performance Rate (PR) and Quality Rate (QR) [15]. Mathematically,

\[
OEE = A \times PR \times QR
\]

In equation (12) Availability (A) can be replaced by model equation (11). The models for Performance Rate (PR) and Quality Rate (QR) are developed below.

**Performance Rate Model:** Performance Rate (PR) is the ratio of actual total production to the maximum total production [15].

Let the designed production rate for the machine tool be the DPR. It is the maximum specified production rate by the manufacturer. Thus the Maximum Total Production (MTP) in any investigation period can be calculated as,
MTP = DPR \cdot T_{opr} \quad (13)

The Actual Total Production (ATP) in the investigation period will be less than or equal to the maximum production due to machine failure that leads to Failure Consequence (FC2) and due to some other factors that are not under the control of the designers. Assigning a zero values to the factors that are not under the control of the designers, ATP can be calculated as:

\[
ATP = (\text{Maximum total production} - \text{Reduction in production due to FC2}) \cdot \text{DPR} \quad (14)
\]

And the expected designed performance rate during investigation period can be expressed as:

\[
PR = \frac{ATP}{MTP} = \frac{T_{opr} - \sum_{n=1}^{N_{CA}} E[N_{CA}] \cdot P_{FC2i} \cdot t_{FC2i} \cdot RPR_i}{\text{DPR} \cdot T_{opr}} \quad (15)
\]

\(t_{FC2}\) and \(RPR\) can be obtained from the production record of the users. It is assumed that the \(RPR\) remains constant during the \(t_{FC2}\).

**Quality Rate Model:** Quality rate is the ratio of the total good production to actual total production [16]. Mathematically,

\[
QR = \frac{\text{Total Good Production}}{\text{Actual Total Production}} = \frac{TGP}{ATP} \quad (17)
\]

The actual total production is calculated in equation (15).

The Total Good Production (TGP) during investigation period will be less than Actual Total Production (ATP) due to inherent rejection rate, machine tool failures that leads to Failure consequence 3 (FC3), and other user related factors that are not under the control of the users. Assigning zero values to the factors that are under the control of the users, TGP can be calculated as:

\[
TGP = T_{opr} - \sum_{n=1}^{N_{CA}} E[N_{CA}] \cdot P_{FC2i} \cdot t_{FC2i} \cdot RPR_i \cdot (1 - NRR) - \sum_{n=1}^{N_{IRR}} E[N_{IRR}] \cdot P_{FC3i} \cdot t_{FC3i} \cdot IRR_i \cdot \text{DPR} \quad (18)
\]

Thus, the designed Quality Rate during investigation period becomes:

\[
QR = \frac{T_{opr} - \sum_{n=1}^{N_{CA}} E[N_{CA}] \cdot P_{FC2i} \cdot t_{FC2i} \cdot RPR_i \cdot (1 - NRR) - \sum_{n=1}^{N_{IRR}} E[N_{IRR}] \cdot P_{FC3i} \cdot t_{FC3i} \cdot IRR_i \cdot \text{DPR}}{\text{DPR} \cdot T_{opr} - \sum_{n=1}^{N_{CA}} E[N_{CA}] \cdot P_{FC2i} \cdot t_{FC2i} \cdot RPR_i \cdot \text{DPR}} \quad (19)
\]

It is assumed that the \(IRR\) remains constant during the time period \(t_{FC3}\). Calculation of \(IRR\) and \(t_{FC3}\) using user’s control chart mechanism can be found in [16].

Thus, from equation (11), (12), (16) and (19),

\[
OEE = \frac{T_{opr} - \sum_{n=1}^{N_{CA}} E[N_{CA}] \cdot P_{FC2i} \cdot t_{FC2i} \cdot RPR_i \cdot (1 - NRR) - \sum_{n=1}^{N_{IRR}} E[N_{IRR}] \cdot P_{FC3i} \cdot t_{FC3i} \cdot IRR_i \cdot \text{DPR}}{\text{DPR} \cdot T_{opr} - \sum_{n=1}^{N_{CA}} E[N_{CA}] \cdot P_{FC2i} \cdot t_{FC2i} \cdot RPR_i \cdot \text{DPR}} \quad (20)
\]

### 3.3 Life Cycle Cost Model

Life Cycle Cost (LCC), in general, includes design and development cost, production and construction cost, operation and maintenance cost, system retirement and phase out cost. A comprehensive cost break down structure can be found in [17]. Life cycle cost may be categorized in many different ways, depending on the type of system and purpose of the analysis. In this research, Life Cycle Cost (LCC) is defined as the sum of acquisition cost,
the discounted sum of corrective and preventive action costs for the intended use of the system.

Let the user’s cost structure be such that the cost of lost production per job and cost of rejection per job are \( C_{lp} \) and \( C_{rej} \) respectively. Cost of lost production per job is assumed to be equal to the profit margin per job of the user. This cost will be different for different users. For example, users having a shorter Payback Period (PBP) for the machine can have higher profit margin per job compared to that of a user having comparatively longer Payback Period (PBP) requirements. Similarly, if the machine is used to make a costlier job then the cost of rejection will be higher. Cost of rejection per job includes all the expenses incurred to manufacture the job as well as the profit margin of that job. Thus, cost of rejection per job also varies with users.

Let the maintenance labour (corrective/preventive) rate per hour be \( C_l \). This may also vary for different users, especially, when the users are located in different countries.

Let, for the \( i \)th component/subassembly, the average fixed cost per corrective action be \( C_{fixCAi} \). Similarly, fixed cost per preventive action for each of the three kinds of the preventive actions mentioned in Section 3.1 be, \( C_{fixPRepairi} \), \( C_{fixOHi} \) and \( C_{fixReplace} \). These costs include the cost of material and equipment required for the maintenance. The cost per failure, due to three Failure Consequences (FC) of the \( i \)th component/subassembly of the machine tool, to the users can be calculated as:

\[
C_{FC1i} = MTTCA_i \cdot (DPR \cdot C_{lp} + C_l) + C_{fixCAi} \\
C_{FC2i} = DPR \cdot RPR_i \cdot t_{FC2i} \cdot C_{lp} + C_{FC1i} \\
C_{FC3i} = DPR \cdot IRR_i \cdot t_{FC3i} \cdot C_{rej} + C_{FC1i}
\]

It is clear from equations (22) and (23), failure costs of FC2 and FC3 apart from downtime cost also includes cost of reduced production and increased rejection respectively.

Total cost per corrective action of machine tool ‘\( C_{CA} \)’ will be;

\[
C_{CA} = \sum_{i=1}^{n} C_{CAi} = \sum_{i=1}^{n} \left( P_{FC1i} \cdot C_{FC1i} + P_{FC2i} \cdot C_{FC2i} + P_{FC3i} \cdot C_{FC3i} \right)
\]

Thus, the total expected cost of corrective action during investigation period ‘\( E[C_{CA}] \)’ can be written as:

\[
E[C_{CA}] = \sum_{i=1}^{n} \left( P_{FC1i} \cdot C_{FC1i} + P_{FC2i} \cdot C_{FC2i} + P_{FC3i} \cdot C_{FC3i} \right) \cdot E[N_{CA}]
\]

and the total expected annual cost of preventive action (preventive repair/replacement/overhauling), to the user can be written as;

\[
E[C_{PA}] = \sum_{i=1}^{n} \left( MTTTPRepair_i \cdot (DPR \cdot C_{lp} + C_l) + C_{fixPRepairi} \right) \cdot E[N_{PRepairi}] + \left( MTTTOH_i \cdot (DPR \cdot C_{lp} + C_l) + C_{fixOHi} \right) \cdot E[N_{OHi}] + \left( MTTTPReplace_i \cdot (DPR \cdot C_{lp} + C_l) + C_{fixPReplacei} \right) \cdot E[N_{PReplacei}]
\]

Let the expected life of the machine be ‘\( L \)’ years. Assume that the cost structure of the user and their shop floor policies like quality control policy, annual operating hours, etc. remains same throughout the life of the machine. Thus, the Life Cycle Cost (LCC) expressed in terms of Present Value of Cost (\( PV_c \)) becomes;

\[
PV_c = \sum_{i=1}^{n} C_{aqi} + \sum_{j=1}^{L} \left( \frac{1}{(1+r)^j} \cdot \left( \sum_{i=1}^{n} E[C_{CAi}] + \sum_{j=1}^{L} E[C_{PAi}] \right) \right)
\]

where, ‘\( r \)’ is the discount rate. It is assumed that ‘\( r \)’ remains constant throughout the life of the machine tool. \( C_{aq} \) is the acquisition cost of the \( i \)th component/subassembly of the machine tool.
The LCC obtained from the above model can be considered as the designed LCC for a given set of user’s cost structure and shop floor policies parameters.

4. Problem Formulation

The problem of simultaneous optimization of machine tool reliability and maintenance can now be formulated as follows.

Minimize 

\[ PV_c = f(RC_1, RC_2, ..., RC_n; MS_1, MS_2, ..., MS_n) \]

Subject to

\[ A = f(RC_1, RC_2, ..., RC_n; MS_1, MS_2, ..., MS_n) \geq a \]

\[ OEE = f(RC_1, RC_2, ..., RC_n; MS_1, MS_2, ..., MS_n) \geq oee \]

where, \( RC_1, RC_2, ..., RC_n \) and \( MS_1, MS_2, ..., MS_n \) are the decision variables representing Reliability Characteristics of alternative and Maintenance Schedule of different components/subassemblies in the machine tool respectively. \( n \) is the number of components/subassemblies in the machine tool. "a" and "oee" are the user specified values of the availability and overall equipment effectiveness.

Additionally, budget constraint can also be added. It is assumed that failure of any one of the components/subassemblies leads to failure of machine. In other words, these can be considered in series from reliability point of view. In above formulations, \( PV_c, A, \) and \( OEE \) can be replaced by models presented in previous section. These models consider user’s cost structure and shop floor level policy parameters. Thus the solution to above problem will give a user specific design for reliability and maintenance schedule.

5. Problem Solution

Selecting optimal machine tool configuration requires evaluating all the possible combinations from the alternatives for each component/subassembly. Computationally it is a complex problem. Complexity further increases when we need to simultaneously select the optimal maintenance schedule for each component/subassembly. In the present research, @RISKOptimizer (http://www.palisade.com/riskoptimizer/) software is used to solve the problem using its inbuilt Genetic Algorithm (GA). For a given failure and repair characteristics of components/subassemblies (which is one of the decision variables in above problem and will vary with configurations), expected number of corrective actions in any year for different preventive maintenances (repair, replace, and overhauling) is obtained from simulation. Number of preventive repairs/replace in any year will depend on the preventive maintenance schedule (which is also a decision variable in above problem). For example, if preventive repair of any subassembly is done after every 1600 hour and there are 4800 operating hours in any year, then number of preventive repair for that subassembly in that year will \( \frac{4800}{1600} - 1 \) = 2. It is assumed that at the end of every year subassembly receives a major overhaul. Therefore, only overhauling will be done at the end of each year and no regular preventive repair is done at the time. In this research, corrective maintenance considered as minimal. Preventive maintenance and overhauling is considered as imperfect with different degree of restoration.

In order to illustrate the above methodology following example of a CNC grinding machine tool is provided. In this study, analysis is performed at subassembly level. Grinding machine failure is studied at following five subassembly levels. Work head, Tailstock, Wheel head, Table sub-assembly including ball screw, and carriage subassembly
The methodology can be used at component level also; however, it will increase the computational time for optimization. It is assumed that, machine operates for 4800 hours per year. Designer has three alternatives for subassembly 1 and subassembly 3; two alternatives for subassembly 2 and only one alternative for subassembly 4 and 5. It is assumed that each of these alternatives for a subassembly satisfy functional requirements of the machine.

Table 2: Failure and Repair Characteristics of Alternatives

<table>
<thead>
<tr>
<th>SS1</th>
<th>SS2</th>
<th>SS3</th>
<th>SS4</th>
<th>SS5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reliability Characteristics</strong></td>
<td>Alt1</td>
<td>Alt2</td>
<td>Alt3</td>
<td>Alt1</td>
</tr>
<tr>
<td>η (hours)</td>
<td>10000</td>
<td>7000</td>
<td>4000</td>
<td>8000</td>
</tr>
<tr>
<td>β</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>C_{age}(\times 10^3)</td>
<td>80</td>
<td>60</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>P_{FC1}</td>
<td>0.3</td>
<td>0.5</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>P_{FC2}</td>
<td>0.2</td>
<td>0</td>
<td>0.5</td>
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<tr>
<td>P_{FR}</td>
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<td>MACAT</td>
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<td>MCATD</td>
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<tr>
<td>C_{fixed} (\times 10^3)</td>
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<td>1.2</td>
<td>1</td>
<td>1.6</td>
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<tr>
<td>C_{repair} (\times 10^5)</td>
<td>4</td>
<td>2</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>C_{overhaul} (\times 10^5)</td>
<td>6.4</td>
<td>4.5</td>
<td>4</td>
<td>6.4</td>
</tr>
<tr>
<td>RPR</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>δ</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>R_{FR}</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>R_{OH}</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Note: All costs are in INR (Indian Currency), and all the times are in hours. SS=Subsystem

Apart from acquisition cost, these alternatives also vary on one or more of their failure and repair characteristics, like time to failure distribution, time required for repair, fixed cost per corrective action, fixed cost per preventive repair, replacement and overhauls, degree of restoration, failure consequences, etc. Table 2 shows such alternatives and their failure and repair characteristics. These data are obtained from the past failure and repair record of similar grinding machines. Expert judgement based methods [18] are used to obtain time to failure distribution parameters and restoration factors. Table 2 also shows average shift in the process mean and reduction is production rate due to failure of any of the components/subassemblies that leads to failure consequences 2 and 3 (FC2 and FC3).
It is assumed that the effective life of the machine on the shop floor is 12 years. Also, the time-to-failure is assumed to follow a two-parameter Weibull distribution. Let us assume that a special purpose machine tool is to be designed for two different users. It is assumed that, both the user use $X$ control chat to monitor the process quality. The cost structure and control chart policy parameters of the two users for which the design is required are as shown in Table 3. These data are obtained based on the discussion with some of the user industries. User 1 updates the production record after every 6 hours. Thus the time required to detect the FC2 (i.e., $t_{FC2}$) will be equal to 6 hours. the same is 8 hours for user 2.

<table>
<thead>
<tr>
<th>Cost structure and control chart parameters of different users</th>
<th>$C_{ip}$</th>
<th>$C_{rej}$</th>
<th>$C_1$</th>
<th>$S$</th>
<th>$t_5$</th>
<th>DPR (jobs/hr)</th>
<th>$t_{FC2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>User 1</td>
<td>80</td>
<td>5000</td>
<td>500</td>
<td>4</td>
<td>5</td>
<td>45</td>
<td>6</td>
</tr>
<tr>
<td>User 2</td>
<td>40</td>
<td>1000</td>
<td>500</td>
<td>5</td>
<td>8</td>
<td>45</td>
<td>8</td>
</tr>
</tbody>
</table>

Note: All costs are in INR (Indian Currency), and all the times are in hours.

The problem is then to select a machine tool configuration that minimizes the life cycle cost to the user while meeting their performance requirements for a 12 year life of the machine tool. Let the design availability (A) and Overall Equipment Effectiveness (OEE) requirement of the user be 0.94 and 0.93 respectively. Note that the designed availability and designed OEE as discussed earlier only accounts for the losses due to machine tool failure. Therefore, the actual availability and OEE values may be lower or equal to the designed availability and OEE depending upon the losses that are due to the user controlled parameters.

For above mentioned data, the optimization problem is solved using RISKOptimizer and the optimal results for users 1 and 2 are shown in Table 4 and 5 respectively. The required budget for both the users is also shown in respective tables. As can be seen from Table 4 and 5, different users have different optimal machine tool configuration and maintenance schedule based on their cost structure and shop floor policies. Thus a customized reliability configuration and customized maintenance schedule is obtained for each specific user.

It was also observed that the optimal solution obtained with different starting solutions and population sizes did not differ from each other. The sensitivity analysis of the proposed methods to user’s cost structure, like cost of lost production, cost of rejection, etc., and user’s shop floor policy parameters, like control chart design parameters, is also performed.

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>Optimal System Configuration</th>
<th>Alt2</th>
<th>Alt1</th>
<th>Alt2</th>
<th>Alt1</th>
<th>Alt1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{Repair}$ (hrs)</td>
<td>2400</td>
<td>2400</td>
<td>-</td>
<td>1600</td>
<td>2400</td>
<td></td>
</tr>
<tr>
<td>$t_{Replace}$ (Years)</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Objective function values

| $PV_C \times 10^4$ (in INR) | 129 |

Constraints

| $A$ | 0.99 |
| $OEE$ | 0.98 |

Required budget

| $\sum_{i=1}^n C_{aq}$ (in INR) | 1255000 |
It was observed that the model is robust for small variation in these parameters. The results of the sensitivity analysis are not presented in this paper. It was also observed that the Present Value of the cost ($PV_C$) is relatively more sensitive to the change in cost of rejection than to cost of lost production.

Table 5: Optimal Machine Tool Configuration and Maintenance Schedule for User 2

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>Optimal System Configuration</th>
<th>Alt3</th>
<th>Alt2</th>
<th>Alt1</th>
<th>Alt1</th>
<th>Alt1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{Repair}}$ (hrs)</td>
<td>1600</td>
<td>-</td>
<td>2400</td>
<td>2400</td>
<td>2400</td>
<td></td>
</tr>
<tr>
<td>$t_{\text{Replace}}$ (hrs)</td>
<td>2 year</td>
<td>3 year</td>
<td>2 year</td>
<td>1 year</td>
<td>2 year</td>
<td></td>
</tr>
<tr>
<td>Objective function values</td>
<td>$PV_C$ ($\times 10^5$) (in INR)</td>
<td>75</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constraints</td>
<td>$A$</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$OEE$</td>
<td>0.98</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Required budget</td>
<td>$\Sigma_{i=1}^{N} C_{aq}$ (in INR)</td>
<td>1115000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6. Conclusion

A design methodology for simultaneous optimization of reliability and maintenance of the machine tools has been proposed in this chapter. It aims at allocating the system level performance goal to lower level components/subassemblies by simultaneously optimizing reliability characteristics and preventive maintenance schedule of the components/subsystems. The reliability characteristics could be anything like, time to failure distribution, time to repair, degree of restoration, failure consequences, etc. Therefore, reliability characteristics are optimized in terms of selection of alternatives. The methodology is based on performance measures that are closer to the heart of the users, like life cycle cost, overall equipment effectiveness and availability. It also considers user’s cost structure and shop floor level policy parameters. Thus, it helps in obtaining user oriented solution (system configuration and maintenance schedule) of the machine tools to the manufacturer, thereby gaining a competitive hand in the market.

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References


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