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Reliability analysis of CNC turning center based on the assessment of trends in maintenance data - a case study

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1. Introduction

The word "reliability" was first coined by poet Samuel Taylor Coleridge in 1816 to praise his friend poet Robert Southey [1]. Since then reliability has been evolved as a concept that represents a commendable attribute of a person or a product. From 1816 to today several revolutionizing social, cultural and technological developments have occurred. The significance of cost of failure and system downtime was first recognized during World War II. It is also observed that, reliability and maintainability greatly influence the life cycle cost (LCC) of the complex systems [2]. Thereafter, the research work started to improve system performance. In mid-1956, reliability engineering became a scientific discipline [3]. The reliability of product/ system is crucial to sustain in the market share in today's competitive marketplace. Reliability analysis helps to manage the product/ system failures while LCC analysis deals with the cost implications over the operational life of the system. Reliability and LCC can have implications in terms of risk, safety, profit margins, cost of maintenance and operations [4-5].

Computerized numerical control (CNC) turning center is one of the complex machine tool that consists of mechanical, electrical, electronics and software systems. As a result of their inherent flexibility, stable machining accuracy and high productivity, CNC turning center is of immense interest to the users. However, the breakdown of a single CNC turning center may halt the production of an entire workshop. Furthermore, repairs are more difficult and expensive when a breakdown occurs without any prior intimation. Such failure creates a lot of trouble to the users and hence the reliability study of such CNC turning systems is essential. In the meantime, the manufacturers are also required to improve the reliability of CNC turning center to sharpen their competitive edge in the marketplace. Considering all these aspects, it is decided to carry out reliability and LCC analysis of CNC turning center.

This paper is structured as follows. The extensive literature survey is presented in section 2, which highlights the applications, methodologies used. Section 3 gives the generalized framework used for the analysis of reliability data. Reliability and LCC analysis is presented in section 4 and section 5 respectively. Reliability improvement methods are suggested and improved reliability and LCC is presented in section 6. Section 7, finally, concludes the paper.

2. Literature Review

The objective of this study is to select a suitable framework for the analysis of time-to-failure (TTF) and time-to-repair (TTR) data based on the assessment of trends in the maintenance data. The literature review is divided into three groups: first group presents various data analysis frameworks and their applications; second group describes reliability study of CNC machine tools carried out over the years and finally third group summarize various LCC models.

In 1976, Ferris-prabhu and Lubart [6] used a simple analytical technique for the assessment of a small system without error correction. The work extended in 1984 by Ascher and Feingold [7] and developed a framework for reliability data analysis, which requires a large number of tests to be conducted for the verification of trends in the data. Barabady and Kumar [8] simplified the developed framework and applied it for crushing plant analysis. In 2009, Louit et al., [9] reviewed several tests available to assess the existence of trends and developed a simplified framework for model selection to represent the failure process for a component or system. The proposed framework discriminates between the use of statistical distributions to represent the time-to-failure (i.e. Renewal approach); and the use of stochastic point process (repairable system approach). It is also observed that, several papers used specific reliability distributions for failure and repair data analysis [10-14]. Castet and Saleh [15-16] conducted a non-parametric analysis of satellite reliability for 1584 Earth-orbiting satellites launched between January 1990 and October 2008. The results of this analysis are useful for space industry for redesigning subsystems and screen programs. Sehgal et al., [17] developed a procedure for the selection of rolling contact bearing which is based on graph theory and matrix method. The proposed procedure compares two or more bearings based on coefficient of similarity/ dissimilarity. Reliability study employed for system reliability improvement by deciding reliability based maintenance schedules, preventive maintenance activities and enhancing spare part ordering decision making [18-22].

Several studies are reported on reliability of CNC assisted machine tools [23-31]. Coding system advised for the collection of field data and for applying quantitative reliability methods. The failure position and subsystem, failure mode and cause were analyzed to indicate the weak subsystem of CNC machine tools. Zhao-Junet al. [27] optimized machining center maintenance policy to improve the reliability. The routine inspection and regular inspection as well as the sequential preventive maintenance under maintenance cost constraints were suggested using power-law process. Furthermore, Wang et al., [28] studied nine ex-factory machining centers and reported early failures during the test. This early failure data were used to predict where subsystems of machining centers. Field failure data collected, sorted careful in order to eliminate abnormal data. Ying-Zhi et al., [29] presented a method for the analysis of failure data of CNC machine tool and a method to eliminate abnormal data. Jie et al., [30] analyzed the data of the CNC machine tools and Weibull 3P distribution is found to be better than Weibull 2P distribution. Lad and Kulkarni [31] used the knowledge and experience of maintenance personnel to estimate reliability of machine tool in the absence of field failure data.

The need of practical reliability details to define LCC of the product was emphasized by Petkar [32]. The importance of grade of installation and grade of equipment while determining the LCC was also discussed. Enparantza et al., [33] discussed a LCC calculation and management system for machine tools to provide LCC data prediction at offer phase and to support the design phase decisions by managing real machine tool behavior data. Waghmode and Patil [34] applied reliability and maintainability techniques to optimize LCC of band saw cutting machine. The total LCC of band saw cutting machine was reduced by almost 22%. Waghmode et al., [35] presented a LCC modeling approach for estimating LCC of pump using the activity based costing (ABC) method. The acquisition cost of the pumps is only a fraction of their LCC. The life cycle energy and maintenance costs dominated the pump LCC. Carpentieri et al., [36] presented a LCC calculation model for the automotive production line considering different operating environments such as cost analysis, LCC calculation and net present value (NPV). There are several case studies presented to describe impact of system failure on LCC.

The above literature review reveals that many reliability studies have been reported which use specific reliability distributions to analyze failure and repair time data. However, trend tests and goodness-of-fit tests give more accurate distributions. Reliability analysis of CNC machine tools is also attempted with an objective to identify the sub-systems of CNC machine with low reliability. But all these studies do not take into account the component reliability analysis to identify the components of CNC machine tool with low reliability. Component reliability analysis will be more accurate approach. Therefore, it is proposed to carry out reliability analysis of CNC machine at component level to find out critical components from reliability and LCC perspective.

3. Framework for Reliability Analysis

A detailed framework for analyzing of TTF and TTR data is presented in Fig. 3.1. It is a generalized framework and can be applied for the analysis of field failure as well as life test data. It gives idea for selecting approach of the analysis such as Bayesian method, parametric and non-parametric methods. The various steps involved in the data analysis framework are discussed in this section.

3.1. Selection of a system

The first step in the reliability study is to select a system for analysis and identify similar systems. The necessity of the reliability study should be defined considering time and cost of the analysis. Thereafter, the whole system is required to be classified into different subsystems and components. The purpose is to increase understanding level of the system and would help to decide analysis approach and sensitive area of analysis. There are two approaches which can be preferred for the analysis: binary state system or multi-state system. Binary state analysis approach considers only two states of the system either working or failed. But there are many systems such as power plants having partial failure states which affect the performance level. Considering the states of the system, binary state system or multi-state system analysis approach can be selected.

3.2. Data collection

There are various sources from which failure and repair time data can be collected. Some of the important data collection methods are history cards, maintenance register, maintenance analysts, reliability testing, and accelerated life testing. The collected data is then to be sorted and classified. It is often found that, a large proportion of failures in a system are due to a small number of cases; hence it is required to use Pareto chart analysis method for finding critical components, subsystems. Pareto chart analysis minimizes the time and cost required for analysis and helps to focus on critical subsystems or components.

3.3. Parametric and non-parametric methods

Another aspect is to select a suitable method for modeling. Modeling could be done using Bayesian, parametric or non-parametric methods. Bayesian method is used in case of inadequate data. If sufficient data is available, parametric methods could be preferred. It is recommended that any set of life data should first be subjected to a non-parametric analysis before moving on to the assumption of an underlying distribution and detailed analysis [37]. However, the biggest disadvantage of non-parametric methods is that extrapolation or prediction of reliability outside the data range is not possible. Therefore, non-parametric methods may be used only during preliminary stages of reliability studies for the purpose of an initial, easier, approximate and faster estimate. For accurate analysis, well known, parametric methods are used.

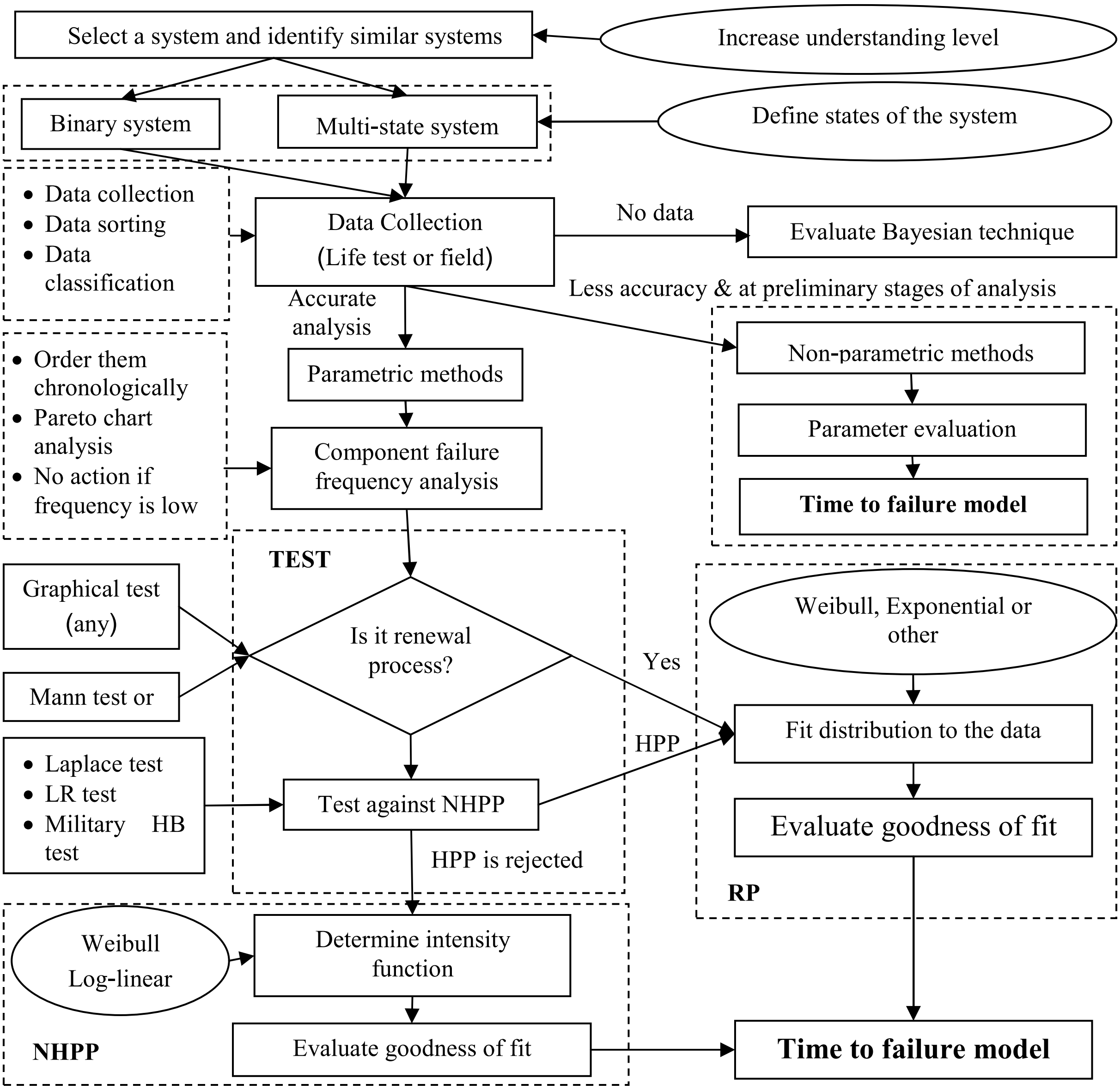

Figure 3.1 – Generalized framework for the selection of TTF and TTR model

3.4. Trend testing and goodness-of-fit

The refined, sorted and classified TTF and TTR data is then tested to validate the assumption of independent and identically distributed (iid) or renewal nature of the data. Graphical methods such as cumulative failures vs. time, scatter plots of successive lives and Nelson-Alon plot or analytical methods such as Mann test can be used. The null hypothesis of these methods is a renewal process (RP), if it is rejected then data can be tested against homogeneous Poisson process (HPP). Laplace test, Lewis-Robinson (LR) test and Military handbook test are used for the verification of HPP. If HPP is rejected then non-homogeneous Poisson process (NHPP) is valid. The approach for fitting an NHPP to non-stationary data are different from the technique involved in fitting a distribution function to iid. Thereafter, chi-square test, or Kolmogorov-Smirnov (K-S) test are used to identify best fit distribution and distribution parameters for a given data set. Best fit distributions are used to describe the reliability characteristics. The concept of importance measure can be used in order to find criticality of each component or subsystem. It enables the weakest areas of a system to be identified and indicates modifications that will improve the system reliability.

4. Case Study

In this section, a case study describing the reliability and LCC analysis of a CNC turning center is presented. CNC turning center consists of a number of components connected to each other logically either in series or in parallel in most cases. The reliability of the CNC turning center depends on the reliability of its components and system configuration. The framework presented in the previous section is used for the analysis of CNC turning center. The methodology followed in the analysis of the case study, comprises the following:

i. Understanding the system configuration, the system components and the faults therein;
ii. Collection, sorting and classification of the TTF and TTR data for each component;
iii. Data analysis for verification of the assumption of RP and/or NHPP;
iv. Fitting the TTF and TTR data for the components with a theoretical probability distribution;
v. The estimation of the reliability and maintainability parameters of each component and subsystem with a best-fit distribution;
vi. Estimation of life cycle cost;

vii. Identification of critical components and faults and the formulation of a better maintenance policy to improve reliability; and

viii. Estimating optimized life cycle cost.

4.1. Data collection, sorting and trend testing

Field failure data is collected from the manufacturers and users of CNC turning center. The data are then sorted and classified which give information such TTF, TTR, frequency, total breakdown hours, total working hours and total maintenance hours. The TTF data obtained due to breakage of component are considered as complete failures. The TTF and TTR data is arranged in chronological order for the use of statistical analysis to determine possible trend.

The next step after the collection and sorting of data is the validation of the iid nature of the TTF and TTR data. The computed values of the test statistic for TTF and TTR data are given in Table 4.1. The null hypothesis of a HPP in which the test statistic U is χ^2 distributed with a 2 (n-1) degree of freedom, the null hypothesis is not rejected at a 5% level of significance in most of the components. The results are verified using graphical method as well and found to be no trend in the data.

Table 4.1 Computed value of the statistic for TTF and TTR

Sr. No.	Components	Value of the statistic for TTF			Value of the statistic for TTR		
		DOF	Calculated statistic U	Rejection of null hypothesis at 5% level of significance	DOF	Calculated statistic U	Rejection of null hypothesis at 5% level of significance
1	Spindle motor	8	2.94	Not rejected (> 2.73)	8	3.47	Not rejected (> 2.73)
2	Spindle motor cooling fan	9	3.57	Not rejected (> 3.50)	9	3.98	Not rejected (> 3.94)
3	Spindle Belt	8	3.25	Not rejected (> 2.73)	8	3.92	Not rejected (> 2.73)
4	Spindle Bearing	10	4.37	Not rejected (> 3.94)	10	3.98	Not rejected (> 3.94)
5	Drawbar	6	3.84	Not rejected (> 1.64)	6	2.90	Not rejected (> 1.64)
6	Spindle pulley	8	2.98	Not rejected (> 2.73)	8	3.17	Not rejected (> 2.73)
7	Hydraulic motor	10	4.89	Not rejected (> 3.94)	10	5.33	Not rejected (> 3.94)
8	Hydraulic vane pump	6	2.58	Not rejected (> 1.61)	6	2.11	Not rejected (> 1.46)
9	Oil seals	8	3.57	Not rejected (> 2.73)	8	3.06	Not rejected (> 2.73)
10	Hydraulic hose	6	2.87	Not rejected (> 1.64)	6	2.54	Not rejected (> 1.64)
11	Solenoid Valve	8	3.52	Not rejected (> 2.73)	8	2.94	Not rejected (> 2.73)
12	Hydraulic Tank	6	1.87	Not rejected (> 1.64)	6	2.09	Not rejected (> 1.64)
13	Thrust Bearing	10	4.92	Not rejected (> 3.94)	10	4.35	Not rejected (> 3.94)
14	Ball Bearing	8	2.87	Not rejected (> 2.73)	8	2.86	Not rejected (> 2.73)
15	Turret Slide	6	2.31	Not rejected (> 1.64)	6	1.83	Not rejected (> 1.64)
16	Slide Cover 'L' Plate	4	1.03	Not rejected (> 0.71)	4	1.47	Not rejected (> 0.71)
17	Tool Holder	12	6.23	Not rejected (> 5.23)	12	6.24	Not rejected (> 5.23)

Sr. No.	Components	Value of the statistic for TTF			Value of the statistic for TTR		
		DOF	Calculated statistic U	Rejection of null hypothesis at 5% level of significance	DOF	Calculated statistic U	Rejection of null hypothesis at 5% level of significance
18	LPMS	8	4.78	Not rejected (> 2.73)	8	3.84	Not rejected (> 2.73)
19	Lubrication hose	10	4.01	Not rejected (> 3.94)	10	4.42	Not rejected (> 3.94)
20	Lubricant Tank	6	1.73	Not rejected (> 1.64)	6	2.49	Not rejected (> 1.64)
21	CPMS	14	7.28	Not rejected (> 6.57)	14	8.48	Not rejected (> 6.57)
22	Coolant hose	10	6.68	Not rejected (> 3.94)	10	4.50	Not rejected (> 3.94)
23	Coolant Tank	4	0.82	Not rejected (> 0.71)	4	1.47	Not rejected (> 0.71)
24	'X' Axis Servo Motor	8	2.89	Not rejected (> 2.73)	8	3.47	Not rejected (> 2.73)
25	'Z' Axis Servo Motor	6	1.79	Not rejected (> 1.64)	6	2.85	Not rejected (> 1.64)
26	Drive card	6	3.64	Not rejected (> 1.64)	6	2.10	Not rejected (> 1.64)
27	Supply Cable	6	2.64	Not rejected (> 1.64)	6	1.87	Not rejected (> 1.64)
28	Drive Battery	12	8.21	Not rejected (> 5.23)	12	5.57	Not rejected (> 5.23)
29	Swarf conveyor	8	2.99	Not rejected (> 2.73)	8	3.37	Not rejected (> 2.73)
30	Control panel	8	4.52	Not rejected (> 2.73)	8	3.58	Not rejected (> 2.73)
31	Panel cooling fan	6	3.64	Not rejected (> 1.64)	6	1.99	Not rejected (> 1.64)
32	Door rollers	4	1.92	Not rejected (> 0.71)	4	1.18	Not rejected (> 0.71)
33	Toughen Glass	4	1.45	Not rejected (> 0.71)	4	1.96	Not rejected (> 0.71)

4.2. Analysis of trend-free data

The trend-free data are further analysed using K-S test to determine best fit distribution. Statistical distributions such as Weibull, normal, log-normal and exponential are examined for goodness-of-fit test. Distribution parameters of the best fit distribution are then estimated. The results of goodness-of-fit tests for TTF and TTR are presented in Table 4.2 and Table 4.3 respectively. Weibull 2P, Weibull 3P, log-normal, Normal and exponential 2P are found to be best fit distribution.

Table 4.2 Best-fit distribution of TTF data

Sr. No.	Component	K-S test (goodness of fit)					Best-fit	Parameters
		Exp. 2P	Log-normal	Normal	Weibull 2P	Weibull 3P		
1	Spindle motor	0.0251	0.01	0.0001	0.001	0.00	Weibull 2P	$\beta = 1.72$, $\theta = 13230$
2	Spindle motor cooling fan	0.0189	0.01	0.3738	0.0158	0.0001	Weibull 3P	$\beta = 0.60$, $\theta = 4271$,$\gamma = 843$
3	Spindle belt	0.3033	0.0843	0.8644	0.4612	0.0494	Weibull 3P	$\beta = 0.56$, $\theta = 5980$,$\gamma = 1484$
4	Spindle bearing	0.8932	0.0909	0.0068	0.0023	0.0030	Weibull 2P	$\beta = 2.21$, $\theta = 14655$
5	Drawbar	0.0041	0.0000	0.0410	0.0001	0.003	Log-normal	$\mu' = 8.24$, $\sigma' = 0.69$
6	Spindle pulley	2.94E-06	1.00E-12	1.00E-12	1.00E-12	3.09E-09	Log-normal	$\mu'= 10.36$, $\sigma'=0.26$
7	Hydraulic motor	0.0023	0.0123	0.018	0.0069	0.0000	Weibull 3P	$\beta = 2.38$, $\theta= 19545$, $\gamma= 11097$
8	Hydraulic pump	0.0049	0.0038	0.0030	0.0009	0.0000	Weibull 3P	$\beta = 3.02$, $\theta= 11507$,$\gamma= 3302$
9	Oil seals	0.0118	0.0033	0.0000	0.0006	0.00038	Normal	$\mu = 13507$, $\sigma = 9855$
10	Hydraulic hose	0.00039	0.0025	0.338 %	0.0239 %	0.0000	Weibull 3P	$\beta = 0.62$, $\theta= 3659$,$\gamma= 4989$
11	Solenoid Valve	1.00E-12	1.00E-12	1.02E-09	2.37E-07	1.00E-12	Weibull 3P	$\beta =0.74$, $\theta = 2274$,$\gamma =6640$
12	Hydraulic Tank	4.70E-10	1.00E-12	1.00E-12	4.89E-10	2.46E-09	Log-normal	$\mu'= 10.83$, $\sigma'=0.19$
13	Thrust Bearing	2.28E-06	1.00E-12	8.10E-11	3.28E-10	1.42E-09	Log-normal	$\mu'= 9.84$, $\sigma'=0.30$
14	Ball Bearing	2.39E-05	2.15E-10	1.00E-12	1.51E-10	9.48E-10	Normal	$\mu =18500$, $\sigma =5349$
15	Turret Slide	2.43E-04	4.50E-11	1.00E-12	1.00E-12	1.00E-12	Normal	$\mu = 18800$, $\sigma =5745$
16	Slide Cover 'L' Plate	3.10E-04	1.00E-12	9.02E-10	1.00E-12	1.00E-12	Weibull 2P	$\beta =7.61$, $\theta = 32183$
17	Tool Holder	4.96E-01	7.41E-02	1.66E-04	3.73E-03	5.80E-11	Normal	$\mu = 1829$, $\sigma =762$
18	LPMS	0.0944	0.0000	0.2757	0.0097	0.0030	Log-normal	$\mu'= 8.82$, $\sigma'= 0.98$
19	Lubrication hose	0.01	0.0025	0.0039	0.0000	0.0009	Weibull 2P	$\beta = 1.98$, $\theta= 14924$
20	Lubricant Tank	1.50E-04	1.00E-12	4.69E-10	5.81E-10	1.00E-12	Log-normal	$\mu'=10.88$, $\sigma'=0.21$
21	CPMS	0.13	0.001	0.0009	0.0000	0.00083	Weibull 2P	$\beta= 1.30$, $\theta= 10903$
22	Coolant hose	0.00056	0.0006	0.0046	0.00	0.00	Weibull 2P	$\beta= 1.58$, $\theta= 6868$
23	Casing of Coolant Tank	2.35E-03	3.36E-07	1.92E-08	4.50E-11	1.00E-12	Weibull 2P	$\beta = 5.33$, $\theta = 55092$
24	X' Axis Servo Motor	2.39E-05	1.09E-09	1.00E-12	2.40E-09	1.00E-12	Weibull 3P	$\beta =4.34$, $\theta = 40282$, $\gamma = -1622$
25	Z' Axis Servo Motor	3.10E-04	1.00E-12	9.02E-10	1.00E-12	1.00E-12	Weibull 2P	$\beta =4.13$, $\theta = 34626$
26	Drive card	2.43E-04	4.70E-11	1.00E-12	1.00E-12	1.93E-09	Normal	$\mu = 29050$, $\sigma =21025$
27	Supply cables	2.43E-04	1.34E-08	5.33E-10	5.34E-10	8.00E-12	Weibull 3P	$\beta =1.05$, $\theta = 6737$, $\gamma =6398$
28	Drive Battery	3.28E-02	1.51E-02	8.76E-03	3.51E-02	4.27E-04	Weibull 3P	$\beta =0.69$, $\theta = 2897$,$\gamma =2398$
29	Swarf conveyor	7.12E-03	1.17E-05	1.97E-10	5.30E-11	1.32E-07	Weibull 2P	$\beta =3.93$, $\theta = 30244$
30	Control panel	7.02E-02	9.48E-04	3.24E-05	1.38E-05	5.03E-08	Weibull 2P	$\beta =2.43$, $\theta = 19327$
31	Panel cooling fan	3.26E-02	2.90E-03	9.47E-08	3.79E-05	1.00E-12	Normal	$\mu =17300$, $\sigma =8624$
32	Door rollers	1.39E-03	7.48E-10	1.00E-12	5.50E-11	3.08E-10	Normal	$\mu =20133$, $\sigma =8727$
33	Toughen Glass	1.00E-12	1.54E-09	1.00E-12	1.00E-12	1.00E-12	Weibull 3P	$\beta =4.83$, $\theta = 48821$, $\gamma =-9856$

Table 4.3: Best-fit distribution of TTR data

Sr. No.	Component	K-S test (goodness of fit)					Best-fit	Parameters
		Exp. 2P	Log-normal	Normal	Weibull 2P	Weibull 3P		
1	Spindle motor	5.23E-08	7.96E-04	4.98E-03	1.16E-02	4.42E-09	Weibull 3P	β = 1.08, θ =5.44, γ =9.13
2	Spindle motor cooling fan	0.2269	0.1506	0.8055	0.4791	0.2945	Log-normal	μ'= 0.64, σ'= 0.68
3	Spindle belt	1.76E-02	8.88E-05	9.01E-06	6.49E-05	1.83E-07	Weibull 3P	β =2.12, θ = 1.11, γ =0.45
4	Spindle Bearing	1.26E-09	1.29E-07	2.03E-05	2.96E-04	1.00E-12	Weibull 3P	β = 0.88, θ = 2.69, γ =7.77
5	Drawbar	1.00E-12	1.00E-12	1.00E-12	2.08E-09	2.56E-09	Exp. 2P	λ= 2.35, t_0=3.72
6	Spindle Pulley	2.39E-05	1.00E-12	1.00E-12	1.00E-12	1.00E-12	Weibull 2P	β =3.80, θ =13.26
7	Hydraulic motor	2.32E-02	6.32E-05	3.12E-09	6.00E-12	4.01E-05	Weibull 3P	β = 1.57, θ = 2.85, γ = 1.87
8	Hydraulic pump	2.32E-02	6.32E-05	3.12E-09	6.00E-12	4.01E-05	Weibull 3P	β = 1.57, θ = 2.85, γ = 1.87
9	Oil seals	6.40E-09	1.85E-03	6.06E-03	1.84E-02	2.15E-08	Weibull 3P	β = 0.99, θ = 2.73, γ = 6.63
10	Hydraulic hose	1.05E-02	8.13E-05	2.13E-08	3.07E-08	1.40E-07	Normal	μ =1.5, σ =0.46
11	Solenoid Valve	1.76E-02	5.36E-05	9.02E-06	4.74E-05	1.83E-07	Weibull 3P	β =2.12, θ = 1.11, γ =0.95
12	Hydraulic Tank	4.46E-07	3.67E-04	3.27E-03	8.41E-03	1.48E-07	Weibull 3P	β =1.14, θ = 2.00, γ =4.57
13	Thrust Bearing	1.99E-04	2.83E-02	1.99E-04	1.30E-01	2.46E-05	Weibull 3P	β =0.93, θ = 2.34, γ =7.77
14	Ball Bearing	1.00E-12	5.20E-11	1.37E-07	1.13E-05	1.14E-09	Exp. 2P	λ =3.00, t_0=8.05
15	Turret Slide	2.43E-04	1.00E-12	1.00E-12	1.00E-12	1.00E-12	Weibull 2P	β =4.99, θ = 22.76
16	Slide Cover 'L' Plate	1.00E-12	1.00E-12	1.00E-12	1.00E-12	1.00E-12	Weibull 3P	β =3.30, θ = 15.79, γ =1.87
17	Tool Holder	2.13E-07	1.00E-12	2.28E-10	1.00E-12	1.00E-12	Weibull 3P	β =1.60, θ = 2.60, γ =2.39
18	LPMS	1.28E-05	1.53E-06	1.28E-04	8.44E-04	4.85E-07	Weibull 3P	β =1.13, θ = 1.17, γ =1.81
19	Lubrication hose	2.28E-06	8.94E-05	1.60E-03	1.97E-03	4.22E-05	Exp. 2P	λ = 0.451, t_0=1
20	Lubricant Tank	1.09E-05	9.67E-05	4.17E-05	3.55E-04	3.84E-06	Weibull 3P	β =1.52, θ = 3.81, γ =4.32
21	CPMS	6.08E-02	5.36E-06	2.52E-03	4.15E-03	7.93E-05	Log-normal	μ'= 0.86, σ'=0.40
22	Coolant hose	2.74E-01	5.09E-02	6.06E-03	6.90E-03	5.22E-03	Weibull 3P	β =2.59, θ = 1.20, γ =0.37
23	Coolant Tank	1.00E-12	1.00E-12	1.00E-12	1.00E-12	1.00E-12	Weibull 3P	β = 3.29, θ = 7.89, γ =0.94
24	'X' Axis Servo Motor	5.23E-08	7.96E-04	4.98E-03	1.16E-02	4.42E-09	Weibull 3P	β = 1.08, θ = 5.44, γ =9.13
25	'Z' Axis Servo Motor	5.08E-10	8.02E-10	7.85E-10	1.00E-12	1.76E-09	Weibull 2P	β = 3.35, θ = 16.15
26	Drive card	6.77E-04	5.10E-05	1.49E-04	2.28E-05	1.12E-07	Weibull 3P	β =2.31, θ = 0.76, γ =0.15
27	Supply cables	1.00E-12	1.00E-12	1.00E-12	1.00E-12	1.00E-12	Weibull 3P	β =1.37, θ = 1.53, γ =2.58
28	Drive Battery	2.18E-01	5.48E-04	8.77E-10	5.98E-10	5.4E-11	Weibull 3P	β =3.93, θ = 3.26, γ =-0.81
29	Swarf conveyor	2.05E-03	6.75E-10	5.68E-06	2.29E-05	2.08E-09	Log-normal	μ'= 0.76, σ'=0.29
30	Control panel	5.42E-09	5.63E-04	1.92E-02	1.53E-02	1.84E-07	Exp. 2P	λ= 0.79, t_0=1.81
31	Panel cooling fan	1.09E-05	8.24E-05	4.17E-05	3.26E-04	3.85E-06	Weibull 3P	β =1.51, θ = 0.95, γ =1.58
32	Door rollers	1.00E-12	3.02E-09	1.00E-12	3.96E-09	1.00E-12	Weibull 3P	β =3.30, θ = 1.97, γ =0.74
33	Toughen Glass	1.00E-12	2.14E-09	1.00E-12	1.00E-12	1.00E-12	Weibull 3P	β =2.77, θ = 1.70

4.3. Reliability and Maintainability Analysis

Reliability characteristics are estimated using best fit distribution. Table 4.4 presents reliability at the end of warranty period (i.e. one year), reliability based maintenance intervals for different reliability levels, mean time to failure (MTTF) and mean time to repair (MTTR) of all thirty three components. The equations used for estimating reliability characteristics are tabulated in Appendix I. All the components of the CNC turning center are functionally arranged in a series configuration. It means that the CNC turning center is in the state of working only when all the components are in the state of working. The reliability of the CNC turning center (R_s), as a whole, can be calculated by Eq. (4.1).

$$\mathrm{Rs} = \prod_{i=1}^{33} \mathrm{Ri} \qquad \ldots 4.1$$

It can be seen that the reliability of the components such as spindle motor, spindle motor cooling fan, spindle belt, drawbar, spindle bearing, oil seals, hydraulic hose, solenoid valve, tool holder, lubrication pump motor system, lubrication hose, coolant pump motor system, coolant hose, supply cables and drive battery is very low. Hence for these components, it is recommended to carry out preventive maintenance. For remaining eighteen components, corrective maintenance is suggested. Therefore, system reliability is calculated by excluding these components. The system reliability at the end of warranty period is

$$\mathrm{R_s} = 1 \times 1 \times 0.9 \times 1 \times 1 \times 0.98 \times 0.98 \times 1 \times 1 \times 1 \times 0.99 \times 0.99 \times 0.85 \times 0.99 \times 0.91 \times 0.88 \times 0.93 \times 0.99$$

$R_s = 0.53$

MTTF of hydraulic vane pump is 13580 hours. This is the lowest MTTF among all the components which are recommended for corrective maintenance. Therefore, the system mean time between failure (MTBF) will be less than the minimum MTBF among all the components.

Therefore, System MTBF= 13000 hours.

Table 4.4 Results of reliability and maintainability analysis

Sr. No.	Component	Reliability R(1 year)	Reliable life at different reliability 't_R'(hrs)			MTTF	MTTR
			0.9	0.75	0.5		
1	Spindle motor	0.61	3576	6412	10691	11793	11.2
2	Spindle motor cooling fan	0.23	946	1348	3169	7227	2.4
3	Spindle belt	0.33	1591	2130	4592	11389	3.6
4	Spindle bearing	0.75	5288	8335	12413	12979	63.6
5	Drawbar	0.11	1552	2366	3781	4814	9.6
6	Spindle pulley	1	22652	26498	31542	32612	12
7	Hydraulic motor	1	18694	22680	27854	28420	4.5
8	Hydraulic vane pump	0.9	8763	10918	13493	13580	4.5
9	Oil seals	0.68	877	6860	13507	13507	9.4
10	Hydraulic hose	0.36	5087	5482	7018	10253	1.5
11	Solenoid valve	0.67	6750	7065	8028	9371	2.0
12	Hydraulic tank	1	39733	44604	50720	51649	6.5
13	Thrust Bearing	1	12746	15317	18785	19666	10.2
14	Ball Bearing	0.98	11645	14893	18500	18500	11.1
15	Turret Slide	0.98	11437	14925	18800	18800	11
16	Slide Cover 'L' Plate	1	23941	27321	30669	30233	16.0
17	Tool Holder	0	852	1315	1829	1829	4.7
18	LPMS	0.40	1922	3487	6757	10931	2.9
19	Lubricant hose	0.71	4795	7959	12404	13228	1.5
20	Lubricant tank	1	40833	46281	53192	54337	8
21	CPMS	0.47	1919	4167	8216	10077	2.6
22	Coolant hose	0.23	1645	3118	5444	6166	1.5
23	Coolant tank	1	36126	43614	51433	50772	8.0
24	'X' Axis Servo motor	0.99	22372	28615	35400	35063	14.5
25	'Z' Axis Servo motor	0.99	20089	25615	31688	31444	14.5
26	Drive card	0.85	2105	14869	29050	29050	1.0
27	Supply cables	0.89	7193	8462	11155	12998	4.1
28	Drive Battery	0.24	2510	2877	4104	6105	2.2
29	Swarf conveyor	0.99	17049	22020	27549	27384	2.5
30	Control panel	0.91	7642	11563	16617	17137	3.0
31	Panel cooling fan	0.88	6249	11484	17300	17300	2.5
32	Door rollers	0.93	8950	14247	20133	20133	2.5
33	Toughen Glass	0.99	20794	27873	35400	34882	1.5

The approach of scheduled maintenance is based on the concept that every component of the CNC turning center has an age at which maintenance is required to ensure safety and operating reliability. The probability distribution model is used to predict the failure behaviour of the components and to find the preventive maintenance interval that will achieve the desired level of operational reliability of the CNC turning center. The maintenance intervals that would achieve different reliability levels in operation are calculated. The reliable life for different reliability value, e.g. 0.90, 0.75 and 0.50, are also calculated. For example, to achieve 90% reliability (R = 0.90) for the spindle motor, maintenance should be carried out before 3238 hours, because after the machine has run for 3238 hours without failure there is a 0.9 probability that it will not fail. The reliability-based time intervals are calculated on the basis of the operating characteristics. However, the maintenance interval estimated for each component and some critical faults is too short for practical implementation. Therefore, the maintenance interval advocated for a 75% reliability level may be adopted initially and then, after observation of the benefits obtained in terms of cost, safety and operational effectiveness of the CNC turning center may be adjusted to a higher value of reliability.

5. Life Cycle Cost Analysis

This section presents LCC analysis of CNC turning center. A CNC turning center has a life of 12 to 15 years. In this case study, the life of the CNC turning center is considered as 12 years. Over the life, CNC turning center comes across the various cost elements such as initial investment costs, installation and commissioning costs, energy costs, operation costs, downtime and lost production costs, maintenance and repair costs, environmental costs and disposal costs. In the paper, all the cost components associated with the CNC turning center have been determined and categorized under different headings such as acquisition costs, operation costs, failure costs, support costs and net salvage costs.

5.1. Acquisition cost

The acquisition cost of the CNC turning center includes management cost, engineering design and manufacturing, material costs, production costs, engineering data, spare parts and logistics, initial training and service during warranty period. The estimated annual acquisition cost per unit is,

Acquisition cost per unit, C_u= $ 21200

5.2. Operating costs

The working hours of CNC turning center are considered as 7320 per year. There are total eight motors used: one for driving spindle, second for 'X' axis drive and third for 'Z' axis drive, fourth for cooling system and fifth for hydraulic pumping system, sixth for lubrication system, and seventh and eights for motors for panel cooling fan. The cost of energy per kWh is assumed as $ 0.09. Tooling cost, cost of hydraulic oil, lubricants and coolant are also considered under operating costs. Therefore, the annual operating cost is estimated as the sum of cost associated with the electricity consumption, hydraulic oil, lubricants, and coolant.

Annual operating cost per unit, C_o = $ 13231

5.3. Failure costs

All the components follow the best fit distribution and using the best fit distribution, the MTTF is estimated for all the components. The cost associated with the corrective maintenance is considered as failure costs. It includes labor costs, part costs and logistic costs. The labor charges for repair are considered as \$ 10 per hour. Table 5.1 shows an estimation of annual failure cost. Therefore, the annual failure cost is estimated as below,

Total failure cost = annual failure costs x Life of CNC turning center = 3607 x 12 = \$ 43284

The expected number of failure events over the life = t_d / MTBF = 12*7320/ 13000 = 6.75 ≈ 7

Cost per failure = C_f = 43284 / 7 = \$ 6184

Table 5.1 – Failure cost estimation

Component	MTTF	Failures/ year	Repair hours	Activity cost, \$/ hr	Labour cost \$	Part's cost, \$	Logistics costs, \$	Total cost \$/ year
1	**2**	**3**	**4**	**5**	**3*4*5=6**	**7**	**8**	**6+7+8**
Spindle pulley	32612	0.22	12	8	21	14	2	37
Hydraulic motor	28420	0.26	4.5	8	9	12	2	23
Hydraulic vane pump	13580	0.54	4.5	8	19	58	9	86
Hydraulic tank	51649	0.14	6.5	8	7	26	4	37
Thrust Bearing	19665	0.37	10	8	30	3	1	34
Ball Bearing	18500	0.4	11	8	35	4	1	39
Turret Slide	18800	0.39	11	8	34	1200	180	1414
Slide Cover 'L' Plate	30233	0.24	16	8	31	15	2	48
Lubricant tank	54336	0.13	8	8	8	5	1	14
Coolant tank	50771	0.14	8	8	9	5	1	15
'X' Axis Servomotor	35062	0.21	14.5	8	24	194	29	247
'Z' Axis Servomotor	31444	0.23	14.5	8	27	212	32	271
Drive card	29050	0.25	1	8	2	192	29	223
Swarf conveyor	27384	0.27	2.5	8	5	83	12	101
Control panel	17137	0.43	3	8	10	827	124	961
Panel cooling fan	17300	0.42	2.5	8	8	16	2	27
Door rollers	20133	0.36	2.5	8	7	13	2	22
Toughen glass	34882	0.21	1.5	8	3	3	0	6
Total								3607

5.4. Support costs

The cost associated with preventive maintenance is considered as support costs. The annual preventive maintenance costs may comprise the labor cost associated with the preventive maintenance and the cost of components that are replaced during preventive maintenance. In addition, there is a fixed support cost of documentation required in regard to the maintenance practices. Fixed support cost is assumed as \$ 50. The labour cost associated with the preventive maintenance is estimated based on two assumptions. They are the preventive maintenance is carried out by a crew of three technicians and the labour rate is \$ 8 per hour. The annual mean maintenance hour is 20. Table 5.2 shows estimation of annual support cost.

Table 5.2 – Support cost estimation

Component	Cost per unit (C_i)	Frequency per year (f_{pi})	$C_i \times f_{pi}$
Spindle motor	3077	0.63	1938
Spindle motor cooling system	154	1.01	155
Spindle Belt	18	0.64	12
Drawbar	12	1.52	19
Spindle Bearing	3462	0.56	1938
Oil seals	23	0.54	12
Hydraulic hose	46	0.71	33
Solenoid Valve	185	0.78	144
Tool Holder	46	4	185
LPMS	154	0.67	103
Lubricant hose	23	0.55	13
CPMS	123	0.73	90
Coolant hose	18	1.19	22
Supply cables	31	0.56	17
Drive Battery	31	1.2	37
		Total	4718

Therefore, annual preventive maintenance cost = 20 × 8 = \$ 160

The annual preventive maintenance cost = 4718+ 160 = \$ 4878

Therefore, annual support cost per unit, C_s = fixed support cost + annual support cost

= 50 + 4878

= \$ 4928

5.5. Net salvage value

At the end of useful life of the CNC turning center, the machine is scrapped.

Therefore, the net salvage value, S = \$ 1500

5.6. Estimation of LCC

LCC models are used to compute the LCC of the engineering systems. Several LCC models are available in the published literature. The model used here have five elements as: acquisition costs, operating costs, failure costs, support costs and net salvage value.

LCC = Acquisition costs + Operating costs + Failure cost + Support costs – Net salvage value

Where,

Net salvage value = Salvage value – Disposal cost

More explicitly,

$$LCC = C_u.N + [F_o + P_A (i, t_d) C_o.N + [P_A (i, t_d) C_f. t_x / MTTF.N] + [F_S + P_A (i, t_d) C_s.N] - [P_F (i, t_d) S.N] \quad ...5.1$$

Where, $P_F (i,t_d)$ = the future amount at the end of year's t_d and is given by Eq. (5.2):

$$P_F (i, t_d) = 1 / (1 + i)^{td} \quad ...5.2$$

Assuming an interest rate of 12 percent and design life of the CNC turning center as 12 years the single present value factor becomes,

$$P_F (i, t_d) = 1/ (1+0.12)^{12} = 0.2567$$

The annuity factor converts equal annual payments over t_d years to a single present day equivalent amount. For an interest rate of 12% and an economic life of 12 years, it can be calculated as,

$$P_A (i,t_d) = [(1 + i)^{td} - 1] / [i (1 + i)^{td}] \quad ...5.3$$

$$= [(1 + 0.12)^{12} - 1] / [0.12 * (1 + 0.12)^{12}]$$

$$= 6.1944$$

The fixed cost of operating is taken as zero and the number of units to be procured is one. The LCC can be estimated by substituting the values of components of LCC Eq. (5.1).

$$LCC= 21154 + [0 + 6.1944 \times 13231] + [6.1944 \times 6184 \times 7320 / 13000] + [50 + 6.1944 \times 4928] – 0.2567 \times 1500$$

$$= 21154 + 81958 + 21569 + 30576 – 385$$

$$LCC= \$ 154872$$

The results of LCC analysis are tabulated in Table 5.3. The detailed LCC analysis is useful for the identification of critical components as well as critical cost of elements/ segment. These critical components are spindle motor, spindle motor cooling fan, spindle belt, drawbar, spindle bearing, oil seals, hydraulic hose, solenoid valve, tool holder, lubrication pump motor system, lubrication hose, coolant pump motor system, coolant hose, supply cables, drive battery.The acquisition cost is almost 14% of the total LCC. Most of the cost is associated with operating cost, failure cost and support cost and contributes almost 87%.

Table 5.3 – Results of life cycle cost of the CNC turning center

Sr. No.	Cost of element / segment	Cost ($)	% of LCC
1	Acquisition cost	21154	13.66
2	Operating cost	81958	52.92
3	Failure cost	21569	13.93
4	Support cost	30576	19.74
5	Net salvage value	-385	-0.25
6	Life cycle cost	154872	100.00

6. Life Cycle Cost Optimization

Certain design modifications and better maintenance policies are suggested and implemented for improving reliability and optimizing LCC. These measures are suggested based on design calculations, selection of better components, reliability centered maintenance policies and discussion with experts. This section presents reliability improvement suggestions, estimation of improved reliability and LCC.

6.1. Reliability Improvement Suggestions

The reliability of spindle belt is low. To improve reliability, the spindle belt having life 15000 hours is suggested. Similarly, spindle bearing having life of 16000 hours is recommended. During maintenance, it is suggested to check alignment of drawbar assembly and routine inspection is suggested in order to improve life. The life of the cutting tool (insert) is found to be less than the design life. Interrupted and discontinuous coolant supply during machining operation is major cause of cutting tool failure. It is also suggested to select the tool carefully. At the time of preventive or corrective maintenance, the coolant, lubricant and hydraulic piping connections should be checked. If these precautions were taken, then there would be no such problem during useful life.

Water/oil contamination in the spool leads to failure of the valves. It is expected to use specified filter and replace it at regular intervals. Unnecessary force applied by the operator damage the switches and push buttons of the control panel. It is found that, most of the accidents and failures are occurred due to faults of the operator and maintenance personnel. Hence, proper training and instruction ware given to them.

Mains voltage fluctuations and abnormal environment harms the CNC turning center, accelerates the ageing and shorten the life of components. The users of CNC turning center should minimize harmful effects from field environmental factors like dust, high temperature, voltage fluctuations and humidity. Meanwhile, the user should carryout machine attendance regularly and corresponding preventive maintenance to extend the service life and defer the advent of wear out failure period.

6.2. Preventive maintenance policy based on RAM analysis

Components of the CNC turning center deteriorate with usage and fail. In order to ensure the reliability, appropriate maintenance policy should be formed and maintenance is to be carried out accordingly. There are generally two kinds of methods of preventive maintenance of CNC turning center: one is routine inspection and the other is regular inspection. The goal of routine inspection is mainly used to examine whether there is enough lubricating oil, enough coolant liquid and whether bolts, key connections and spindle belt are loosened and whether there are leakage of oil. Table 6.1 gives the list of the testing parts and testing items. There is regular inspection besides routine inspection for a CNC turning center. The regular inspection of CNC turning center mainly includes spindle servo-motor inspection, lubrication subsystem inspection and hydraulic subsystem. Table 6.2 shows the regular inspection items and inspection interval.

Table 6.1- Routine inspection items

Testing part	Testing items
Oil level gauge of the lubricate parts	• If there is enough oil • If the oil is contaminated
Surface of coolant liquid	• If the amount of the coolant liquid is fit • If the coolant liquid is obviously contaminated • If the filter is clogged
Guide ways	• If there is enough lubricating oil • If the scratch chip board damages
Pressure gauge	• If the pressure is proper
Spindle belt	• If the tension is proper • If there are cracks and scratches
Pipe and appearance	• If there is the leakage of the hydraulic oil • If there is the leakage of the coolant liquid • If there is the leakage of the lubricant
The moving parts	• If there are noise and vibrations • If the parts move smoothly
Control panel	• If the functions of the switch and handle are normal • If it displays alarm
Electric wire	• If there is a disconnection • If the insulated coat is wearing out
Rotating part	• If there are noise and vibrations • If there is abnormal heat
Cleaning	• Clean the surface of the chuck, Guide ways and chip machines
Work piece	• If the machining center keeps the machining accuracy under the control

Table 6.2- Regular inspection items

Testing part		Testing items	Period
Hydraulic subsystem	Hydraulics	• Change the oil, clean the filters	6 months
	Pipe joints	• Testing the leakage of the oil	6 months
Lubrication subsystem	Lubrication devices	• Clean the filters	6 months
	Pipe	• Testing if there are the leakage, blockage and damage of pipes	6 months
Coolant subsystems	Filter	• Clean the chips plate	Depends on the situation
	Chips plate	• Change the coolant liquid, clean the filters and water tank	
Spindle belt	Belt	• Test the tension	6 months
	Pulley	• Clean the pulley	1 months
Spindle Servo-motor	Sound, vibration & temperature rise	• Test the abnormal noise of the bearing	6 months
		• Clean the air filters	1 months

Testing part		Testing items	Period
Servo motor of X and Z axis	Sound and temperature rise	• Test the abnormal noise of the bearing & abnormal temperature rise	1 months
Clamping system	Clamp devices	• Disassemble the clamp and clean it	1 year
	Cylinder	• Test the leakage of the cylinder	3 months
Control Panel	Electrical devices	• Test if there is odors, change color and damages of the interface	6 months
	Connecting screws	• Clean the connection screws	1 months
Electric subsystem	Limit switches	• Test and fastening connection screws again	6 months
	Sensor, Magnetic valve	• Test the function and activity of electric devices	1 months
X and Z axis	Clearance & Backlash	• Measure the clearance and backlash by dial gage	6 months
Base	Level of base	• Test and adjust the level of base by dial gage	1 year
Tool holder	Tool holder	• Test the origin of tool and adjust it	1 months

6.3. Spare estimation

Spares are expected to cover actual item replacements occurring as a result of corrective and preventive maintenance. They should compensate for repairable item in the process of undergoing maintenance. Spare should recompense the procurement lead times required for replacement item acquisition and also compensate for the condemnation of repairable items. Reliability tool is used here to optimize the LCC of the system through estimating spare requirements. The Poisson process is used for the estimation of spares. The spare requirements during warranty period is estimated and presented in **Table** 6.3.

$$R_S(t) = \sum_{n=0}^{S} \frac{e^{-\lambda t}(\lambda t)^n}{n!} \quad \ldots 6.1$$

Table 6.3 Spares estimation

Sr. No.	Component	Spares estimation during warranty period (for 90% confidence)	Sr. No.	Component	Spares estimation during warranty period (for 90% confidence)
1	Spindle motor cooling fan	1	8	Ball Bearing	1
2	Spindle belt	1	9	Tool Holder	2
3	Drawbar	2	10	Lubricant hose	1
4	Oil seals	4	11	CPMS	1
5	Hydraulic hose	1	12	Coolant hose	1
6	Solenoid valve	1	13	Drive Battery	1
7	Thrust Bearing	1	14	Door rollers	2

6.4. Improved Reliability and MTBF

An effective implementation of above suggested measures has improved reliability of components and system reliability. Table 6.4 shows the approximate improvement in reliability, MTBF and MTTR of components.

Improved system reliability R_s at the end of the warranty period and change in system reliability are:

$$R_s = 1 \times 1 \times 1 \times 1 \times 1 \times 1 \times 1 \times 1 \times 1 \times 1 \times 1 \times 1 \times 0.98 \times 1 \times 1 \times 1 \times 1 \times 1$$

Rs = 0.98

Change in system reliability = Improved system reliability – Earlier system reliability

= 0.98 – 0.53 = 0.45 (84.90% increase)

The improved MTBF of the system will be approximately as given below,

Improved system MTBF = 17000 hours.

Table 6.4 – Improved reliability, MTBF and MTTR

Sr. No.	Component	Earlier reliability R(1)	Improved reliability R(1)	Earlier MTTF (Hours)	Improved MTTF (Hours)	Earlier MTTR	Improved MTTR
1	Spindle motor	0.64	0.9	11609	20000	11.2	08
2	Spindle motor cooling fan	0.23	0.6	7227	10000	2.4	2
3	Spindle belt	0.33	0.95	11389	15000	3.6	2.5
4	Spindle bearing	0.75	0.95	12979	16000	63.6	40
5	Drawbar	0.11	0.5	4814	8000	9.6	8
6	Spindle pulley	1	1	32612	45000	12	05
7	Hydraulic motor	1	1	28420	35000	4.5	4.5
8	Hydraulic vane pump	0.9	1	13580	18000	4.5	4.5
9	Oil seals	0.68	0.8	13507	16500	9.4	08
10	Hydraulic hose	0.36	0.75	10253	13000	1.5	1.5
11	Solenoid valve	0.67	0.8	9371	11000	2.0	2
12	Hydraulic tank	1	1	51649	60000	6.5	6
13	Thrust Bearing	1	1	19666	25000	10.2	10
14	Ball Bearing	0.98	1	18500	25000	11.1	10
15	Turret Slide	0.98	1	18800	29280	20.9	15
16	Slide Cover 'L' Plate	1	1	30233	43560	16.0	15
17	Tool Holder	0	0.6	1829	5000	4.7	4.7
18	LPMS	0.40	0.9	10931	20110	2.9	3
19	Lubricant hose	0.71	0.88	13228	35000	1.5	1.5
20	Lubricant tank	1	1	54337	60000	8	8
21	CPMS	0.47	0.7	10077	20120	2.6	2.6
22	Coolant hose	0.23	0.75	6166	15000	1.5	1.5
23	Coolant tank	1	1	50772	60000	8.0	8.0
24	'X' Axis Servomotor	0.99	1	35063	35063	14.5	12
25	'Z' Axis Servomotor	0.99	1	31444	35000	14.5	12
26	Drive card	0.85	0.98	29050	40000	1.0	1
27	Supply cables	0.89	0.97	12998	20000	4.1	4
28	Drive Battery	0.24	0.65	6105	12000	2.2	2
29	Swarf conveyor	0.99	1	27384	32000	2.5	2.5
30	Control panel	0.91	1	17137	29280	3.0	3
31	Panel cooling fan	0.88	1	17300	30000	2.5	2.5
32	Door rollers	0.93	1	20133	29150	2.5	2.5
33	Toughen Glass	0.99	1	34882	41000	1.5	1.5

6.5. Improved LCC

In this section, improved LCC based reliability improvement methods are presented. Many reliability improvement methods are suggested in such a way that they hardly increase acquisition cost. The acquisition cost of the CNC turning center is increased by almost $ 54 on account of reliability improved measures.

Improved acquisition costs per unit = $ 21208

With proper supply of coolant to the machining operations and other measures increased life of the tools considerably. The improved annual operating cost is:

Improved annual operating costs per unit = $ 11079

Table 6.5 gives improved failure cost.

Table 6.5 – Failure cost estimation

Component	**MTTF**	**Failures/ year**	**Repair hours**	**Activity cost, Rs./ hr**	**Labour cost Rs.**	**Part's cost, Rs.**	**Logistics costs**	**Total cost Rs./ yr**
1	**2**	**3**	**4**	**5**	**3*4*5=6**	**7**	**8**	**6+7+8**
Spindle pulley	45000	0.16	5	8	6	10	2	18
Hydraulic motor	35000	0.21	4.5	8	8	10	1	19
Hydraulic vane pump	18000	0.41	4.5	8	15	44	7	65
Hydraulic tank	60000	0.12	6	8	6	23	3	32
Thrust Bearing	25000	0.29	10	8	23	3	0	26
Ball Bearing	25000	0.29	10	8	23	3	0	26
Turret Slide	29280	0.25	10	8	20	769	115	905
Slide Cover 'L' Plate	43560	0.17	15	8	20	10	2	32
Lubricant tank	60000	0.12	8	8	8	5	1	13
Coolant tank	60000	0.12	8	8	8	5	1	13
'X' Axis Servomotor	35063	0.21	12	8	20	193	29	242
'Z' Axis Servomotor	35000	0.21	12	8	20	193	29	242
Drive card	40000	0.18	1	8	1	141	21	163
Swarf conveyor	32000	0.23	2.5	8	5	70	11	86
Control panel	29280	0.25	3	8	6	481	72	559
Panel cooling fan	30000	0.24	2.5	8	5	9	1	16
Door rollers	29150	0.25	2.5	8	5	9	1	16
Toughen glass	41000	0.18	1.5	8	2	3	0	5
Total								2477

The failure cost per year = $ 2477. Therefore, the total failure cost over the life becomes,

Total failure cost =2477 * 12 = $ 29724

The expected number of failure events over the life = t_d / MTBF = 12*7320/ 17000 =5.17(06 say)

Cost per failure = C_f = 29724 / 6 = $ 4954

Thus the improved cost per failure will be $ 4954.

Table 6.6 shows improved support cost estimation. Improved annual mean maintenance hour is 15 hours.

Therefore, improved annual preventive maintenance cost = 15 × 8 = $ 120

The annual preventive maintenance cost = 3234+ 120 = $ 3354

Therefore, annual support cost per unit, C_s = fixed support cost + annual support cost

= 50 + 3354 = $ 3404

Thus, there is a significant cost saving is obtained in annual support cost.

Table 6.6 – Support cost estimation

Component	**Cost per unit (C_i)**	**MTBF**	**Frequency per year (f_{pi})**	**$C_i \times f_{pi}$**
Spindle motor	3077	20000	0.37	1138
Spindle motor cooling system	154	10000	0.73	112
Spindle Belt	18	15000	0.49	9
Drawbar	12	8000	0.92	11
Spindle Bearing	3462	16000	0.46	1592
Oil seals	23	16500	0.44	10
Hydraulic hose	46	13000	0.56	26
Solenoid Valve	185	11000	0.67	124
Tool Holder	46	5000	1.46	67
LPMS	154	20110	0.36	55
Lubricant hose	23	35000	0.21	5
CPMS	123	20120	0.36	44
Coolant hose	18	15000	0.49	9
Supply cables	31	20000	0.37	11
Drive Battery	31	12000	0.61	19
Total				3234

There is no change in the net salvage value. Therefore,

Net salvage value, S = $ 1500

Improved LCC is estimated by using Eq.(4.2),

Improved LCC = 21208 + [0 + 6.1944 × 11079] + [6.1944 × 4954× 7320 / 17000] + [50 + 6.1944 × 3404] – 0.2567 × 385

= 21208 + 68628 + 13214 + 21136 – 385

Improved LCC = $ 123801

Comparison of earlier and improvement LCC, each cost elements and cost saving are presented Table 6.7.

Table 6.7 – Improved LCC and cost savings

Sr. No.	Cost of element / segment	Earlier cost ($)	Improved cost ($)	Savings ($)	Cost savings (%)
1	Acquisition cost	21154	21208	-54	-0.03
2	Operating cost	81958	68628	13330	16.26
3	Failure cost	21569	13214	8355	38.74
4	Support cost	30576	21136	9440	30.87
5	Net salvage value	-385	-385	00	00
6	Life cycle cost	154872	123801	31071	20.06

7. Conclusions

Reliability and life cycle cost of the CNC turning center is presented in this paper. CNC turning center consists of many components which decide system reliability. Time-to-failure and time to repair data are used to estimate system reliability, reliability based maintenance intervals, MTTF and MTTR. Critical components are identified using reliability, maintainability and life cycle cost analysis. The analysis shows that the spindle bearing, spindle belt, spindle drawbar, insert, tool holder, drive battery, hydraulic hose, lubricant hose, coolant hose and solenoid valve are the components with low reliability. With certain design changes and implementation of reliability based maintenance policies system reliability is improved, especially during warranty period. The reliability of the CNC turning center is improved by nearly 45% at the end of warranty period and system MTBF is increased from 15000 hours to 17000 hours. The life cycle cost analysis shows that the acquisition cost of the CNC turning center is 14% of the total life cycle cost. Maintenance cost, operating cost and support costs dominates the LCC and contribute almost 87% of the total LCC. Hence, it is concluded that the initial cost of the CNC turning center should not be the only criteria of procurement. The reliability improvement methods increased the initial cost by only 0.25%; but the total LCC is reduced by almost 20%. Operating costs, failure costs and support costs are redued by 16%, 39% and 31% respectively.

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Appendix I

Distribution	Reliability function	MTTF/ MTTR
Weibull 2P	$R_{(t)} = e^{-(\frac{t}{\theta})^{\beta}}$	$MTTF/\ MTTR = \theta\Gamma(1+\frac{1}{\beta})$
Weibull 3P	$R_{(t)} = e^{-(\frac{t-t_0}{\theta})^{\beta}}$	$MTTF/\ MTTR = t_0 + \theta\Gamma(1+\frac{1}{\beta})$
Normal	$R_{(t)} = \int_{t}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} \exp[-\frac{1}{2}\frac{(t^{'}-\mu)^2}{\sigma^2}]dt^{'}$	$MTTF/\ MTTR = \mu$
Log-normal	$R_{(t)} = \int_{\ln t}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} \exp[-\frac{1}{2}\frac{(t^{'}-\mu')^2}{\sigma'^2}]dt^{'}$	$MTTF/\ MTTR = e^{\mu'} + \frac{1}{2}\sigma'^2$
Exponential 2P	$R_{(t)} = e^{-\lambda(t-t_0)}$	$MTTF/\ MTTR = t_0 + \frac{1}{\lambda}$

Abbreviations

ABC - Activity based costing

CNC - Computerized numerical control

CPMS – Coolant pump motor system

DOF - Degree of freedom

HPP - Homogeneous Poisson process

iid - Independent and identically distributed

K-S - Kolmogorov-Smirnov

LCC - Life cycle cost

LPMS – Lubricant pump motor system

L-R - Lewis-Robinson

MTBF – Mean time between failure

MTTF – Mean time to failure

MTTR - Mean time to repair

NHPP - Non-homogeneous Poisson process

RP - Renewal process

TTF – Time-to-failure

TTR – Time-to-repair

Notations

β – Shape parameter of Weibull 2P or 3P distribution

θ – Scale parameter of Weibull 2P or 3P distribution

γ – Location parameter of Weibull 3P distribution

μ' – log-mean of log-normal distribution

σ' – log-standard deviation of log-normal distribution

μ – Mean of normal distribution

σ – Standard deviation of normal distribution

λ – Failure rate or hazard rate

t_0 – location parameter of exponential 2P distribution

R_s – Reliability of CNC turning center

R_i - Reliability of the i^{th} components

t – Reliable life in hours

C_u - Acquisition costs per unit

C_o – Annual operating costs per unit

t_d - Life of CNC turning center

C_f - Cost per failure

C_i - Cost per unit

F_{pi} - Frequency per year

C_s – Annual support cost per unit

S – Net salvage value

N - Number of machines to be procured

F_o = Fixed operating cost

F_S = Fixed support cost

t_x = Operating hours per unit per year,

t_d= Design life in years,

t_x/ MTTF - The expected number of failures per year

P_F (i,t_d) = the future amount at the end of year's t_d

P_A (i,t_d) = Annuity factor