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Selection of time-to-failure model for computerized numerical control turning center based on the assessment of trends in maintenance data

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Abstract

This article provides a generalized framework for selection of time-to-failure model based on the assessment of trends in failure and repair time data. This framework is based on modifications of existing frameworks and can be applied for binary as well as multi-state systems. The proposed framework is applied for reliability analysis of a computerized numerical control turning center. For analysis purpose, the failure data are collected for 50 computerized numerical control turning center over a period of 7 years for three different working conditions, that is, when machining material is steel, aluminum and cast iron. The data collected are then processed using the proposed framework and the best-fit distribution is found for the time-to-failure data. Furthermore, the reliable life and reliabilities of the different sub-systems are estimated. From the analysis, it is found that spindle system, computerized numerical control system, electrical and electronic system, hydraulic system and cooling system are found to be critical from reliability and maintainability point of view. The analysis presented here is expected to help the users and manufacturers of computerized numerical control turning center to estimate the reliability in accurate manner.

Keywords

Computerized numerical control turning center, reliability analysis, best-fit distribution, trend tests

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Introduction

Computerized numerical control (CNC) turning centers are the special purpose machine tools with a high level of automation and complicated structure. CNC turning centers have become the heart of manufacturing industries due to their accuracy, inherent flexibility and productivity.[1,2] The failure of such complicated structure may cause the production line or even the whole workshop to stop functioning. The repairs are difficult and expensive when an unexpected failure occurs.[3] It is difficult to prevent failures, but they can be predicted and probability of occurrence can be minimized. In this context, reliability, maintainability and availability of CNC turning centers are crucial especially whenever it is a part of mass production system.[4,5] Therefore, it is required to identify critical failure modes, components and sub-systems by analyzing field failure data.[6] System reliability can be improved by design modifications and developing proper maintenance strategy.

Reliability, maintainability and availability techniques have been gradually accepted as tools for the planning and operations of automatic and complex systems such as CNC turning center.[7,8] It is also seen that the operation and maintenance costs are major contributors to life cycle cost (LCC) of most of repairable systems and contribute up to 60% of LCC.[9,10] The LCC can be optimized by implementing preventive and predictive maintenance strategy effectively. Equipment parameter checks, oil replacement or refill, lubrication

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and partial or complete overhauls at specified periods are the preventive and predictive maintenance strategies. Reliability study also helps to minimize unplanned maintenance as it is responsible for considerable production loss.

In this article, reliability analysis of two CNC turning center models, say $CNCTC_1$ and $CNCTC_2$, is presented. The analysis of $CNCTC_1$ and $CNCTC_2$ is carried out for three different machining materials: steel, aluminum and cast iron. This CNC turning centers are manufactured in India and typically used for machining of automobile components. The major objectives set were as follows:

- To study CNC turning center configuration and increase understanding of the nature of failure patterns;
- To develop a framework for time-to-failure (TTF) and time-to-repair (TTR) model selection based on the assessment of trends in maintenance data;
- To select best-fit distribution for a CNC turning center using proposed framework and estimate reliability characteristics in precise quantitative terms;
- To identify and discuss reliability characteristics for $CNCTC_1$ and $CNCTC_2$ with three different machining materials: steel, aluminum and cast iron;
- To identify critical sub-systems from reliability and maintainability point of view.

The structure of the article is as follows: section "CNC turning center configuration" gives the configuration of CNC turning center. An extensive literature survey is presented in section "Literature review," which gives reliability study of CNC-assisted systems and published frameworks of TTF model selection. Section "Development of framework for reliability analysis" discusses the proposed TTF model selection framework used for the analysis of CNC turning center. Section "Reliability analysis of CNC turning center" presents a case study describing the application of the proposed framework for reliability analysis of a CNC turning center. The quantitative results are also presented which identifies critical sub-systems from reliability and maintainability perspective. Finally, the significant conclusions are presented in section "Conclusion."

CNC turning center configuration

The configuration of a CNC turning center is given in Figure 1. It consists of 14 different sub-systems: main transmission (MT), spindle system (SS), chuck system (ChS), turret system (TS), X- and Z-axis system (XZAS), hydraulic system (HS), pneumatic system (PS), coolant system (CS), electrical and electronic system (EES), computerized numerical control system (CNCS), lubrication system (LS), swarf conveyor (SC), tail-stock system (TSS) and other system (OS). The

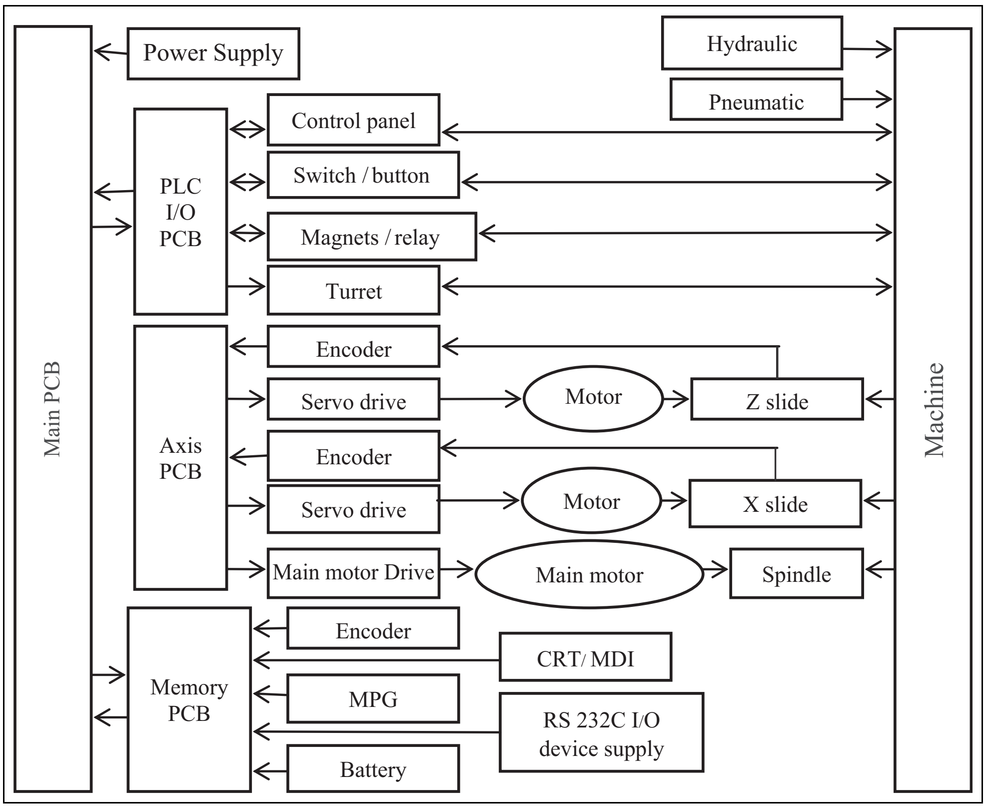

Figure 1. Configuration of CNC turning center.[1–4]

spindle is driven by a servomotor with step-less speed regulations through MT. The MT consists of servomotor and its cooling fan, pulley, shaft and belts. The SS includes spindle bearings, housing and spindle elements. The job clamping and de-clamping at chuck is carried out by drawbar through HS. Alternating current (AC) or direct current (DC) servomotors are used to drive X- and Z-axes through ball lead screws, and controlled simultaneously. The turret or tool-holder may change tools automatically. Most of the sub-systems are precisely controlled by CNC system.

CNC system is the heart of the CNC turning center. It consists of programmable logic control (PLC), printed circuit board (PCB), power supply. The input/output (I/O) PCB connects the control panel, buttons, limit switches, magnets, turret and other sub-systems. The axis PCB controls the slide axes and the spindle through semi-closed or closed-loop electronic control motor drive and photoelectric encoder. Memory PCB connects additional encoder, cathode ray tube (CRT), multiple document interface (MDI), manual pulse generator (MPG), backup battery and RS-232 serial communication device. There are some electronic components, such as relays, contactor switches, regulators and buttons, are fixed in a cabinet. Limit switches, proximity switches and encoders are located on the machine.

Literature review

Many reliability studies have been performed to study CNC-assisted systems such as lathes, machining centers, milling centers and band saw cutting machines.[11–15] Most of the reliability studies of CNC-assisted systems are carried out using specific reliability distribution and not by trend analysis or goodness-of-fit (GoF) tests. To predict reliability characteristics accurately, it is essential to select appropriate model for the analysis. Therefore, it is necessary to use various statistical tests for a better understanding of failures patterns and reliability modeling. It can also be used for decision-making process concerning planning of operation and maintenance activities.[14–17]

Several procedures have been proposed for the reliability modeling of repairable systems.[18–30] Sehgal et al.[20] suggested a procedure for the evaluation and selection of components such as rolling contact bearings for a given application considering reliability aspect, which is based on graph theory and matrix method. Pulido et al.[21] presented a comprehensive methodology using Bayesian approach for obtaining prior distribution in reliability and require only prior intervals for the mean and the standard deviations of TTF of the product. The proposed methodology has to be verified when sufficient reliability data are available in order to develop posterior distribution. Kim and Yum[22] carried out a comparative simulation study on selection between Weibull and log-normal distribution. Maximum likelihood and scale invariant procedures are compared and use complete as well as censored samples. Barabady and Kumar[23] presented a framework for reliability analysis of repairable system. χ^2 distribution has been used for trend analysis and Kolmogorov–Smirnov (K-S) test for best-fit distribution. Louit et al.[24] reviewed several tests available to assess the existence of trends and presented a framework for model selection to represent the failure process for a component or system. The model selection framework is directed toward the discrimination between the use of statistical distributions to represent the TTF (renewal approach), and the use of stochastic point process (repairable system approach), when there may be the presence of system aging or reliability growth.

Regattieri et al.[25] introduced a framework defining a general approach for failure process modeling (FPM). Lad and Kulkarni[26] estimated reliability of machine tool in the absence of field failure data. It uses the knowledge and experience of maintenance personnel to obtain the parameters of lifetime distribution of the repairable and non-repairable components/assemblies. Castet and Saleh[27] conducted a non-parametric analysis of satellite reliability for 1584 Earth-orbiting satellites. Barabadi[28] presented a case study using Weibull distribution for different components of power distribution system. Weibull probability plot (WPP) is found to be simple and highly relevant approach. Barabadi et al.[29] presented a case study estimating the number of spare parts required for an item. Proposed methodology focuses on selection of best-fit distributions and various factors such as operational environment, maintenance policy, operator skills. Bobrowski et al.[30] compared parametric, semi-parametric and non-parametric models. A new model selection procedure presented using GoF measure and it has been applied to all three types of regression models.

From the literature, it is observed that most of the data analysis frameworks are either specific or requires large number of tests to be conducted. Many of them are carried out under false premises such as by assuming system as binary state system. However, in actual practice, various degraded states (multi-states) should be considered. This article provides a simplified generalized framework for reliability and maintainability analysis. Proposed methodology discriminates binary and multi-state system analysis approaches and also gives clear idea for the use of Bayesian technique, non-parametric method or parametric method.

Development of framework for reliability analysis

In this section, a generalized framework for the analysis of TTF and TTR data of CNC turning center is proposed. Proposed framework can be used under various conditions and practical situations. Modeling of binary as well as multi-state system (MSS) is also possible.

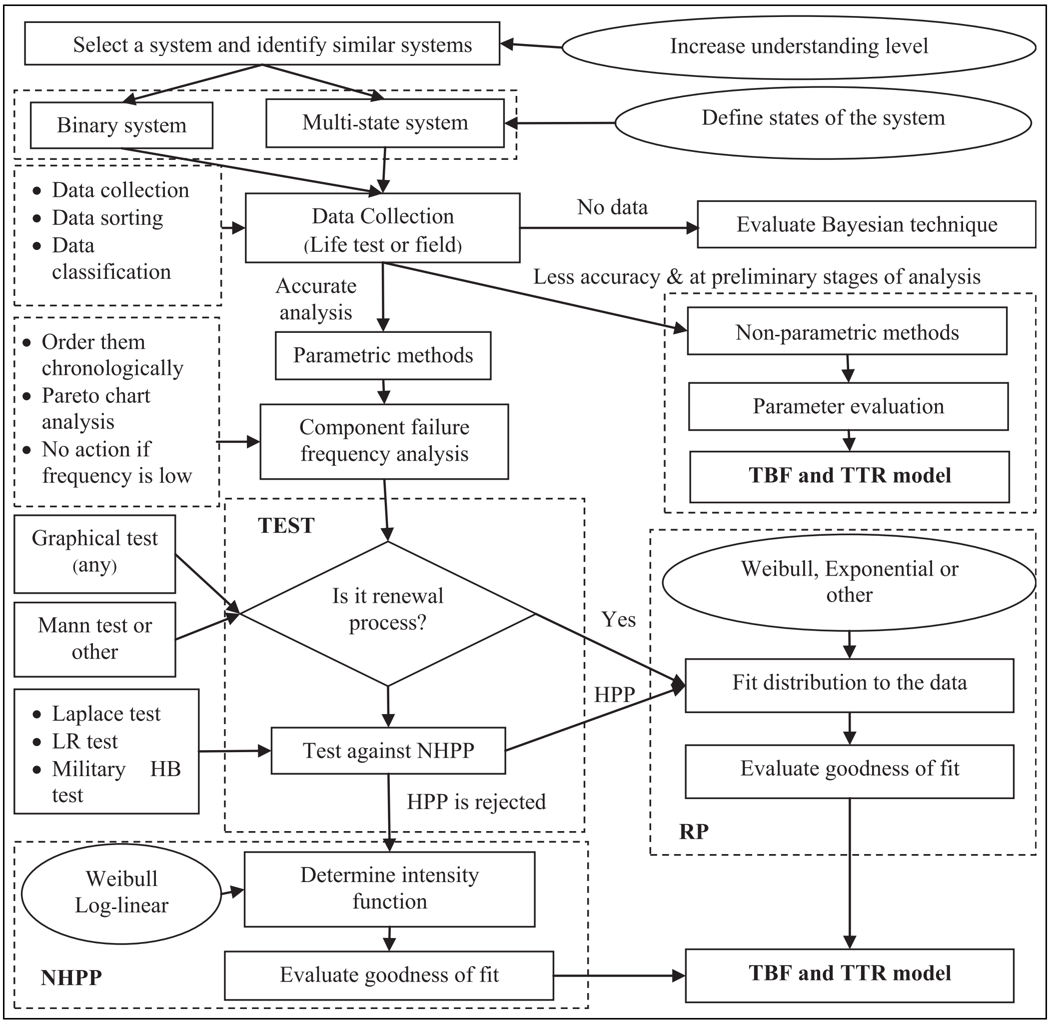

Figure 2. Generalized framework for time-to-failure and time-to-repair model selection.

Figure 2 shows the proposed generalized framework for selection of TTF model for repairable systems. The proposed framework is used for the analysis TTF and TTR data of CNC turning center.

Selection of the system and data collection

The first step involved in reliability analysis is the selection of a system. Reliability analysis require cost, time and expertise. Therefore, parameters such as type of product, necessity of analysis, level of safety and risk requirement and cost–benefit aspect should be considered while selecting the system. Subsequently, the whole system should be divided into different sub-systems, assemblies, sub-assemblies and components. A complex system may consist of large number of components. Therefore, Pareto analysis or analytic hierarchy process (AHP) can be used to identify critical components and sub-systems for further analysis.

The data collection is the basis of failure analysis. Field failure data, such as machine history cards, reports generated by service engineers, maintenance register and expert opinions can be used for Pareto analysis or AHP. Data generated from reliability testing can also be used. The maintenance reports should contain the information such as failure date and time, failure phenomenon, description of the failure cause, repair process and repair time, other information about machining center failure. The more detailed and truly the failure data are, the more accurate the analysis result is. The next step after data collection, sorting and analysis is to decide appropriate approach for data analysis. Several approaches for reliability analysis are presented and compared in section “Data analysis approach.”

Data analysis approach

Reliability analysis can be carried out using various approaches. Considering failures modes (complete or partial failures), binary and MSS analysis approach can be used. Again, based on the availability of the data, Bayesian, parametric and non-parametric methods can be used. This is discussed in sub-sequent sections.

Binary and multi-state system. Binary system analysis considers only two states of the system: functioning and faulty. Binary state system analysis is widely used due to its simplicity, ease for application and modeling.[31,32]

However, there are many systems, such as power generation units and manufacturing systems, whose overall performance can settle on different levels, for example, 100%, 90%, 50% of the total capacity. In the literature, such systems are referred to as multi-state systems.[33–35] Multi-state failure analysis introduces "degraded states" or "partial failures states" and thus provides more insight into the degradation behavior of an item, and its progression toward complete failure. Modeling of such systems is a challenging task; feasibility of the solution is also critical.[36–38]

Selection of approach based on the availability of the data. One major problem in reliability analysis is the lack of sufficient data.[39] The amount of information available in limited data sets is minor. Many data sets are for maintenance management rather than reliability study and therefore, careful scrutiny of such data is required.[40] Bayesian method provides optimal solution using standard models when lack of data is a problem.[41,42] Bayesian techniques can be used to model by incorporating all the prior information available: previous systems estimates; actual data from similar systems; information from reliability sources and expert judgment. The posterior distributions representing the failure process can be developed using newly gathered data. Special care should be taken while developing prior distribution.[43]

Parametric or non-parametric methods are used when sufficient data are available. Non-parametric methods are approximate and easy to use and reliability parameters are directly evaluated based on the definitions of each parameter without bothering about the distribution of the data. Kaplan–Meier, simple actuarial and standard actuarial are some of the non-parametric methods. The extrapolation of reliability characteristics in case of non-parametric methods is not accurate. Moreover, the confidence bounds are usually wider than those calculated via parametric analysis. Therefore, non-parametric methods may be used only during preliminary stages of reliability studies.[44] This method can also be used when none of the statistical distribution fits to the data.

Parametric methods are used for reliability analysis of a system precisely. In parametric methods, failure data are fitted to statistical distribution such as the Weibull, normal, exponential and/or log-normal. Advanced techniques such as GoF test are used for modeling the failure data. Software packages are available and can be used for choosing best-fit distribution. Parametric analysis gives a better understanding of the failure mechanisms and the resulting model can be used for analytical evaluation over the lifespan of the system. Sometimes, best-fit distribution is selected based on type of component or based on past experience and then distribution parameters are evaluated using the failure data.

Reliability analysis approach for repairable and non-repairable system is different.[45] In case of non-repairable system, the entire system is required to replace after failure. A repairable system is one which restored to working conditions after every failure by means of any method other than replacement of entire system. Repairable system analysis approach does not assume that time-between-failure (TBF) are independent and identically distributed (iid). Modeling of repairable systems does not use statistical distributions, but use stochastic point processes. The repairable systems reliability is modeled by various point processes (PP), such as the homogeneous Poisson process (HPP), non-homogeneous Poisson process (NHPP), renewal process (RP), generalized renewal process (GRP). To discriminate various point processes, trend testing methods are used. The required and popular trend testing methods are described in section "Trend testing techniques."

Trend testing techniques

A first step in model selection is the assessment of the existence of trend or time dependency in the data. Reliability study uses data which are collected over some period of time. The need of trend testing is a series of observations of such data. In statistical terms, this is a determination of whether the probability distribution from which they arise has changed over time. There are several trend testing techniques used for this task. The selection of proper test is described here.

Graphical methods. Several graphical tests are available for trend testing and should be selected according to situation. Some of them are described here. Timeline plotting is a method used to identify possible trend in the data at preliminary stage. Figure 3 shows three theoretical situations in relation to TTF of a particular system. For A, there is no clear trend; for B, system is said to be deteriorating as the time tends to get shorter and for C, the system is said to be improving as the time between arrivals tends to get longer.

Cumulative failure against time plot is another powerful tool.[44] Figure 4 shows generic plots expected with interpretation. This solution may not enough if there is a slight trend and analytical test should be performed.[18] Another limitation of this test that the assessment of trend is based on interpretation and interpretation may be wrong for large sample size. A complementary test to the cumulative failures against time plot is scatter plot of successive service lives (i.e. plotting the service

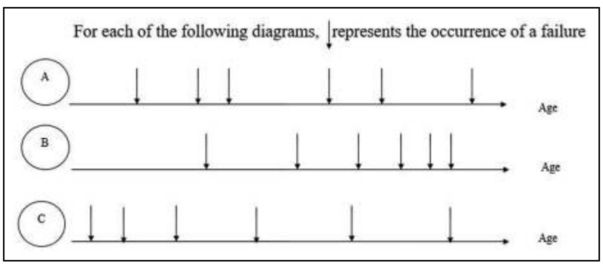

Figure 3. Possible trends in time between failures.

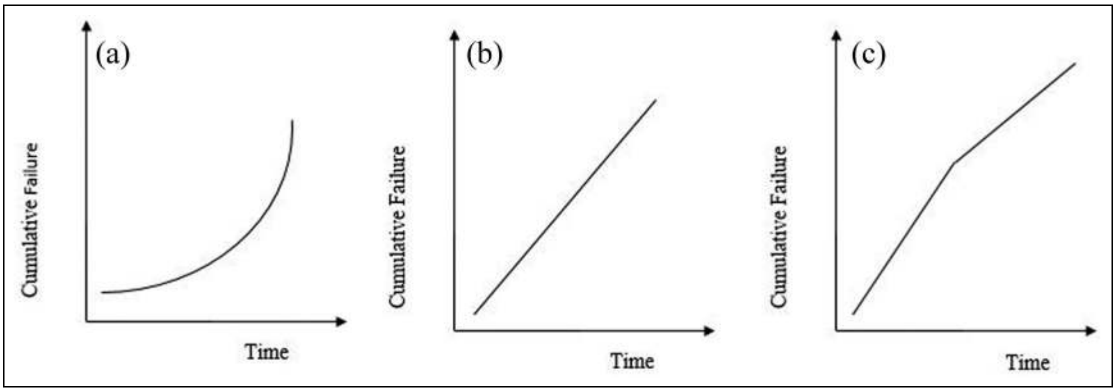

Figure 4. Cumulative failure versus time plots (a: increasing, b: no trend, c: two clearly different periods).

life of the ith failure, against (i − 1)th failure). If only one cluster of points is observed, there is no trend in the data. Two or more cluster of points or linear plots indicate trend. This test is also very helpful in identifying and eliminating unusual values for the failure time in a set of data, which may be related to poor data collection or accidents.

Above tests are used when the data of a single system are under observation. However, in case of data of multiple systems, the Nelson–Aalen plot is used.[45] In this test, linear plot results no trend and any deviation from a straight line indicates trend. The Nelson–Aalen plot is equivalent to the cumulative failures versus time plot when the data are of a single system. The total test on time (TTT) plot is used whenever the data of similar pieces of equipment are combined. Similar piece of equipment means this equipment should have same design, hardware, function, installation, working conditions and maintenance procedures.

Analytical methods. Analytical methods can also be preferred over graphical methods. Null hypothesis and alternative hypothesis of the analytical methods decide whether trend is present in the data or not. A complete survey of analytical trend tests presented by Ascher and Feingold[18] and Elvebakk[46] described popular tests. The Mann test, Lewis–Robinson test and military handbook (MH) test are some of the popular methods.[47] Some of them are briefly described here.

The Mann test is an analytical method used only when a single system is under consideration.[48] The null hypothesis for the Mann test is a RP. If null hypothesis is accepted, reliability analysis is continued by fitting a distribution to the data. If the alternative hypothesis is valid, then there will be monotonic trend. The test statistic is calculated counting the number of reverse arrangements, M, among the TBF. Let, T_1, T_2,...,T_n be the inter-arrival time of n failures. Then a reverse arrangement occurs whenever $T_i < T_j$ for $i < j$. In general

$$M = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} I(T_i < T_j) \quad (1)$$

I(.) is an indicator variable used for counting the reverse arrangements present in the data set. It takes the value of 1 whenever the condition is met, in this case, when ($T_i < T_j$). If the hypothesis of an RP is correct, then expected number of reverse arrangements is almost equal to $n(n-1)/4$. If this deviation is large, trend is present in the data.

The Laplace test, a well-known method has a null hypothesis of HPP versus an alternative hypothesis of NHPP with monotonic intensity. In other words, if the null hypothesis is not rejected, then we can assume that time between failures is iid exponentially distributed. If not, then a NHPP should be used. The test is optimal for NHPP with log-linear intensity function. Lewis–Robinson (LR) test is also used for testing of the RP assumption.[49] MH test is optimal for NHPP with increasing power-law intensity (reliability deterioration with Weibull intensity function). TTT-based statistic for both the Laplace and MH test are also available for the pooling of data from several systems.[50] Another test, known as the Anderson–Darling test,[51] has been found to be very powerful against non-monotonic trends, but normally simpler graphical tests are able to detect this situation. For this reason, it will not be described here.

Reliability analysis of CNC turning center

In this section, the proposed framework is applied for the reliability analysis of the CNC turning center. The data are collected from three different working conditions, that is, when machining material is steel, aluminum and cast iron. The partial failures are eliminated during preventive maintenance schedules. Therefore, binary state system analysis approach is selected for reliability analysis instead of multi-state system analysis approach. The data of 50 CNC turning centers over a period of 7 years are collected. TTF data of a CNC turning center $CNCTC_2$ are given in Appendix 1. Sufficient data are available for the analysis. Therefore, it is decided to analyze the data using parametric method as it is accurate and gives better reliability characteristics.

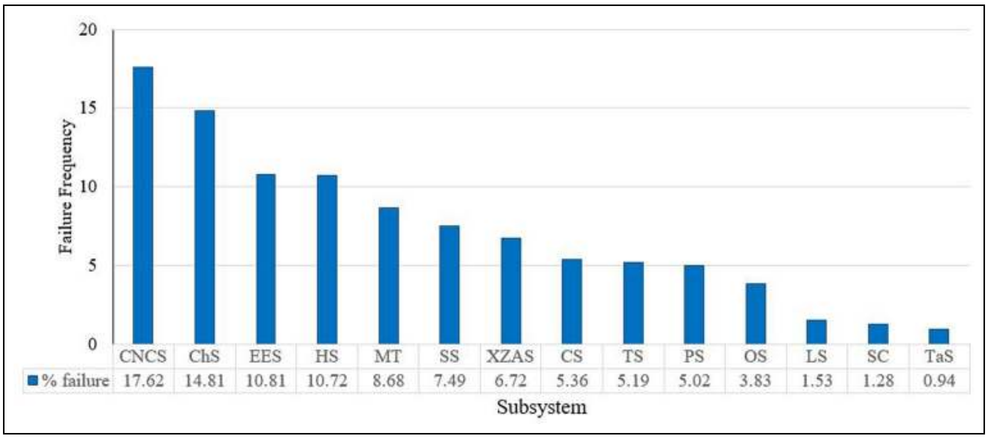

Figure 5. Pareto chart for CNC turning center.

Data collection

Data collection is the basis for the reliability analysis. The most critical task in reliability analysis is the collection of the field data accurately and systematically. The required data for the analysis are extracted from the history cards, maintenance and service reports produced by maintenance and service engineers. The selected CNC turning centers were working under similar environmental and operating conditions. The database includes the following information:

- Product name, model, size and code;
- Machine number;
- Failure date and time;
- Repair time;
- Downtime;
- Cost of spares and labor;
- Failure phenomenon;
- Description of failure cause;
- Other information about CNC turning center failure.

Pareto chart analysis

Every failure of the CNC turning center is categorized as MT, SS, ChS, TS, XZAS, HS, PS, CS, EES, CNCS, LS, SC, TSS and OS based on the function sharing, function independence and convention division principles. The objective of the Pareto analysis is to identify weaker sub-systems of the CNC turning center. These sub-systems are taken for further analysis. The failure count of each sub-system is used for Pareto analysis and is presented in Figure 5. It is observed that the CNCS have the most failures followed by ChS, EES, HS, MT, SS, XZAS and CS. The sum failures of the first seven sub-systems accounted for 76.85%. Furthermore, 17.62% of all failures are observed at the CNCS and it is the most critical sub-system from reliability perspective. It is also observed that OS, LS, SC and TaS have few failures. It can also be seen that the failures of electrical, electronic and control system components (contribute 28.43% of total failures) are more as compare to the components of other sub-systems.

Trend testing

The first step in model selection is to verify the existence of trend or time dependency in the data. If there is a clear trend in the TBF data, then non-stationary models such as NHPP are used for reliability modeling. Successive TTFs are plotted on timeline and preliminary analysis is carried for several CNC turning centers. Preliminary analysis shows that there is no trend in the data. Furthermore, the result of preliminary analysis is verified in this section using graphical as well as analytical techniques.

Cumulative failures versus time. Figure 6 gives cumulative failures versus time plot for a given data set of the CNC turning center $CNCTC_2$. It is seen that the linear plot gives the least error as compare to non-linear plot. When the plot is linear, it is concluded that there is no trend present in the data and the RP is valid. For the most of the CNC turning center data set, a renewal assumption is valid.

Scatter plot of successive service life. Scatter plot of successive service life is presented in Figure 7. Only one cluster of points is obtained for the given data set. Therefore, it is verified that there is no trend in the data. There are two data points, which are far away from the cluster of points. These are the anomalies and revision of these data points is required. From graphical tests (cumulative failure vs time and scatter plot of successive service life), it is concluded that there is no trend in the data and RP is valid.

Mann test. The outcome of the graphical tests is verified using analytical method. For this purpose, Mann test has been used. Table 1 presents value of M for reverse

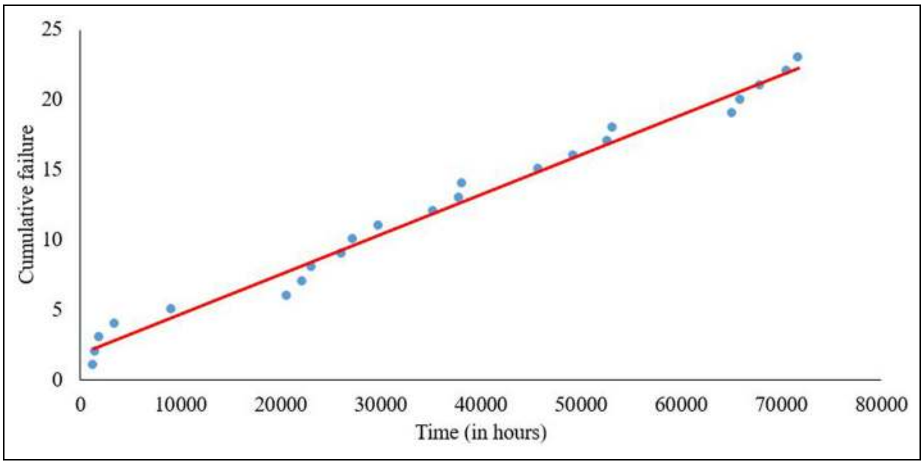

Figure 6. Cumulative failures versus time for a CNC turning center $CNCTC_2$.

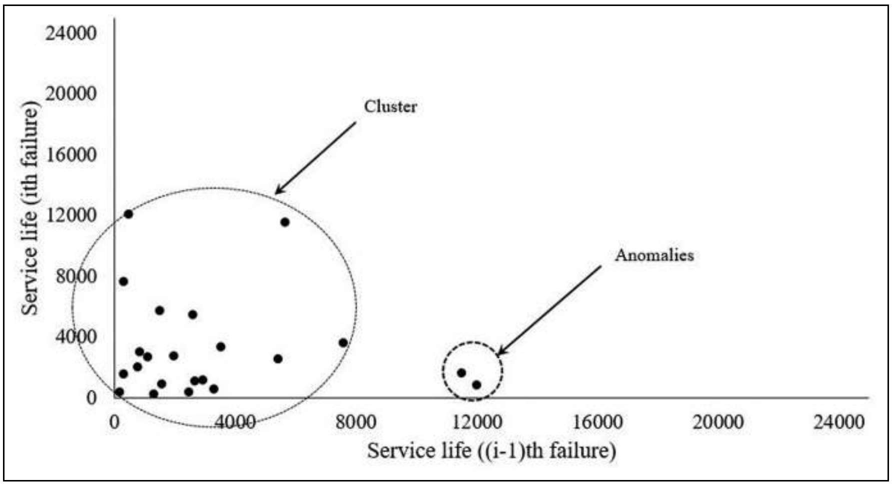

Figure 7. Scatter plot of successive service life plot.

Table 1. Comparison of value of M for reverse arrangements and using formula.

CNC turning center	Reverse arrangements (M)	M = n(n − 1)/4	Percentage deviation
	1	2	(1–2) × 100/1
$CNCTC_2$	142	126.5	10.92

CNC: computerized numerical control.

arrangements of failure points and value of M using formula. The expected number of reverse arrangements (M) is very close to the value of M obtained from $n(n-1)/4$ and therefore, there is no trend in the data. From analytical and graphical test, it is clear that there is no trend in the data and reliability analysis can be carried out as a RP.

Best-fit distribution and reliability evaluation

Trend-free data are further analyzed to determine the accurate characteristic of the failure time distributions of the CNC turning center. Different types of statistical distributions are examined and their parameters are estimated using ReliaSoft's Weibull ++ 10 software.[16] The software fits several distribution models based on the data, using a number of different methods. Weibull 3P distribution is the best-fit distribution for $CNCTC_1$ and $CNCTC_2$ with aluminum as machining material and Weibull 2P distribution is better for both $CNCTC_1$ and $CNCTC_2$ with steel and cast iron as working material. The best-fit distribution results of TBF data are presented in Table 2. The best-fit distribution for $CNCTC_2$ (aluminum) is observed to be

Table 2. Best-fit distribution for TBF data using K-S test.

Machine	Exp. 1P	Exp. 2P	Log-normal	Normal	Weibull 2P	Weibull 3P	Best-fit distribution
$CNCTC_2$ (aluminum)	0.2365	0.1284	0.6586	0.9999	0.3957	0.1387	Weibull 3P $\beta = 0.95$, $\theta = 1206$, $\gamma = 2.355$
$CNCTC_1$ (aluminum)	0.9961	0.9999	0.9380	0.9999	0.0627	0.0338	Weibull 3P $\beta = 0.84$, $\theta = 1248$, $\gamma = 15.66$
$CNCTC_2$ (steel)	0.9527	0.9992	0.8282	0.9999	0.0001	0.0007	Weibull 2P $\beta = 0.86$, $\theta = 2100$
$CNCTC_1$ (steel)	0.8446	0.6057	0.9794	0.9999	0.0031	0.0033	Weibull 2P $\beta = 0.91$, $\theta = 1956$
$CNCTC_2$ (cast iron)	0.9999	1.00	0.7348	0.9999	0.1921	0.2158	Weibull 2P $\beta = 0.82$, $\theta = 2972$
$CNCTC_1$ (cast iron)	0.9387	0.9513	0.6994	0.9889	0.0016	0.0039	Weibull 2P $\beta = 0.83$, $\theta = 2856$

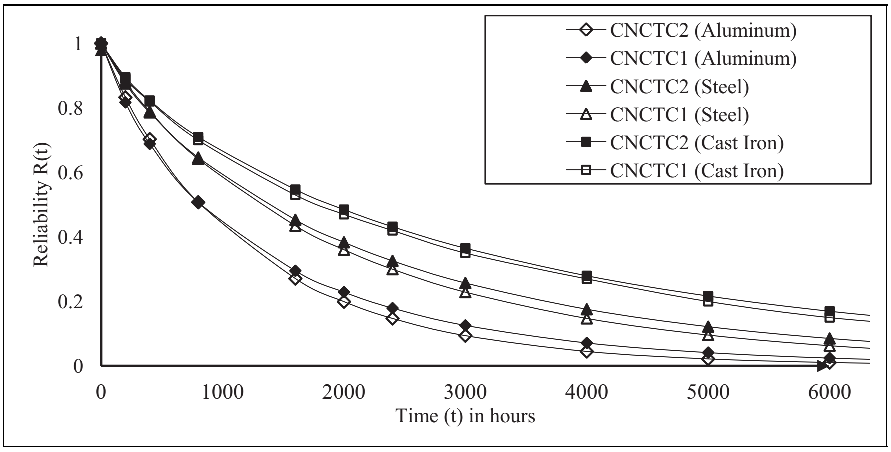

Figure 8. Comparative reliability versus time curve.

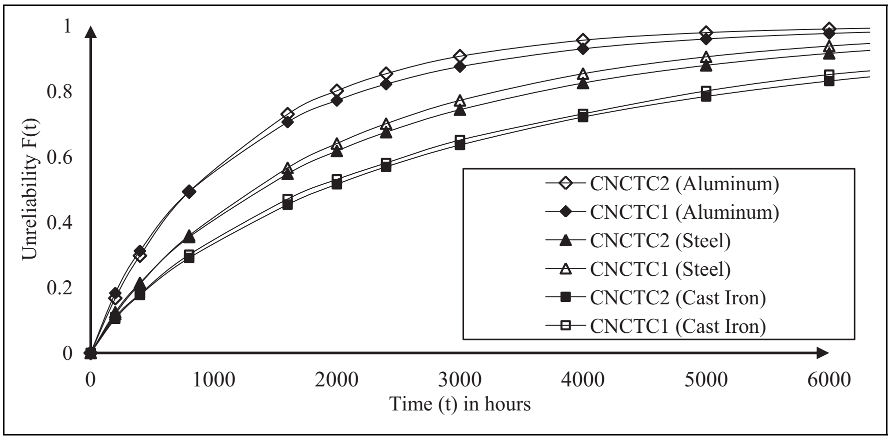

Figure 9. Comparative unreliability versus time curve.

exponential 2P. However, the location parameter of exponential 2P is negative. The location parameter gives the assured life of the system/component and could not be negative. Therefore, Weibull 3P is taken as best-fit distribution. Comparative results of reliability versus time and unreliability versus time are presented in Figures 8 and 9, respectively.

Table 3 gives the summary of best-fit distribution of sub-systems TBF data. The best-fit distribution for 12 sub-systems is estimated using K-S test. For MT, Weibull 2P is considered as best-fit distribution because the location parameter of Weibull 3P is negative. CNCS, ChS, EES, CS, OS and PS follow Weibull 3P distribution. Weibull 2P is the best-fit distribution for MT and HS. XZAS, SS and LS follow log-normal distribution. Exponential 1P distribution is best-fit distribution for TS. For repair data, Weibull 3P and log-normal distributions are found to be best-fit distributions for most of the sub-systems. Best-fit distributions of sub-systems TTR data using K-S test is summarized in Table 4. LS and SS require considerable time for maintenance activities followed by TS, CNCS, EES and ChS. These sub-systems are critical from maintainability perspective. The results of

Table 3. Best-fit distribution for TBF data for sub-systems of CNC turning center.

Sr. no.	Sub-systems	K-S test (goodness of fit)						Best-fit distribution
		Exp. 1P	Exp. 2P	Log-normal	Normal	Weibull 2P	Weibull 3P	
1	CNCS	9.95	9.56	76.11	99.88	1.45	0.79	Weibull 3P $\beta = 1.02$, $\theta = 2079$, $\gamma = 0.5$
2	MT	29.61	86.38	46.47	98.54	2.99	2.07	Weibull 2P $\beta = 0.88$, $\theta = 2158$
3	XZAS	99.18	99.69	20.30	99.70	31.99	37.71	Log-normal $\mu' = 7.086$, $\sigma' = 1.346$
4	HS	51.24	32.94	35.44	51.97	1.02	1.58	Weibull 2P $\beta = 1.14$, $\theta = 2448$
5	ChS	65.00	48.06	80.83	99.67	48.09	42.30	Weibull 3P $\beta = 1.1$, $\theta = 2319$, $\gamma = 19$
6	SS	99.99	99.99	22.38	99.96	49.62	53.15	Log-normal $\mu' = 7.039$, $\sigma' = 1.55$
7	EES	88.52	88.84	39.03	99.26	0.98	0.76	Weibull 3P $\beta = 0.81$, $\theta = 1832$, $\gamma = 2.2$
8	CS	70.04	80.83	29.68	89.13	0.68	0.22	Weibull 3P $\beta = 0.78$, $\theta = 1674$, $\gamma = 8.2$
9	TS	0.15	0.16	66.09	89.28	2.91	6.46	Exp. 1P MTTF = 1736
10	LS	95.49	67.61	3.22	97.53	33.52	26.42	Log-normal $\mu' = 6.873$, $\sigma' = 1.459$
11	OS	53.10	28.30	0.01	22.36	0.13	0.00	Weibull 3P $\beta = 0.55$, $\theta = 1948$, $\gamma = 79$
12	PS	52.45	34.06	6.91	71.31	2.12	1.53	Weibull 3P$\beta = 0.87$, $\theta = 2722$, $\gamma = 1.1$

K-S: Kolmogorov–Smirnov; CNCS: computerized numerical control system; MT: main transmission; XZAS: X- and Z-axis system; HS: hydraulic system; ChS: chuck system; SS: spindle system; EES: electrical and electronic system; CS: coolant system; TS: turret system; LS: lubrication system; OS: other system; PS: pneumatic system.

Table 4. Best-fit distribution for TTR data for sub-systems of CNC turning center.

Sr. no.	Sub-system	K-S test (goodness of fit)						Best-fit distribution	MTTR (h)
		Exp. 1P	Exp. 2P	Log-normal	Normal	Weibull 2P	Weibull 3P		
1	CNCS	100	100	98.90	100	99.99	98.62	Weibull 3P $\beta = 0.66$, $\theta = 8.84$, $\gamma = 0.5$	12.4
2	MT	99.99	99.99	98.56	99.99	99.98	99.17	Log-normal $\mu' = 0.975$, $\sigma' = 0.859$	3.8
3	XZAS	100	99.99	96.48	99.99	99.91	97.02	Log-normal $\mu' = 2.30$, $\sigma' = 1.567$	34
4	HS	98.72	99.98	97.67	99.86	97.78	89.68	Weibull 3P $\beta = 0.94$, $\theta = 3.22$, $\gamma = 0.47$	3.8
5	ChS	99.53	99.99	74.11	99.99	98.97	93.84	Log-normal $\mu' = 1.563$, $\sigma' = 0.887$	7.0
6	SS	99.99	99.99	65.85	99.99	58.02	19.37	Weibull 3P $\beta = 0.71$, $\theta = 36.3$, $\gamma = 0.45$	46
7	EES	100	99.99	93.05	99.99	99.69	88.11	Weibull 3P $\beta = 0.58$, $\theta = 6.4$, $\gamma = 0.49$	10.5
8	CS	99.67	94.95	45.51	99.20	90.24	81.54	Log-normal $\mu' = 1.05$, $\sigma' = 0.72$	3.70
9	TS	99.99	99.99	35.46	99.99	66.59	29.42	Weibull 3P $\beta = 0.60$, $\theta = 10.05$, $\gamma = 0.9$	16
10	LS	99.99	99.63	96.92	99.99	99.62	87.93	Weibull 3P $\beta = 0.34$, $\theta = 15.7$, $\gamma = 0.99$	85
11	OS	97.89	88.27	92.32	99.05	97.42	90.02	Exp. 2PMTTF = 1.44, $\gamma = 0.90$	2.3
12	PS	97.52	99.43	99.89	99.99	99.99	98.51	Weibull 3P $\beta = 0.71$, $\theta = 1.22$, $\gamma = 0.47$	2

K-S: Kolmogorov–Smirnov; CNCS: computerized numerical control system; MT: main transmission; XZAS: X- and Z-axis system; HS: hydraulic system; ChS: chuck system; SS: spindle system; EES: electrical and electronic system; CS: coolant system; TS: turret system; LS: lubrication system; OS: other system; PS: pneumatic system; MTTR: mean-time-to-repair.

maintainability analysis are used optimizing system downtime.

Reliable life at different reliability levels, reliability at different times and MTBF for 12 sub-systems are estimated and given in Table 5. CNCS, ChS, EES, HS, MT, TS and XZAS are critical sub-systems from reliability perspective. The results of reliability analysis are used for deciding maintenance intervals of sub-systems of CNC turning center based on the confidence level of maintenance persons.

Conclusion

Reliability-based design should be an integral part of design and maintenance management for the effective utilization of product or system over its useful life. In this article, a generalized framework for reliability data analysis is proposed which discriminates between the renewal approach to model TTF data and the use of a non-stationary model such as NHPP. The suggested framework is simple and can be used for the analysis of the failure processes commonly found in industrial operations. It can also be used for binary state systems as well as multi-state systems. The proposed framework is used for the analysis of CNC turning center and found suitable for the analysis of failure and repair data.

The scale parameter varies from 1200 to 1250 h for aluminum and from 1955 to 2100 h for steel. Reliability of model $CNCTC_1$ is found to be less than $CNCTC_2$. Also, the failure rate of CNC turning center $CNCTC_1$ is more. Weibull 3P is the best-fit distribution for aluminum whereas Weibull 2P is best-fit distribution for steel and cast iron. Shape parameter varies from 0.83

Table 5. Reliability and reliable life of CNC turning center.

Sr. no.	Sub-system	Reliable life in hours for given reliability level						Reliability at given time				MTBF (h)
		99%	95%	90%	80%	75%	50%	2190	4380	6570	8760	
01	CNCS	21	111	226	475	610	1449	0.35	0.12	0.04	0.01	2061
02	MT	11	73	165	390	521	1420	0.36	0.16	0.07	0.03	2304
03	XZAS	52	131	213	385	482	1195	0.33	0.17	0.10	0.07	2955
04	HS	43	182	341	658	822	1775	0.42	0.14	0.05	0.01	2334
05	ChS	54	173	316	608	762	1678	0.39	0.14	0.04	0.01	2260
06	SS	31	89	156	309	400	1140	0.34	0.19	0.13	0.1	3810
07	EES	8	48	114	287	392	1184	0.32	0.13	0.06	0.03	2068
08	CS	13	46	103	254	385	1056	0.29	0.12	0.05	0.03	1936
09	TS	17	89	183	387	499	1203	0.28	0.08	0.02	0.01	1736
10	LS	32	88	149	283	361	966	0.29	0.15	0.09	0.06	2799
11	OS	79	88	112	207	282	1081	0.35	0.21	0.14	0.10	3380
12	PS	15	90	205	485	650	1787	0.44	0.22	0.12	0.06	2924

K-S: Kolmogorov–Smirnov; CNCS: computerized numerical control system; MT: main transmission; XZAS: X- and Z-axis system; HS: hydraulic system; ChS: chuck system; SS: spindle system; EES: electrical and electronic system; CS: coolant system; TS: turret system; LS: lubrication system; OS: other system; PS: pneumatic system; MTBF: mean time between failure.

to 0.94, which shows that there is a little variation in shape parameter for different machining material and the failure data show decreasing failure rate. CNCS, ChS, EES, HS, MT, TS and XZAS are critical sub-systems from reliability perspective. LS, SS, TS, CNCS, EES and ChS are critical sub-systems from maintainability perspective.

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Appendix I

Table 1. TTF data for CNC turning center $CNCTC_2$.

Failure no.	Age at failure (h)	Cumulative failures (h)	Failure no.	Age at failure (h)	Cumulative failures (h)
1	1342	1342	13	2509	37,806
2	214	1556	14	335	38,141
3	329	1885	15	7601	45,742
4	1533	3418	16	3575	49,317
5	5680	9098	17	3335	52,652
6	11,542	20,640	18	501	53,153
7	1606	22,246	19	12,023	65,176
8	876	23,122	20	790	65,966
9	2971	26,093	21	1984	67,950
10	1121	27,214	22	2684	70,634
11	2638	29,852	23	1053	71,687
12	5445	35,297			