ELSEVIER

Reliability Engineering and System Safety 72 (2001) 247–252

RELIABILITY
ENGINEERING
&
SYSTEM
SAFETY

www.elsevier.com/locate/ress

A comprehensive reliability allocation method for design of CNC lathes

Yiqiang Wang[a], Richard C.M. Yam[b], Ming J. Zuo[c,*], Peter Tse[b]

[a]*College of Mechanical Engineering, Jilin University of Technology, Changchun 130025, People's Republic of China*
[b]*Manufacturing Engineering and Engineering Management Department, City University of Hong Kong, Hong Kong, People's Republic of China*
[c]*Department of Mechanical Engineering, University of Alberta, 4-9 Mechanical Engineering Building, Edmonton, Alta., Canada T6G 2G8*

Received 21 March 2000; accepted 7 February 2001

Abstract

In the design and development of computerized numerical control lathes, an effective reliability allocation method is needed to allocate system level reliability requirements into subsystem and component levels. During the allocation process, many factors have to be considered. Some of these factors can be measured quantitatively while others have to be assessed qualitatively. In this paper, we consider seven criteria for conducting reliability allocation. A comprehensive failure rate allocation method is proposed for conducting the task of reliability allocation. Example data from field studies are used to illustrate the proposed method. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Computerized numerical control lathes; Reliability allocation; Comprehensive failure rate allocation method

1. Introduction

Reliability allocation is an important task in the design and development of computerized numerical control (CNC) lathes. This is also a difficult task because of the large number of factors that have to be taken into consideration in the design process. One of such challenges is how to specify the required reliability levels of the components. With a given overall reliability goal for the CNC machine, proper reliability allocation method has to be used to translate the system reliability goal into reliability levels for all subsystems and components for design and test of CNC machines [1].

When performing reliability allocation for CNC lathes, many factors have to be considered. Some of these factors can be measured quantitatively while others have to be assessed qualitatively. For example, the historical frequency of failures can be measured quantitatively. However, it is more difficult to quantify the cost sensitivity to the reliability level. A comprehensive methodology should be applied to perform reliability allocation for CNC lathes. Based on our analysis of factors affecting reliability allocation for CNC lathes, we list seven criteria for reliability allocation. A comprehensive failure rate allocation method is proposed to perform the reliability allocation for CNC lathe design.

2. Criteria for reliability allocation

There are many measures of system performance. One may choose to use mean time between failures (MTBF), availability or reliability for a specified duration, or simply the failure rate. In this paper, we use the failure rate λ as the measure of performance of the CNC system. Failure rate is defined to be the probability of failure in the next unit time given that the device or system has been working properly up to that point of time. For the exponential life distribution the failure rate is constant. We will use λ_s^* to represent the specified system failure rate. Given this specified system level failure rate, we need to determine how to allocate λ_s^* into the subsystems of the CNC machine such that the system failure rate does not exceeded the specified value.

Assume that the CNC machine has n subsystems. All these subsystems have to work properly for the CNC machine to work properly. We will use λ_i to represent the failure rate of the ith subsystem $(i = 1, 2, \ldots, n)$. The system's failure rate λ_s can be expressed as a function of these subsystems' failure rates:

$$\lambda_s = f(\lambda_1, \lambda_2, \ldots, \lambda_n). \tag{1}$$

When we conduct reliability allocation, we must make sure that λ_s is less than or equal to λ_s^*. Because there are many factors, such as complexity, cost, state of the art, and maintenance that have to be considered in the design of a CNC system, there is no single mathematical model that can be used for reliability allocation [2,3]. In the following, we

---

* Corresponding author. Tel.: +1-780-492-4466; fax: +1-780-492-2200.
E-mail address: ming.zuo@ualberta.ca (M.J. Zuo).

0951-8320/01/$ - see front matter © 2001 Elsevier Science Ltd. All rights reserved.
PII: S0951-8320(01)00018-7

summarize the criteria that should be used in practical CNC machine reliability allocation.

1. *Frequency of failure*. The failure data of subsystems of existing CNC machines should be utilized in design of new CNC machines. The subsystem that has a low frequency of failure is already very reliable. In the new design, it is natural to allocate a high reliability to this subsystem. There is no point to make it less reliable in the new design. For example, an existing system is comprised of n subsystems U_1, U_2,…, U_n. We often improve the reliabilities of these subsystems proportionally in order to improve the reliability of such a system in a new design [4].
2. *Criticality of failure*. The criticality of the failure of a subsystem represents the impact of its failure on the machine, its surroundings, and its operator, it reflects synthetically the probability of failure and severity [5]. If a subsystem's failure may cause injury to the operator and/or damage to the machine and the properties around it, we say that the criticality of the failure of this subsystem is high. This is the relative effect of each subsystem upon the achievement of the system's mission objectives. The criticality of the subsystem has a direct relationship with reliability allocation [6]. The subsystem with high criticality of failure should be allocated a high reliability.
3. *Maintainability*. Maintainability is the inherent characteristic of an item related to its ability to be restored when the specified maintenance task is performed as required [7]. The mean repair cost and the mean machine down time are used in this paper to assess the maintainability of a subsystem if it is failed. The higher or longer the repair cost or down time, the worse the maintainability of the subsystem is. The subsystem with poor maintainability should be allocated a high reliability.
4. *Complexity*. The complexity of a subsystem is defined as the ratio between the number of essential parts within the subsystem (whose failures will cause the subsystem to fail) and the total number of such essential parts in the whole CNC machine. The higher the complexity of a subsystem is, the more frequently the subsystem may fail. It is more difficult to improve the reliability of a subsystem if it is composed of many essential parts. As a result, the subsystem with low complexity should be allocated a high reliability [6].
5. *Manufacturing technology*. The reliability goal specified by the designer for a subsystem is assured through the manufacturing process. For a subsystem that is produced with advanced manufacturing technology, it is relatively easy to assure its reliability. For a subsystem for which there is no advanced manufacturing technology available, it is harder to guarantee a high reliability. As a result, the subsystem to be produced with advanced manufacturing technology should be allocated a high reliability.
6. *Working condition*. The working condition represents the temperature, moisture, vibration, electromagnetic interference, contamination, corrosion and so on under which the subsystem has to work. It also takes into account the operational time requirement [6]. The worse the working condition of a subsystem is, the more difficult to guarantee its reliability. The subsystem with good working condition should be allocated with a high reliability.
7. *Cost*. In CNC machine design, our final goal is to minimize the total cost including design, development, manufacture, operation, and maintenance of the whole system subject to system reliability requirement. In reliability allocation among subsystems, we need to seek a balance between reliability and cost of each subsystem. The sensitivity of cost to reliability should be taken into account when improving the reliability of a subsystem. The cost sensitivity to reliability is defined as the ratio ($\Delta C/\Delta R$) of the cost increment ΔC and the reliability increment ΔR. The higher the cost sensitivity to reliability, the more it costs to improve the reliability of the subsystem. The subsystem whose cost sensitivity to reliability is low should be allocated a high reliability.

Among these criteria for reliability allocation, some can be measured quantitatively while others require subjective assessment. In this paper, we propose a comprehensive method for reliability allocation in design of CNC lathes considering all these seven criteria.

3. The comprehensive reliability allocation method

Based on previous analyses of CNC lathes [8–10], a CNC lathe may be divided into 15 subsystems, namely, the turret, clamping accessory, electric and electronic subsystem, main transmission, X feed subsystem, Z feed subsystem, CNC subsystem, power supply, hydraulic subsystem, servo subsystem, cooling subsystem, Swarf conveyors, lubricating subsystem, spindle assembly, and guard, denoted by U_1, U_2,…,U_{15}, respectively. As a result, we have a subsystem vector, $\mathbf{U} = \{U_1, U_2, \ldots, U_n\}$. The seven reliability allocation criteria summarized in Section 2, namely, frequency of failure, criticality of failure, maintainability, complexity, manufacturing technology, working condition, and cost, are denoted by V_1, V_2,…,V_7, respectively. As a result, we have a reliability allocation criterion vector, $\mathbf{V} = \{V_1, V_2, \ldots, V_m\}$. Here we have used n to represent the number of subsystems in the CNC lathe and m to represent the number of allocation criteria to be used. In this paper, we have $n = 15$ and $m = 7$.

For each reliability allocation criterion V_k ($1 \leq k \leq m$), we can calculate a relative ratio for failure rate allocation between the ith subsystem and the jth subsystem, denoted by $\beta_{ij}^{(k)}$, i.e. the relative ratio of the failure rate of the ith subsystem to the sum of the failure rates of the ith and the jth subsystems. The range of such ratios is between 0 and 1. We also have the following equation:

$$\beta_{ij}^{(k)} = 1 - \beta_{ji}^{(k)}, \quad \text{for} \quad i \text{ and } j = 1,2,\ldots,n; \quad k = 1,2,\ldots,m. \tag{2}$$

If $\beta_{ij}^{(k)} > 0.5$, it means that subsystem i should be allocated a higher failure rate than subsystem j. For example, suppose $\beta_{ij}^{(1)} = 0.75$. This represents that for the frequency of failure criterion, the ith subsystem U_i should be allocated a higher failure rate than the jth subsystem U_j, because the ith subsystem U_is historical failures are more frequent than that of the jth subsystem U_j. Obviously, $\beta_{ii}^{(k)} = 0.5$. The failure rate allocation ratio matrix, $\mathbf{B}^{(k)}$, for criterion k may be expressed in the following form:

$$\mathbf{B}^{(k)} = \begin{bmatrix} \beta_{11}^{(k)} & \beta_{12}^{(k)} & \cdots & \beta_{1n}^{(k)} \\ \beta_{21}^{(k)} & \beta_{22}^{(k)} & \cdots & \beta_{2n}^{(k)} \\ \cdots & \cdots & \cdots & \cdots \\ \beta_{n1}^{(k)} & \beta_{n2}^{(k)} & \cdots & \beta_{nn}^{(k)} \end{bmatrix}_{n\times n}, \qquad k = 1,2,\ldots,m. \tag{3}$$

Each row of the matrix $\mathbf{B}^{(k)}$ represents the failure rate allocation ratio between a specific subsystem and every other subsystem. The average value of the entries in row i of the matrix $\mathbf{B}^{(k)}$ represents the relative allocation factor for subsystem i based on allocation criterion k. Define

$$\gamma_{ki} = \frac{1}{n} \sum_{j=1}^{n} \beta_{ij}^{(k)}, \qquad k = 1,2,\ldots,m; \quad i = 1,2,\ldots,n. \tag{4}$$

Then, we have a matrix, $\boldsymbol{\Gamma}$, that represents the relative failure rate allocation factor for all subsystems and all allocation criteria as shown below

$$\boldsymbol{\Gamma} = \begin{bmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1n} \\ \gamma_{21} & \gamma_{22} & \cdots & \gamma_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \gamma_{m1} & \gamma_{m2} & \cdots & \gamma_{mn} \end{bmatrix}_{m\times n}. \tag{5}$$

The kth row of matrix $\boldsymbol{\Gamma}$ represents the relative failure rate allocation factors for all subsystems using the kth allocation criterion. Take the first row as an example. The allocated failure rate of a subsystem should be proportional to the corresponding entry of the first row based on the frequency of failure criterion.

Let a_i represent the comprehensive failure rate allocation factor for subsystem i $(1 \le i \le n)$ considering all allocation criteria. Also define vector $\mathbf{A}$ as follows:

$$\mathbf{A} = \{a_1, a_2, \ldots, a_n\}. \tag{6}$$

Vector $\mathbf{A}$ is called the comprehensive failure rate allocation vector for all subsystems. $\mathbf{A}$ is defined by

$$\mathbf{A} = \mathbf{W}\cdot\boldsymbol{\Gamma}, \tag{7}$$

where $\mathbf{W} = \{w_1, w_2, \ldots w_m\}$ is the weighting vector and w_k $(1 \le k \le m)$ represents the weight or the importance of the kth allocation criterion. $\mathbf{W}$ may be obtained with the expert rating method

$$w_k' = \frac{1}{N} \sum_{r=1}^{N} w_{kr}, \qquad k = 1,2,\ldots,m, \tag{8}$$

where w_{kr} is the rated weight of the kth criterion by the rth expert and $w_k{}'$ is the average rated weight of the kth criterion considering all N experts. The weight vector $\mathbf{W}$ may be normalized as follows:

$$w_k = w_k' / \sum_{j=1}^{m} w_j', \qquad k = 1,2,\ldots,m. \tag{9}$$

The comprehensive failure rate allocation vector $\mathbf{A}$ indicates that the allocated failure rate of each subsystem should be proportional to the corresponding entry of this vector after all allocation criteria have been considered. That is,

$$\lambda_1 : \lambda_2 : \cdots : \lambda_n = a_1 : a_2 : \cdots : a_n. \tag{10}$$

Since the system reliability model for the CNC lathes is the series model with n subsystems [8], we have

$$\lambda_s = f(\lambda_1, \lambda_2, \ldots, \lambda_n) = \sum_{i=1}^{n} \lambda_i. \tag{11}$$

Using Eqs. (10) and (11), we can obtain

$$\lambda_i = \frac{a_i}{\sum_{j=1}^{n} a_j} \lambda_s^*, \tag{12}$$

where λ_s^* is the failure rate target of the CNC lathe specified by the designer.

4. Reliability allocation for CNC lathe

For the frequency of failure criterion, $\beta_{ij}^{(1)}$ is calculated by

$$\beta_{ij}^{(1)} = \frac{n_i}{n_i + n_j}, \tag{13}$$

where n_i and n_j are the observed relative failure frequencies of the ith subsystem U_i and the jth subsystem U_j, respectively. For example, Table 1 lists the relative failure frequencies of the subsystems of the medium-sized CNC lathes during an observation period of two years at the First Automobile Works (FAW), an automobile-fabricating group in China. The relative failure frequency of the ith subsystem is defined as the ratio between the number of failures of the ith subsystem and the number of failures of all subsystems.

For the criticality of failure criterion, $\beta_{ij}^{(2)}$ is calculated with

$$\beta_{ij}^{(2)} = \frac{\mathrm{CR}_j}{\mathrm{CR}_i + \mathrm{CR}_j}, \tag{14}$$

Table 1
Observed relative failure frequencies of each subsystem

Code	Subsystem	Relative failure frequency
M	Turret	0.269
J	Clamping accessory	0.099
V	Electric and Electronic system	0.096
S1	Main transmission	0.084
X	X feed system	0.075
Z	Z feed system	0.065
NC	CNC system	0.063
E	Power supply	0.049
D	Hydraulic system	0.041
F	Servo system	0.038
W	Cooling system	0.035
K	Swarf conveyors	0.030
L	Lubricant system	0.029
S2	Spindle assembly	0.013
Q	Guard	0.008

Table 3
Mean down time and mean repair cost for each subsystem of the CNC lathe

Code	Subsystem	Mean repair cost (man-hours)	Mean down time (h)
M	Turret	2.72	1.97
J	Clamping accessory	1.99	1.16
V	Electric and electronic system	0.75	0.50
S1	Main transmission	2.64	1.03
X	X feed system	2.38	1.35
Z	Z feed system	2.00	1.92
NC	CNC system	1.03	1.01
E	Power supply	0.76	0.55
D	Hydraulic system	1.82	0.98
F	Servo system	0.89	2.42
W	Cooling system	3.05	2.76
K	Swarf conveyors	4.04	1.71
L	Lubricant system	2.33	1.17
S2	Spindle assembly	2.89	1.37
Q	Guard	4.79	2.36

where CR_i and CR_j represent the criticality of failure of subsystem i and subsystem j, respectively. To calculate CR_i for subsystem i, we need to consider the failure modes of each essential component of the subsystem. The failure criticality of the jth failure mode of the kth component in a subsystem is a product of three terms: (1) the probability of failure of this component in a specified interval, (2) the probability that the failure of the component is caused by a specific failure mode, and (3) the probability that the failure mode will cause severe damage to the system. For detailed discussion of the method for calculation of CR_i, the readers are referred to [4, p. 13.20]. We have followed this method and calculated the criticality of failure of the 15 subsystems under consideration and tabulated the results in Table 2. The detailed data analysis and calculations are documented in [8].

Table 2
Failure criticality of each subsystem for the CNC lathe from historical data

Code	Subsystem	Criticality of failure
M	Turret	0.0003177
J	Clamping accessory	0.0002813
V	Electric and Electronic system	0.0002092
S1	Main transmission	0.0001693
X	X feed system	0.0001402
Z	Z feed system	0.0001427
NC	CNC system	0.0001575
E	Power supply	0.0001418
D	Hydraulic system	0.0000834
F	Servo system	0.0001368
W	Cooling system	0.0001219
K	Swarf conveyors	0.00007905
L	Lubricant system	0.000048
S2	Spindle assembly	0.00004038
Q	Guard	0.00003148

For the maintainability criterion, $\beta_{ij}^{(3)}$ is calculated with

$$\beta_{ij}^{(3)} = \frac{T_{Dj} + T_{Hj}}{T_{Di} + T_{Dj} + T_{Hi} + T_{Hj}}, \tag{15}$$

where T_{Di} and T_{Dj} are the mean down time of the ith subsystem U_i and the jth subsystem U_j, respectively, and T_{Hi} and T_{Hj} are the mean repair cost of the ith subsystem U_i and the jth subsystem U_j, respectively. Table 3 lists these data obtained from the FAW during an investigation period of two years.

For the complexity criterion, $\beta_{ij}^{(4)}$ is calculated with

$$\beta_{ij}^{(4)} = \frac{n_i}{n_i + n_j}, \tag{16}$$

where n_i and n_j are the approximate number of essential parts in subsystem i and subsystem j, respectively. The approximate number of parts of each subsystem of the CNC lathe is listed in Table 4 [11,12]. Based on the data given in Table 4, we can calculate $\beta_{ij}^{(4)}$ for all i and j values.

For the criteria of manufacturing technology, working condition, and cost, we do not have data available to calculate $\beta_{ij}^{(5)}$, $\beta_{ij}^{(6)}$, and $\beta_{ij}^{(7)}$ directly. Instead, they are obtained with the expert rating method. For each of these three criteria, a group of experts are asked to provide a rating score for each subsystem of the CNC lathe under consideration. The guideline for providing such scores is that the lower the manufacturing technology level, or the worse the working condition for a subsystem, or the more costly it is to improve the reliability of a subsystem, the higher the rating score should be. The rating scores have to be in the range from 0 to 1.

Table 4
The complexity of each subsystem of the CNC lathe

Subsystem	M	J	V	S1	X	Z	NC	E	D	F	W	K	L	S2	Q
Number of parts	300	150	250	80	100	100	30	50	80	50	40	50	30	60	10

Table 5
Average rating scores from experts for each of the three criteria

Subsystem	M	J	V	S1	X	Z	NC	E	D	F	W	K	L	S2	Q
Manufacturing technology ($k = 5$)	0.98	0.70	0.26	0.34	0.40	0.40	0.14	0.20	0.40	0.20	0.30	0.44	0.34	0.38	0.10
Working condition ($k = 6$)	0.96	0.76	0.20	0.44	0.40	0.40	0.10	0.24	0.34	0.14	0.30	0.56	0.26	0.44	0.14
Cost ($k = 7$)	0.98	0.70	0.30	0.58	0.50	0.50	0.14	0.26	0.40	0.20	0.36	0.46	0.34	0.54	0.10

Let $\mathbf{\Omega}_r^{(k)} = \{\omega_{1r}^{(k)}, \omega_{2r}^{(k)}, \dots, \omega_{nr}^{(k)}\}$ represent the vector of rating scores assigned to all subsystems provided by the rth expert for the kth criterion. The averages of the rating scores for each criterion and each subsystem provided by all experts can be calculated as

$$\omega_i^{(k)} = \frac{1}{N}\sum_{r=1}^{N}\omega_{ir}^{(k)}, \qquad i = 1,2,\dots,n;\ \ k = 5,6,7, \tag{17}$$

where N is the number of experts and $k = 5,6,7$ represent the manufacturing technology, working condition, and cost criteria, respectively. Table 5 lists the average rating scores obtained from a group of experts.

With the results in Table 5, we can calculate the relative allocation ratio of failure rate among each pairs of subsystems for each of the three criteria under consideration, namely, $\beta_{ij}^{(k)}$ for $k = 5, 6,$ and 7

$$\beta_{ij}^{(k)} = \frac{\omega_i^{(k)}}{\omega_i^{(k)} + \omega_j^{(k)}}, \qquad k = 5,6,7. \tag{18}$$

With the relative failure rate allocation ratios obtained as described in the foregoing, we have obtained the following matrix $\mathbf{\Gamma} = (\gamma_{ij})_{n\times n}$ using Eq. (4).

$$\mathbf{\Gamma} = \begin{bmatrix} 0.82 & 0.66 & 0.65 & 0.62 & 0.60 & 0.57 & 0.56 & 0.51 & 0.47 & 0.45 & 0.44 & 0.40 & 0.32 & 0.25 & 0.18 \\ 0.29 & 0.31 & 0.37 & 0.42 & 0.46 & 0.46 & 0.43 & 0.46 & 0.58 & 0.47 & 0.49 & 0.59 & 0.69 & 0.73 & 0.77 \\ 0.42 & 0.52 & 0.72 & 0.48 & 0.48 & 0.47 & 0.62 & 0.71 & 0.55 & 0.51 & 0.38 & 0.38 & 0.49 & 0.45 & 0.33 \\ 0.72 & 0.61 & 0.69 & 0.49 & 0.87 & 0.87 & 0.31 & 0.40 & 0.49 & 0.40 & 0.36 & 0.40 & 0.31 & 0.43 & 0.14 \\ 0.74 & 0.68 & 0.45 & 0.51 & 0.55 & 0.55 & 0.32 & 0.39 & 0.55 & 0.39 & 0.48 & 0.57 & 0.51 & 0.54 & 0.25 \\ 0.74 & 0.69 & 0.40 & 0.57 & 0.55 & 0.55 & 0.26 & 0.44 & 0.52 & 0.32 & 0.49 & 0.63 & 0.45 & 0.57 & 0.32 \\ 0.71 & 0.65 & 0.45 & 0.60 & 0.57 & 0.57 & 0.29 & 0.42 & 0.52 & 0.36 & 0.50 & 0.55 & 0.48 & 0.59 & 0.23 \end{bmatrix}. \tag{19}$$

The weighting vector **W** is obtained with the expert rating method:

$$\mathbf{W} = \{\,0.20 \quad 0.10 \quad 0.08 \quad 0.14 \quad 0.17 \quad 0.15 \quad 0.16\,\}. \tag{20}$$

The comprehensive failure rate allocation vector **A** can then be calculated with Eq. (7):

$$\mathbf{A} = \{0.68\ 0.61\ 0.53\ 0.54\ 0.59\ 0.59\ 0.39\ 0.46\ 0.52\ 0.41\ 0.45\ 0.51\ 0.45\ 0.49\ 0.29\}. \tag{21}$$

We specify MTBF = 500 h as the reliability goal of the overall CNC lathe, that is, $\lambda_s^* = 0.002$. Substituting $\lambda_s^* = 0.002$ into Eq. (12), we have:

$$\{\lambda_i\} = \{0.000181,\ 0.000163,\ 0.000141,\ 0.000145,\ 0.000158,\ 0.000156,\ 0.000103,\ 0.000123,\ 0.000138,\ 0.000108,\ 0.000120,\ 0.000135,\ 0.000120,\ 0.000131,\ 0.000076\}. \tag{22}$$

Correspondingly, we have

$$\{\mathrm{MTBF}_i\} = \{5523.56,\ 6140.60,\ 7067.28,\ 6890.52,\ 6318.62,\ 6398.46,\ 9679.27,\ 8154.97,\ 7230.30,\ 9222.45,\ 8305.45,\ 7412.56,\ 8346.89,\ 7645.18,\ 13099.09\}. \tag{23}$$

Table 6
The observed MTBF and allocated MTBF of each subsystem of the CNC lathes

Code	Subsystem	Observed MTBF (h)	Allocated MTBF (h)
M	Turret	752.14	5527.98
J	Clamping accessory	2044.06	6142.52
V	Electric and electronic system	2118.84	7074.42
S1	Main transmission	2413.13	6875.32
X	X feed system	2714.77	6319.49
Z	Z feed system	3102.59	6407.56
NC	CNC system	3217.50	9704.35
E	Power supply	4136.79	8166.75
D	Hydraulic system	4964.14	7230.40
F	Servo system	5265.00	9198.31
W	Cooling system	5791.50	8317.55
K	Swarf conveyors	6682.50	7397.87
L	Lubricant system	6949.80	8342.06
S2	Spindle assembly	15795.00	7637.27
Q	Guard	24820.71	13077.68

The MTBF observed in the FAW in China within two years and the allocated MTBF in this design process for each subsystem of the CNC lathes are listed in Table 6. It can be seen that the MTBFs of most subsystems of existing CNC lathes do not meet the expected reliability goals. Actions must be taken to improve the reliability of the subsystems of CNC lathes, such as turret, clamping accessory, and so on.

5. Conclusions

A comprehensive method is proposed in this paper for allocating the required system reliability level into each subsystem. This method can also be used to allocation subsystem reliability requirement into each critical component in the subsystem

It can be seen that the reliability indexes of most subsystems of existing CNC lathes observed do not meet the allocated reliability requirements. Actions should be taken to improve the reliabilities of these subsystems, such as the turret, clamping accessory, and so on.

Reliability allocation of CNC lathes should consider various factors such as the performance, design, manufacture, use, maintenance, cost, and reliability of the system. The comprehensive failure rate allocation method described in this paper reflects such an endeavor of considering all these factors.

Acknowledgements

This research was partially supported by the Research Grants Council of the Hong Kong Special Administrative Region Government and the Natural Sciences and Engineering Research Council of Canada. Critical comments and suggestions from referees have been very helpful in revision of this manuscript.

References

[1] Rui K, Xu H, Ping Z. Reliability allocation for automobile product. In: Proceedings of the Third International Conference on Reliability, Maintainability and Safety (ICRMS'96), 1996:110–5.

[2] Aggarwal KK. Reliability engineering. Dordrecht: Kluwer Academic Publishers, 1993.

[3] Blanks HS. Reliability in procurement and use: from specification to replacement. Chichester: Wiley, 1992.

[4] Grant W, Coombs Jr. CF. Handbook of reliability engineering and management. New York: McGraw-Hall, 1988. p. 1834–41.

[5] Dai Shu-Ho, Wang Ming-O. Reliability analysis in engineering applications. New York: Van Nostrand Reinhold, 1992. p. 421.

[6] Kececioglu D. Reliability engineering handbook. Vol. 2. Englewood Cliffs, NJ: Prentice-Hall, 1991. p. 363–99.

[7] Knezevic J. Reliability, maintainability and supportability: a probabilistic approach. London: McGraw-Hill, 1993. p. 99–103.

[8] Wang Y. Research on reliability analysis and design method of CNC lathes. PhD Dissertation, Jilin University of Technology, 1999.

[9] Wang Y, Jia Y, Yu J, Yi S. Field failure database of CNC lathes. Int J Quality Reliab Mgmt 1999;16(4):330–40.

[10] Wang Y, Jia Y, Yu J, Zheng Y, Yi S. Failure probabilistic model of CNC lathes. Reliab Engng Syst Safety 1999;65(3):307–14.

[11] Changcheng Machine Building Mill. Operation and Maintenance Manual of CK7815 CNC Lathe, 1998.

[12] Shengyang No. 1 Machine Building Mill. Operation and Maintenance Manual of S1-273 CNC Lathe, 1996.