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Research Article

Analysis of the Reliability Model of the Tool Magazine Subsystem in the Processing Center

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Abstract: Tool magazine is an important part of a processing center. Tool magazines have the advantage of reducing work parts turnover, handling, and storage time. In addition, some research shows that the use of tool magazine in machine tools in the machining center can make the cutting time utilization rate of machine tools 3-4 times higher than that of ordinary machine tools, and has better machining consistency, thus improving processing accuracy and processing efficiency, shortening the production cycle. Therefore, the reliability, efficiency and accuracy of the tool magazine have a crucial impact on the stability of the machine tool. Therefore, the reliability analysis of CNC machine tool magazine is considerably important. In view of this problem, this paper puts forward that the reliability model of the tool magazine is established after the parameter estimation and hypothesis test, and then the maintainability model of the tool magazine is built, it ends with the fault analysis of the tool magazine.

Keywords: Tool Magazine, Processing Center, Reliability, Repairability, Failure Analysis

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1 Introduction

CNC machines are the basis of manufacturing industry, so the reliability of CNC machines research become important in the past decades[1]. Tool magazine, as one of the important components of high-precision machine center, it's failure time, maintainability, and reliability will directly affect the quality of CNC machines[2]. In the past, researchers have shown that the Weibull distribution plays an extremely important role in the application of reliability estimation of any product[3], such as Lai Chin[4], have discussed the Weibull distribution and its application. The current mainstream method is to use the least square method of the two-parameter Weibull distribution[5,6] to perform in depth study. In this paper, the reliability model is established based on the Weibull distribution, and then the maintenance model of the tool magazine is carried out by using the logarithmic normal distribution of the variable 'time', and with the inspiration of failure analysis on tool magazine carried out by Zhongsong Zhang[7], this paper discusses the failure analysis of the tool magazine[8]. With the above consideration, this paper introduced the two-parameter Weibull distribution into the reliability analysis of the tool magazine [9,10].

2 Build a subsystem system reliability model

Based on the failure time of a processing center, the reliability model of key components is established. Tool magazine, in my case. Table 1 shows the cumulative running time of the tool magazine, failure time, t_i.

Table 1. Failure time of tool magazine

i	t_i (h)	i	t_i (h)	i	t_i (h)
1	12	11	211	21	394
2	45	12	234	22	417
3	54	13	237	23	557
4	54	14	259	24	565
5	61	15	266	25	591
6	63	16	271	26	729
7	70	17	274	27	769
8	92	18	296	28	944
9	96	19	346	29	1044
10	104	20	372		

2.1 Parameter estimation of the reliability model

Based on previous studies on the reliability of any processing centers, we know that the cumulative fault distribution functions of processing centers are subject to the Weibull distribution, so tool magazine should follow the same distribution as well.

The two parameters Weibull distribution function is:

$$F(t) = 1 - exp[-\left(\frac{t}{\alpha}\right)^{\beta}], \qquad t \geq 0 \tag{1}$$

In the function (1) the parameters are as follow:

α—scale parameter α >0;

β—shape parameter β >0;

The corresponding reliability function:

$$R(t) = exp[-\left(\frac{t}{\alpha}\right)^{\beta}], \; t \geq 0 \tag{2}$$

2.2 Least squares method with respect to Y

After deciding the reliability model of the machining center obeys the Weibull distribution in the previous section, it is necessary to estimate the parameters of the Weibull distribution model. When estimating the parameters of the Weibull distribution model of the machining center, the regression line is often directly fitted in the y direction. Keeping this rule, we can perform a linear regression model with respect to y. The symbol in the article are defined as follow:

$$l_{xx} = \sum_{i=1}^{n} x_i^2 - n\bar{x}^2, \; l_{yy} = \sum_{i=1}^{n} y_i^2 - n\bar{y}^2,$$

$$l_{xy} = l_{yx} = \sum_{i=1}^{n} x_i y_i - n\bar{x}\bar{y}, \; \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i,$$

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

Estimation of least square method with respect to y

The linear regression model respect to y

$$y=a+bx+\varepsilon \tag{3}$$

In the equation: a, b—regression coefficients;

ε—deviation.

The corresponding least square constraints

$$Q_y = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n}(y_i - a - bx_i)^2 = min \tag{4}$$

In the equation: Q_y—sum of squares of deviation;

ε_i—the ith sample deviation.

When the derivative of Q_y with respect to a is equal to 0 and the derivative of Q_y respect to b is also equal to 0, Q_y hence reach it's minimum. Consequently the estimation of A, B can be:

$$\begin{cases} \hat{B} = \frac{l_{xy}}{l_{xx}} \\ \hat{A} = \bar{y} - \hat{B}\bar{x} \end{cases} \tag{5}$$

Since we know the two parameter Weibull distribution function.(1), then we can perform linear transform the equation(1) and get:

$$\ln\ln\frac{1}{1-F(t)} = -\beta\ln\alpha + \beta\ln t$$

Let $y_i = lnln\frac{1}{1-F(t_i)}$ and t_i represents ith failure point when sorting time from small to large. And x_i=ln t_i , A=-β lnα, B=β. Take y_i=lnln $lnln\frac{1}{1-F(t_i)}$ x_i=ln t_i back into equation 5 we will be able to get A, B. But before we do any calculation, we need to make an estimate on F(t_i). Normally we will use median ranks to estimate(t_i), so $\hat{F}(ti) \approx \frac{i-0.3}{n+0.4}$. Finally, we conclude that $\hat{\beta} = \hat{B}, \hat{\alpha} = exp(-\hat{A}/\hat{B})$.

Because the sample size n>14 for the tool magazine with fault data, the y-direction parameter estimation method can be directly used. Based on the above discussion, in combination of the cumulative failure time data of the tool magazine (table 1), we get the result of β=1.047013, α=342.31388.

2.3 Hypothesis testing of reliability model

2.3.1 Linear correlation test

The liner correlation coefficient is

$$\rho = \frac{l_{yx}}{\sqrt{l_{xx} \cdot l_{yy}}} \tag{6}$$

If |ρ $|\hat{\rho}|>\rho_{\alpha}$, we would assume that the correlation relationship between x and y is significant. ρ_α is the critical value of correlation coefficient ρ, which can be found out by the table, or it can be calculated by approximate formula. In this paper, the approximate formula is used to take the level of significance α=0.1, hence

$$\rho_\alpha = \frac{1.645}{\sqrt{\upsilon - 1}} \quad (7)$$

Because there are 29 failures in the tool magazine, the failure time distribution of the tool magazine is hypothetically tested by the correlation coefficient method when v is 29. Using equation (6) we get $\hat{\rho}$ = 0.9837073 and ρ_a=0.311. sinceρ $\hat{\rho}$ >ρ_a, we can get the conclusion that x and y have a strong correlation, so the failure time of tool magazine should follow Weibull distribution.

2.3.2 Hypothesis test for distribution model

We will perform Kolmogorov-Smirnov test to check the failure time distribution function that we obtained above is correct. The main concept is that if the hypothesis is true then D_n should be small, otherwise the hypothesis will be false if D_n is large.

If the distribution function derived from the estimated parameters meets the following conditions, then we can conclude that the parameters that are estimated are reasonable.

$$D_n = \sup_{-\infty<x<+\infty} |F_n(t) - F_0(t)| = max\{d_i\} \leq D_{n,\alpha} \quad (8)$$

In the equation above,

$F_0(t)$ — the original hypothetical distribution function.

$F_n(t)$ — the empirical distribution function with n samples.

$D_{n,\alpha}$—critical value.

d_i as stated below:

$$d_i = max\left\{F_0(t_i) - \frac{i-1}{n}, \frac{i}{n} - F_0(t_i)\right\} \quad (9)$$

The tool magazine hazard function is then calculated as $F(t) = 1 - exp[-\left(\frac{t}{342.31388}\right)^{1.047013}]$, then we will now perform Kolmogorov-Smirnov test. We get D_n =0.105712, with significance level of 0.1, $D_{n,\alpha}$= 0.302683. Because $D_n \leq D_{n,a}$, the hypothesis tests are accepted.

Table 2. Hypothesis test values

$F_0(t) = 1\text{-}exp[-(\frac{t}{\alpha})^\beta]$	$\frac{i-1}{n}$	$\frac{i}{n}$	d_i
0.026151	0	0.034483	0.026151
0.104641	0.034483	0.068966	0.070158
0.125933	0.068966	0.103448	0.056967
0.125933	0.103448	0.137931	0.022485
0.142338	0.137931	0.172414	0.030075
0.146997	0.172414	0.206897	0.059899
0.163194	0.206897	0.241379	0.078185
0.212875	0.241379	0.275862	0.062987
0.221692	0.275862	0.310345	0.088653
0.239116	0.310345	0.344828	0.105712
0.44397	0.344828	0.37931	0.099142
0.481262	0.37931	0.413793	0.101952
0.48596	0.413793	0.448276	0.072167
0.519267	0.448276	0.482759	0.070991
0.529451	0.482759	0.517241	0.046693
0.536607	0.517241	0.551724	0.019365
0.540852	0.551724	0.586207	0.045355
0.570927	0.586207	0.62069	0.049763
0.632695	0.62069	0.655172	0.022477
0.661464	0.655172	0.689655	0.028191
0.684154	0.689655	0.724138	0.039984
0.706349	0.724138	0.758621	0.052271
0.812759	0.758621	0.793103	0.054138
0.817567	0.793103	0.827586	0.024464
0.832392	0.827586	0.862069	0.029677
0.89362	0.862069	0.896552	0.031551
0.906881	0.896552	0.931034	0.024154
0.948316	0.931034	0.965517	0.017282
0.963232	0.965517	1	0.036768

In conclusion the reliability model of tool magazine follows Weibull distribution, it's shape parameter is 1.047, scale parameter is 342.3138. The failure time distribution function of tool magazine F(t), probability density function f(t), reliability function R(t), and failure rate function λ(t) , can be represented as follows:

$$F(t) = 1 - exp\left[-\left(\frac{t}{342.3138}\right)^{1.047}\right] \quad (10)$$

$$f(t) = \frac{1.047}{342.3138}\left(\frac{t}{342.3138}\right)^{0.047} exp\left[-\left(\frac{t}{342.3138}\right)^{1.047}\right] \quad (11)$$

$$R(t) = exp\left[-\left(\frac{t}{342.3138}\right)^{1.047}\right] \quad (12)$$

$$\lambda(t) = \frac{1.047}{342.3138}\left(\frac{t}{342.3138}\right)^{0.047} \quad (13)$$

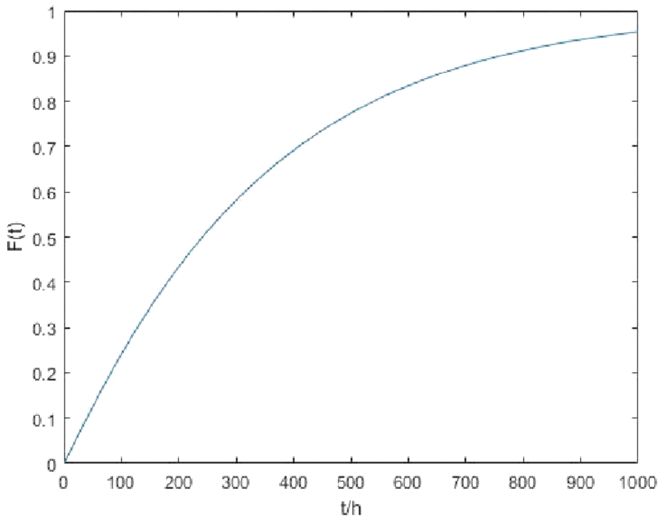

Figure 1. F(t)-failure time distribution function

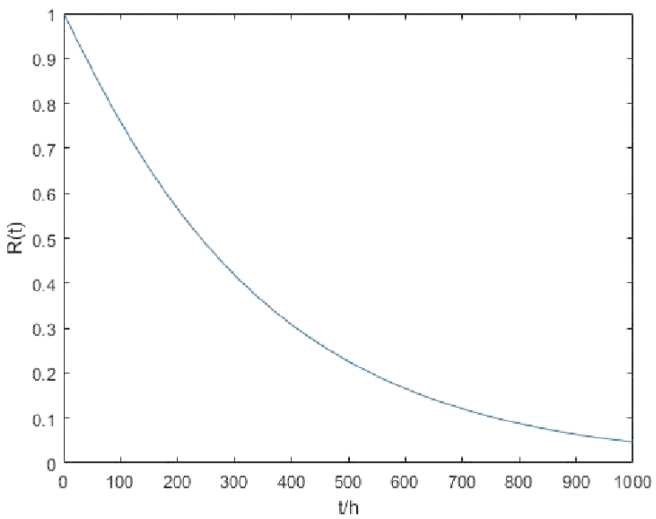

Figure 2. R(t)-reliability function

2.4 Reliability evaluation of tool magazine

Mean time between failure (MTBF), is a measure of how reliable a product or component can be, it is measure as the time between each failure. MTBF is then used to represent the average working time without any faults, which the mathematical expectation E(t) of the failure interval time, t.

Estimated MTBF of tool magazine:

$$MTBF = \int_0^\infty tf(t) = \alpha\Gamma\left(1 + \frac{1}{\beta}\right) \quad (14)$$

$$=342.31388 \times \Gamma\left(1 + \frac{1}{1.047013}\right) = 333.7443(h) \quad (15)$$

3 Maintainability modeling of tool magazine

After analyzing the reliability of the tool magazine in the processing center, the maintenance of the tool magazine needs to be studied. Even if the reliability of the tool magazine is high and the failure rate is low, the credibility level of the tool magazine is obviously not high if it is difficult to repair after a failure or requires a longer repair time. The establishment of maintainability model is the key to quantitative research on the maintenance of the system, and also to lay the foundation for further research on the degree of maintenance impact, so this section will study the maintainability model of the tool magazine in the processing center.

In this paper, we performed a field test and monitored 7 tool magazines for 7 different processing centers, the repair time data obtained as shown in Table 3.

Table 3. Repair time data

Group	Repair time	Number of times appeared	Frequency
1	0.5	10	0.3448
2	1	7	0.24137
3	1.5	6	0.20689
4	2	3	0.103448
5	3.5	1	0.03448
6	5.5	1	0.03448
7	7.5	1	0.03448

3.1 Parameter estimation of maintainability model

If the natural log of repair time t, lnt follows normal distribution, then the distribution function of repair time follows logarithmic normal distribution.

Hence the probability density function of logarithmic normal distribution is:

$$m(t) = \frac{1}{\sigma t\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{ln\,t-\mu}{\sigma}\right)^2} \quad (16)$$

In the equation: μ—the mean value of lnt; 0.088

σ—the variance of lnt; 0.732

The integral of logarithmic normal distribution is:

$$M(t) = \int_0^t \frac{1}{\sigma x\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{ln\,x-\mu}{\sigma}\right)^2} dx \quad (17)$$

Using the maximum likelihood estimate method to estimate μ, σ^2 parameters for the maintainability model. The basic idea of maximum likelihood estimate is that if a parameter has the greatest probability of a sample observation occurring, we will then use this value as the true value of the parameter estimate. Assuming that the observed machining center repair time, t_1, t_2, ⋯ t_n is a sample from a population of the normal distribution of the number of pairs, then the function will be written as:

$$L(t;\mu,\sigma) = \prod_{i=1}^{n} m(t_i) = \prod_{i=1}^{n} \frac{1}{\sigma t_i\sqrt{2\pi}} exp\left(-\frac{1}{2}\left(\frac{ln\,t_i-\mu}{\sigma}\right)^2\right) \quad (18)$$

Take the natural log of both side:

$$ln\,L\,(t;\mu,\sigma) = -\sum_{i=1}^{n} ln\,t_i - \frac{n}{2} ln(2\pi\sigma^2) - \sum_{i-1}^{n}(ln\,t_i-\mu)^2 / (2\sigma^2) \quad (19)$$

The corresponding maximum likelihood estimate equation will be:

$$\begin{cases} \frac{\partial\, ln\,L(t;\mu,\sigma)}{\partial\mu} = \frac{1}{2\sigma^2}\sum_{i=1}^{n} 2(ln\,t_i-\mu) = 0 \\ \frac{\partial\, ln\,L(t;\mu,\sigma)}{\partial\sigma^2} = -\frac{n}{2}\frac{2\pi}{2\pi\sigma^2} + \frac{1}{2\sigma^4}\sum_{i=1}^{n}(ln\,t_i-\mu)^2 = 0 \end{cases} \quad (20)$$

The parameters of logarithmic normal distribution will be:

$$\begin{cases} \hat{\mu} = \frac{1}{n}\sum_{i=1}^{n} ln\,t_i \\ \hat{\sigma}^2 = \frac{1}{n}\cdot\sum_{i=1}^{n}(ln\,t_i-\hat{\mu})^2 \end{cases} \quad (21)$$

Under the premise that the repair time for tool magazine is subject to logarithmic normal distribution, by using equation(21) we will then get estimated $\hat{\mu}$ =0.08804, $\hat{\sigma}^2$ =0.535963, $\hat{\sigma}$=0.732095.

Hence the maintainability model function M(t) is:

$$M(t) = \int_0^t \frac{1}{0.732\sqrt{2\pi}} \cdot e^{-\frac{1}{2}(\frac{ln\,x-0.088}{0.732})^2} \cdot dx$$

Probability density function of maintainability model m(t) is:

$$m(t) = \frac{1}{0.732t\sqrt{2\pi}} \cdot e^{-\frac{1}{2}(\frac{ln\,t-0.088}{0.732})^2}$$

Unrepairable model function G(t) is:

$$G(t) = 1 - M(t) = 1 - \int_0^t \frac{1}{0.732x\sqrt{2\pi}} \cdot e^{-\frac{1}{2}(\frac{ln\,x-0.088}{0.732})^2} \cdot dx$$

Repairable rate function u(t) is:

$$u(t) = \frac{m(t)}{1-M(t)} = \frac{m(t)}{G(t)} = \frac{\frac{1}{0.732t\sqrt{2\pi}} \cdot e^{-\frac{1}{2}(\frac{ln\,t-0.088}{0.732})^2}}{1-\int_0^t \frac{1}{0.732x\sqrt{2\pi}} \cdot e^{-\frac{1}{2}(\frac{ln\,x-0.088}{0.732})^2} \cdot dx}$$

The graph of maintainability model function M(t), probability density function of maintainability model m(t), unrepairable model function G(t), repairable rate function u(t) are shown below.

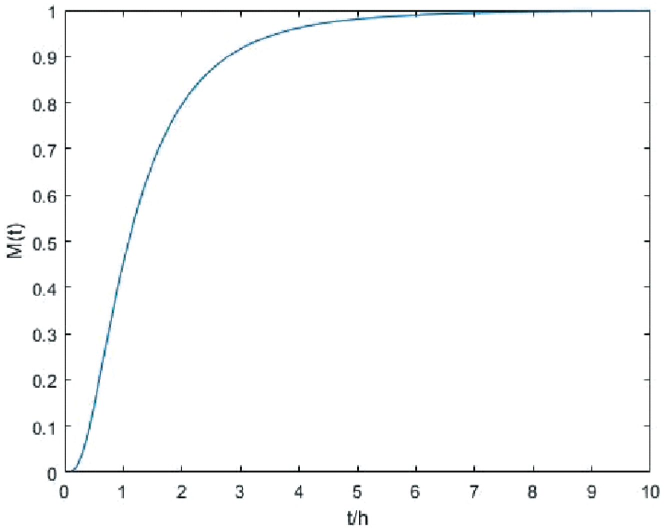

Figure 3. Maintainability model function

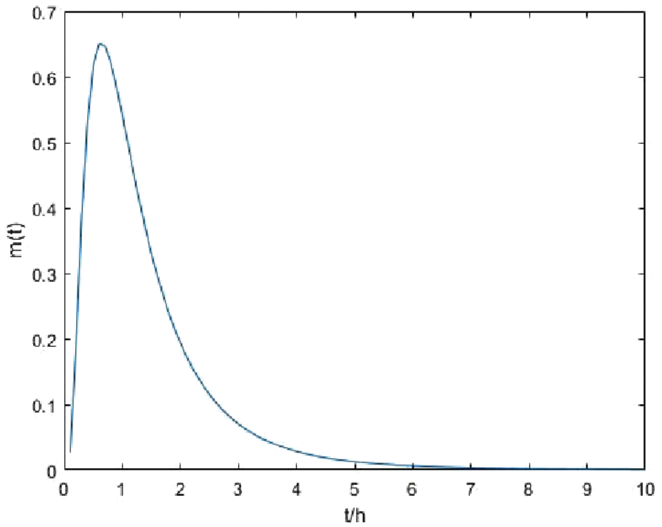

Figure 4. Probability density function of maintainability model

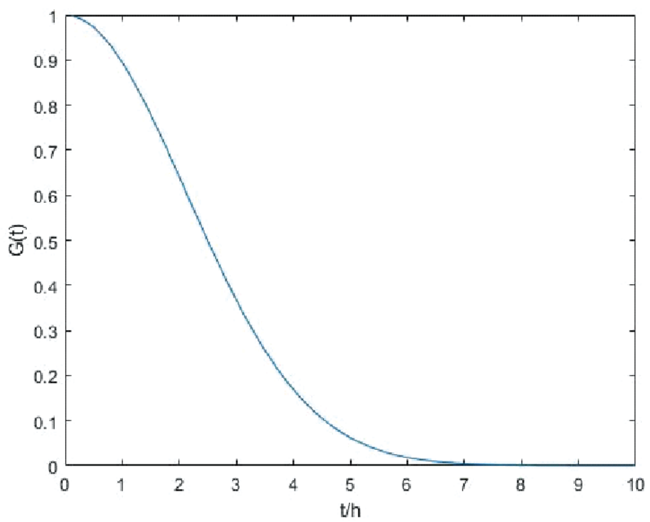

Figure 5. Unrepairable model function

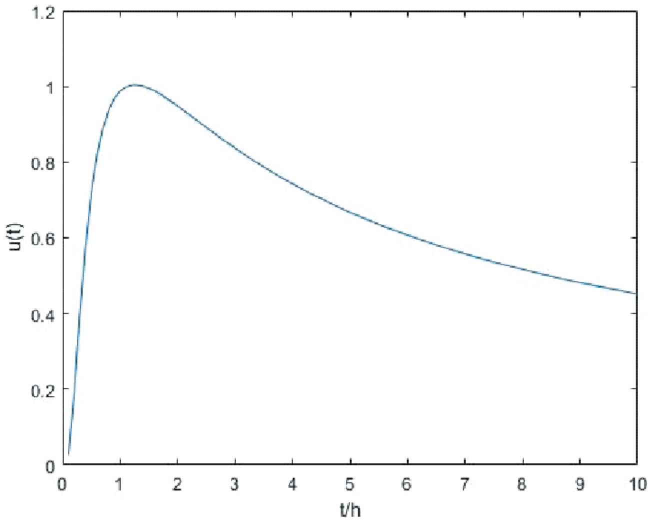

Figure 6. Repairable rate function

3.2 Maintainability evaluation of tool magazine

Mean time to repair (MTTR)

The observed MTTR is:

$$MTTR = \frac{1}{n}\sum_{i=1}^{n} t_i \tag{22}$$

In the equation: n— the cumulative maintenance frequency of tool magazine is n=29;

t_i—the i th repair time

Hence we obtained the observed average repair time MTTR=1.5h.

The equation for estimated MTTR value would be:

$$MTTR = \int_0^{\infty} tm(t)dt = exp(\mu + \frac{\sigma^2}{2}) \tag{23}$$

By doing the calculation above, we obtained MTTR=1.423h, which is close to our observed value.

4 Fault analysis of tool magazine

In this section we perform a fault analysis of the tool magazine. The most frequent failure mode of the tool magazine is the tool magazine offset (71.41%). From the tool magazine failure type frequency graph (Figure 3) and the failure mode frequency table (Table 3) fault types occur most often are dissonance types. Also, from the tool magazine fault cause frequency table (Table 4), and the fault cause frequency graph (Figure 4), the analysis shows that the main causes are parts damage (28.57%) and eelectronic component malfunction (28.57%).

Table 4. Tool magazine failure type frequency table

Codes	Failure type	Failure mode	Number of time occurred	Frequency
0407	Dissonance	TM Dissonance	5	71.43%
0501	Functional	Moving parts failure	1	14.29%
0503	Functional	Trans position not accurate	1	14.29%

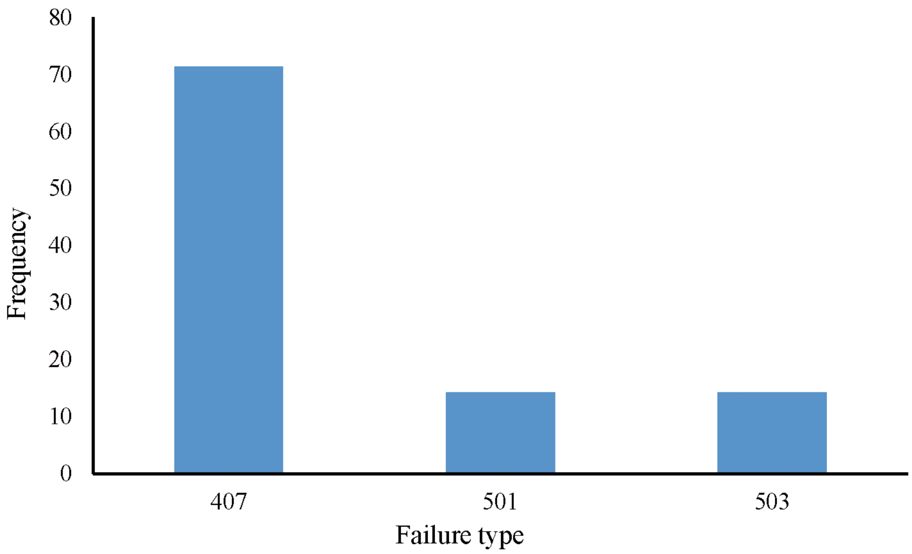

Figure 7. Tool magazine failure type frequency graph

Table 5. Tool magazine failure cause frequency table

Codes	Cause	Number of times occurred	Frequency
33	Electronic component malfunction	2	28.57%
34	Parts damage	2	28.57%
31	Misoperation	1	14.29%
22	Drifting	1	14.29%
36	Improper adjustment	1	14.29%

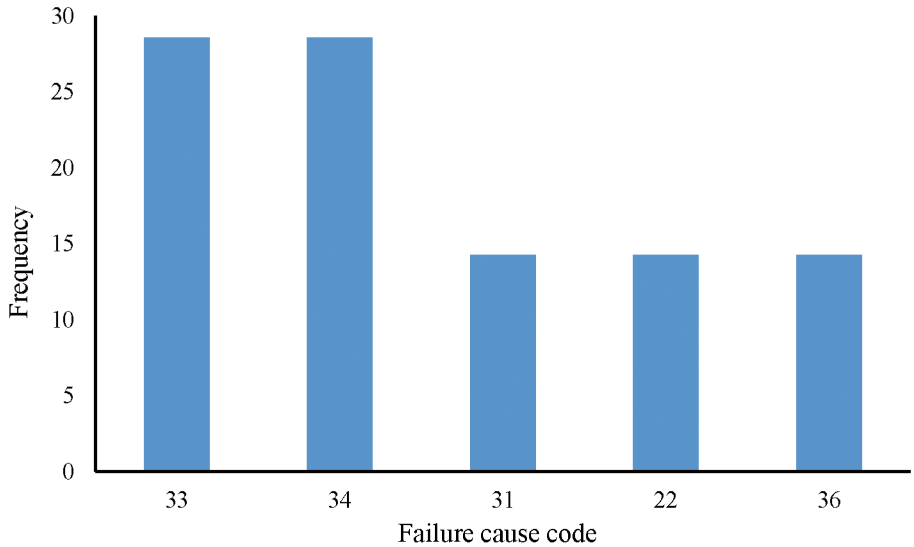

Figure 8. Tool magazine failure cause frequency graph

5 Conclusion

This paper focuses on the modeling and evaluating reliability and maintainability model of the tool magazine in the processing center, and the failure analysis. In the reliability model parameter estimation, the fitting of the least square method in reliability model is discussed, and by using the linear regression fitting we conclude a reasonable parameter for Weibull distribution. According to the conclusion, we obtained $\beta = 1.047$ (shape parameter) and $\alpha = 342.313$ (scale parameter) for the reliability modeling of the tool magazine. As we discussed in the maintainability modeling of tool magazine section, if the natural log of t follows the normal distribution, then the repair time should follow logarithmic normal distribution as well. Then we used maximum likelihood estimate method to the parameters for maintainability model distribution. The parameter estimation of the maintainability model is obtained, $\mu = 0.088$, $\sigma^2 = 0.536$, follow by the evaluation of maintainability of tool magazine. Finally, the failure analysis of the tool magazine is carried out and found that the tool magazine dassonance fault mode is the most frequent, at 71.43%, the main cause of which is the electrical components failure and parts failure.

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