INVESTIGATION ON OPERATIONAL RELIABILITY OF HEAT PUMP SYSTEMS

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ABSTRACT

Estimation of the mean time between failures (hereinafter termed MTBF) for random failure is a well-known part of equipment engineering, but no discussion of MTBF presently exists in connection with building equipment. In this study, an investigation of MTBF estimation for random failure is made using field data of building equipment operations, and a comparison of results is conducted by applying two methods of interval estimation. The study touches upon the relationship of the results achieved by the Bayesian approach with the assessed values of practical operations. The author employed simulation of a maximum-likelihood method with the Bayesian method in estimating the failure rate and then analyzed it by using the data of building equipment and devices for a period of random failure. Especially it estimated the comparison between heat pump system and other building system. These results suggest the most suitable and practical way of MTBF estimation for actual maintenance sites.

Key Words: ***operational, reliability, building, equipment, heat pump system.***

1 INTRODUCTION

Estimation of the MTBF for Random Failure is the basic subject to be studied, and much discussion of such subject is being made at present in connection with the building equipments. A close examination of the interval estimation of MTBF is indispensable in establishing the maintenance periods of building automation system (BAS), etc.

In this study, the MTBF estimation for random failure is investigated using the field data of building equipment operations and the comparison of the results is conducted by applying two methods for the interval estimation. Furthermore, it touches upon the relationship of the analysis results achieved by the Bayesian approach with the assessed values of the practical operations. A simulation of maximum-likelihood method in comparison with Bayesian method in estimating the failure rate is performed, and then it is analyze by using the data of building equipments and devices for random failure period to find the most suitable and practical way of MTBF estimation for actual maintenance sites.

It analyzed with the data acquired in thirty facilities for the office building on the Tokyo, Japan. The author selected those facilities from the 352 materials at hand because all those facilities are completed in Oct. of 1994 and their age is just ten years in Sep. of 2004. Especially it estimates the comparison between heat pump system and other building system. These results suggest the most suitable and practical way of MTBF estimation for actual maintenance sites.

2 CONCEPT OF RANDOM FAILURE

The concept of random failure differs depending on respective building equipment systems or devices as there is no definite criterion at present. However, any failures which occur during the period after elapse of the usual one-year guarantee period and before start of abrasion failure may be considered as the random failure.

3 THEORETICAL BACKGROUND OF ASSESSMENT IN RANDOM FAILURE

3.1 Maintenance Curve and MTBF

The conceptual maintenance curve is well known as “bathtub” curve. But in reality the functional conditions are changing up and down along with the repeat of functional degradation and restoration depending upon the regular inspection conditions during the period of random failure.

It is attempted in this study to estimate the intervals between the upper limit value and the lower limit value of MTBF in order to maintain the wholesome functions required for building equipments. Then it is examined and compared with application of the field data of actual building equipments by two methods of interval estimation. Moreover, it refers to the relationship between the analysis results by the Bayesian approach and the assessed values.

3.2 Interval Estimation of MTBF in Exponential Distribution

3.2.1 Outline of Interval Estimation

To perform the interval estimation of MTBF in exponential distribution, it is necessary to estimate the interval from the assessed values. In other words, there exists a certain value in the interval of the upper and lower limits of MTBF, and the interval estimation is to estimate the change of the value between those limits. The probability for existence of MTBF within that interval is called the assessed value.

3.2.2 The Closing Data

In most cases, the maintenance data of building equipments are the closing data. In fact, there are many cases in conducting sample analysis of the data from population, or many cases in using the data accumulated for a certain period of time. The closing is generally divided into two categories; one is fixed time closing and the other is fixed number closing.

3.2.3 c^2 (Chi-Square) Distribution

c^2 (Chi-Square) distribution is used for interval estimation. In the cases of fixed time closing and fixed number closing, c^2 distribution, assuming the assessed values as (1-a), multiplies to the value calculated from MTBF=T/r (where T is Total Operation Time, and r is Total Number of Failure) by c^2 (2r, a). 2r in c^2 (2r, a) denotes the degree of freedom of c^2 distribution, and a, the probability (ratio of risk) that goes out of the interval.

3.2.4 Bayesian Method

Bayesian method can be characterized in respect of using the prior information obtained from the past information jointly with the data in estimating and inspecting the parameter which is important for the estimation of failure rate. Fig. 1(a) shows the estimation method by sampling distribution and Fig. 1(b) shows the estimation method by Bayesian method. When combining the data with the prior information, the Bayesian theorem is used as shown in Fig. 1(b).

The difference between the conventional method and the Bayesian method can be summarized as follows.

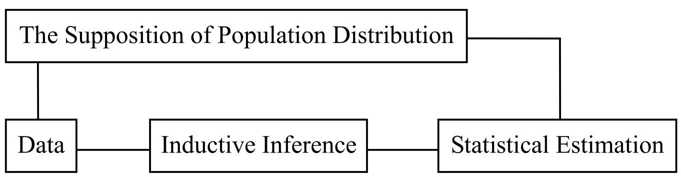
1. With the use of prior information, the Bayesian method will work with a small number of data in obtaining the same accuracy compared with the case of conventional sampling distribution method. And it can alleviate the problem of decreasing number of the data, when subdividing the item-classifications of the field data at the site.
2. The Bayesian method provides wider scope of applications being capable of using the past information reflected as the prior information despite the population distribution is changed due to the improvement of system, equipments, or devices.

Here, the expansion of the Bayesian method for random failure (period) is shown. In this study, the probability density function of the population distribution is considered as the exponential one. That is , given with $f(t|\alpha)=l \exp(-\alpha t)$ $(t>=0,l>0)$, and when evaluating ex post facto distribution $g(\alpha|T)$ of L by the Bayesian theorem after data $T=(t_1,\ldots,t_n)$ is observed, it becomes,

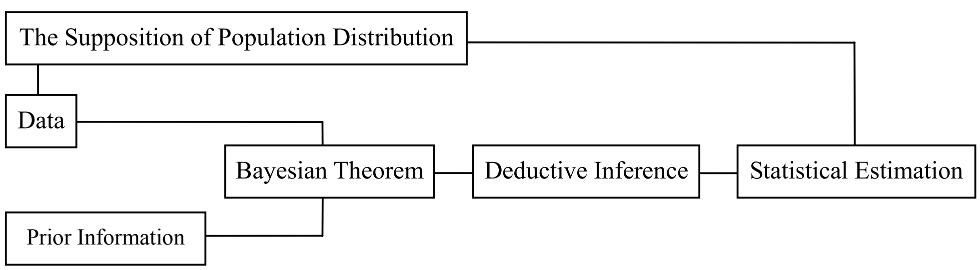
$$g(\lambda \mid T) = \frac{f(T,\lambda)}{f(T)}$$

$$= \frac{(\alpha + T)^{\beta+n}}{\Gamma(\beta+n)} \lambda^{\beta+n-1} \exp(-\lambda(\alpha + T))$$

In the above equation, ex post facto distribution g(α|T) becomes gamma distribution of the parameter (α+T), (β+n). By using the equation, one can estimate failure rate by the Bayesian method. For further details of the gamma distribution can be found in many published materials.



(a) The Estimation for Sampling Distribution



(b) The Estimation for Bayesian Method

Fig. 1. Estimations for Sampling Distribution and Bayesian Method

4 ESTIMATION OF PARAMETER BY THE BAYESIAN METHOD

In the study, the random failure period is assumed. A maximum of twenty-two random numbers are generated, a total of fifty pieces observatory data are input, and five closing data corresponding to three, five, ten, fifteen, and twenty-two are set, respectively.

Furthermore, the failure rate or ex post facto distribution a, b. Finally, the calculated results are examined and compared with the result of the conventional maximum-likelihood method to obtain the following discussions.

The difference between the results by the maximum-likelihood method and the Bayesian method becomes small with the growth of the number of test data but when the number of the available test data is less than fifteen, the Bayesian method has to be used. As for the MTBF, the difference between the results by the two methods is not large at all. Therefore for newly completed building equipment systems and devices, the Bayesian method should be applied.

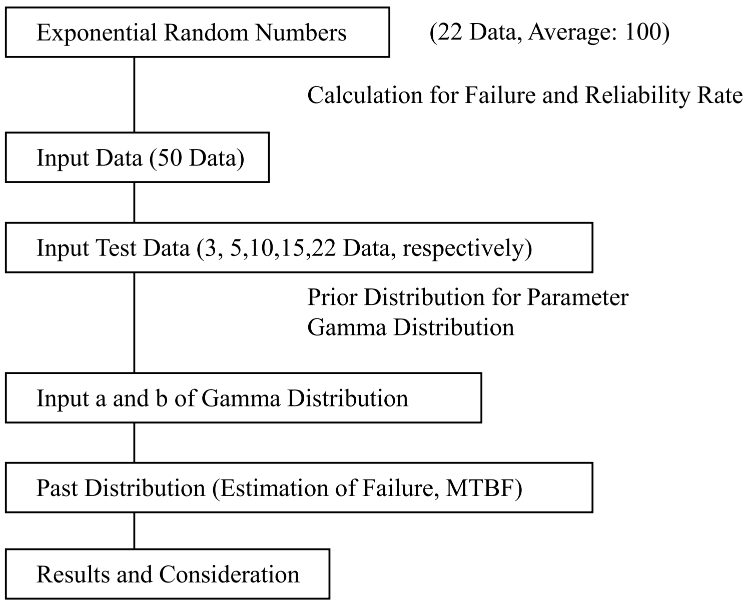


Fig. 2. Simulation Flow Chart for the Study

Table 1. Simulation Results by the Maximum-Likelihood Method and the Bayesian Method

Test Data	**Maximum-Likelihood Method**		**Bayesian Method**	
	Failure Rate	**MTBF(Days)**	**Failure Rate**	**MTBF(Days)**
3	0.057	17.618	0.071	19.024
5	0.051	19.464	0.059	20.367
10	0.043	23.325	0.046	23.854
15	0.039	25.805	0.041	26.192
22	0.015	69.161	0.015	68.854

5 COMPARISON AND EXAMINATION OF SIMULATION RESULTS

Table 2 summarizes the simulation results with four different test data points by the maximum-likelihood method and Bayesian method for failure rate and MTBF. Consideration of these tables can be summarized as follows.

1. The Bayesian method can handle a small number of data points, which the maximum-likelihood method cannot, and one could note the higher values calculated in estimating the failure rate

compared with the maximum-likelihood method.

2. The Bayesian method moves closer to the maximum-likelihood method if test data grow in number; therefore, it can be applied even to recently installed building equipment systems and devices, where only a small number of data are available. One can also notice that there is no big difference in the results of the two methods for analysis of MTBF, which is the reciprocal of failure rate.

6 APPLICATION TO BUILDING EQUIPMENT—MAINLY ESTIMATE THE COMPARISON BETWEEN HEAT PUMP SYSTEM AND OTHER BUILDING SYSTEM

6.1 Analysis Data Applied

The data used in this study are the result of an analysis of four systems, whose total operating hours could be clearly determined among the air-conditioning devices and the electrical installations of a certain building. Table 2 summarizes the systems chosen, names of equipment and devices, number of failure cases, and MTBF.

In this study, it analyzed with the data acquired in thirty facilities for the office building on the Tokyo, Japan. The author selected those facilities from the 352 materials at hand because all those facilities are completed in Oct. of 1994 and their age is just ten years in Sep. of 2004.

Especially it estimated the comparison between heat pump system and other building system. These results suggest the most suitable and practical way of MTBF estimation for actual maintenance sites.

6.2 About the Estimation Method

Estimation of MTBF for the period of random failure is examined and compared by applying the interval estimation methods of fixed time closing and fixed number closing, with the use of actual building equipment. The assessed values are estimated on both sides at intervals of 60%, 80%, 90%, and 95%. Those results are shown in Tables 3 through 8.

Table 2. Names of Equipment and Devices, Number of Failure Cases, and MTBF

Names of Equipment and Devices	Number of Failures	MTBF
Heat Pump	183	718.43
Chiller Unit	72	1826.00
Return Fan	54	2434.67
Power Facilities	186	706.84

6.3 Comparison Between Bayesian Estimation and the Results of Fixed Time Closing

Table 7 is summary of the values of MTBF in the Bayesian estimation data, using the formula of g (λ/T), together with results of upper limit and lower limit assessed values at 60% by fixed time closing; as obtained Table 3 and 4.

As shown in those tables, the Bayesian method estimation is included in the interval of upper limit and lower limit assessed values at 60% by fixed time closing; therefore, it is considered useful for practical applications. Also, it suggests a standard value by which one can judge the assessed values of general building equipment by comparison with assessed values of 80%, 90% and 95%. And it estimated the comparison between heat pump system and other building system.

6.4 Results of Simulation

Simulation was conducted on four pieces of building equipment and devices, whose total operating hours were clearly determined as mentioned above. Table 8 lists the equipment and devices, number of failure cases, mean value of failure rates, standard deviations, fluctuation coefficient, and results of failure rate estimation by the Bayesian method. It assumed the operating hours as five years (43,200 hours), as calculated from the above values together with values obtained by the conventional maximum-likelihood method.

The tendency and characteristics from Table 8 can be summarized as follows:

1. When the result of failure rate estimation by the Bayesian method is compared with result of the maximum-likelihood method, the Bayesian method shows higher values. This result is the outcome of using a more accurate estimation of the failure rate with the addition of the prior information, that is, a prior distribution of the parameter in the population of the data.
2. Seeing the simulation result those Tables, the transition of failure rates varies by each system, piece of equipment, or device. Accordingly, the estimation to determine the regular inspection

period can easily be made by the Bayesian method. For example, in the case of the chiller unit, the failure rates greatly decrease before and after 80 days MTBF, so the regular inspection period should be set before the failure rates decrease. The estimation is considered possible by this method for maintaining the building equipment systems and devices below a certain failure rate.

Table 3. Relation Between Assessed Values and Upper Limit for Fixed Time

Names of Equipment and Devices	Assessed Values			
	60%	80%	90%	95%
Heat Pump	8.1×10^2	8.6×10^2	9.0×10^2	9.4×10^2
Chiller Unit	22.1×10^2	24.4×10^2	26.5×10^2	28.5×10^2
Return Fan	30.5×10^2	34.2×10^2	37.7×10^2	41.1×10^2
Power Facilities	7.9×10^2	8.4×10^2	8.8×10^2	9.2×10^2

Table 4. Relation Between Assessed Values and Lower Limit for Fixed Time

Names of Equipment and Devices	Assessed Values			
	60%	80%	90%	95%
Heat Pump	6.4×10^2	6.1×10^2	5.8×10^2	5.6×10^2
Chiller Unit	15.1×10^2	13.9×10^2	13.0×10^2	12.3×10^2
Return Fan	19.5×10^2	17.7×10^2	16.4×10^2	15.4×10^2
Power Facilities	6.3×10^2	6.0×10^2	5.7×10^2	5.5×10^2

Table 5. Relation Between Assessed Values and Upper Limit for Fixed Number

Names of Equipment and Devices	Assessed Values			
	60%	80%	90%	95%
Heat Pump	8.1×10^2	8.6×10^2	9.0×10^2	9.4×10^2
Chiller Unit	22.1×10^2	24.4×10^2	26.5×10^2	28.5×10^2
Return Fan	30.5×10^2	34.2×10^2	37.7×10^2	41.1×10^2
Power Facilities	7.9×10^2	8.4×10^2	8.8×10^2	9.2×10^2

Table 6. Relation Between Assessed Values and Lower Limit for Fixed Number

Names of Equipment and Devices	Assessed Values			
	60%	**80%**	**90%**	**95%**
Heat Pump	6.5×10^{2}	6.2×10^{2}	5.9×10^{2}	5.7×10^{2}
Chiller Unit	15.7×10^{2}	14.4×10^{2}	13.5×10^{2}	12.7×10^{2}
Return Fan	20.5×10^{2}	18.6×10^{2}	17.2×10^{2}	16.1×10^{2}
Power Facilities	6.4×10^{2}	6.1×10^{2}	5.8×10^{2}	5.6×10^{2}

Table 7. The Summary of the Estimate Values

Names of Equipment and Devices	Shape Parameter	Bayesian Estimation	Upper Limit Assessed Values at 60%	Lower limit Assessed Values at 60%
Heat Pump	0.71	7.3×10^{2}	8.1×10^{2}	6.4×10^{2}
Chiller Unit	0.74	19.2×10^{2}	22.1×10^{2}	15.1×10^{2}
Return Fan	0.71	26.1×10^{2}	30.5×10^{2}	19.5×10^{2}
Power Facilities	0.65	7.2×10^{2}	8.0×10^{2}	6.3×10^{2}

Table 8. Results of Simulation for Six Building's Equipment and Devices

Names of Equipment and Devices	Sampling Data	Failure Rate (Days) For Past Information	Bayesian Estimation (Gamma,Exponential Distribution)	Bayesian Estimation (Gamma,Poisson Distribution)	Maximum-likelihood Estimation	MTBF for Bayesian method (Days)
Heat Pump	183	0.0181	0.040	0.034	0.039	30.1
Chiller Unit	72	0.0308	0.027	0.014	0.026	75.1
Return Fan	54	0.0138	0.021	0.010	0.020	102.5
Power Facilities	186	0.0324	0.044	0.035	0.043	29.1

7 CONCLUSIONS

1. When the data of fixed time closing are compared with the data of fixed number closing, the fixed time closing has a wider confidence interval. That is, the data of fixed time closing are considered more desirable to adopt in estimating the most suitable and practical MTBF for actual maintenance sites of building equipment.
2. The confidence interval of MTBF is wider when failure rates are lower but narrower when failure rates are higher. For example, if heat pump and the return fan system are compared at the assessed values of 60%, the maintenance failure of the heat pump system is 8.1×10^2(minutes), while that of return fun is 35×10^2(minutes).
3. Although the number of failure cases is the same, the confidence interval increases for a higher assessed value, which can be the basic data for judgment of which assessed value should be adopted at the site.
4. It is concluded that a more accurate estimation of MTBF during random period failure can be made by using Bayesian estimation along with interval estimation of MTBF.
5. It is believed that the Bayesian estimation method can be the standard for proper determination of the operating assessed values for general building equipment, as the method includes the upper and lower limits of the assessed values at 60% by fixed time closing. The writers intend to calculate the results for more equipment systems and devices selected for the assessment of random failure.
6. From simulation results derived by exponential random numbers, it is known that the greater the number of test data points, the smaller the value of the shape parameter, making a gentle slope on Weibull probability paper. Again, in the comparative examination of the simulations by the maximum-likelihood and the Bayesian method, it is known that the Bayesian method can handle a small number of data points, which are seemingly impossible to handle by the maximum-likelihood method. Also, in estimating the failure rate, the Bayesian method yields the higher values than the maximum-likelihood method.
7. From the results of application to building equipment systems and devices, it is clear that Bayesian method, by use of historical information, can estimate a more accurate failure rate. Furthermore, it is considered to provide estimations that enable maintaining the building equipment systems and devices below a certain level of failure rate.

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