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SENSITIVITY ANALYSIS IN FUZZY RELIABILITY ANALYSIS

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Abstract: In this paper the failure possibility and the error possibility are used to represent reliability of a technical component and that of a human operator, respectively. The failure possibility and the error possibility are fuzzy sets on the interval [0,1]. In a man-machine system, reliability of the technical component and that of the human operator are usually affected by many factors, e.g., the environment in which a machine is operated, psychological stress of the human operator, etc. The possibility is derived from not only the failure or the error rate but also estimates of these factors. The fuzzy reasoning plays an important role in the derivation. The reliability analysis is performed by the use of the possibility obtained by the present method. Moreover this paper discusses the sensitivity analysis which evaluates what extent the change of the estimation of each factor has an influence on reliability of a man-machine system. The important factors to be ameliorated are shown through the sensitivity analysis.

1. Introduction

It is not likely that enough amount of data with respect to the failure of a technical component or human error can be collected to estimate the failure rate or the error rate. The estimation of the failure and the error rates cannot help being dependent on engineering judgement. Moreover technical component reliability and human reliability are affected by many factors, e.g., the environment in which a machine is operated, psychological stress of a human operator, etc. The failure and the error rates are modified by experts to consider the effect of these factors. So reliability is a subjective concept.

In the conventional reliability analysis the failure and the error rates are expressed by the triplet[1][2], i.e., the recommended value, its lower and upper bounds, in order to deal with imprecision caused by lack of data and the estimation of the effect of the factor.

The fuzzy theory is available to deal with subjectivity. There have been various applications of the fuzzy theory in a variety of fields [3]. The fuzzy theory is also applied to the reliability analysis and the risk analysis.

The concept of "fuzzy probability" is employed in [4] and [5] since it may be difficult to assign exact values to the probabilities of occurrence of failures, and in the absence of genuine probability data, estimates of failure probabilities are customarily supplied by personnel familiar with the operation of the system.

An automated risk analyzer is presented in [6]. The risk analyzer allows natural language estimates because of overall complexity and inherent imprecision. Overall complexity exists in the analyzed system. Inherent imprecision implies that there just isn't sufficient data for such a mathematically precise estimate. So it is unrealistic to calculate the failure probability. Schmucker[6] says that in making replacement of "EXTREMELY LOW" for the failure probability 0.00162, we are sacrificing the "precision" of numerical estimate to gain the believability and confidence of an inexact, "fuzzy" estimate that is both more realistic and easier to interpret.

A structural model of human reliability[7] is proposed by the use of the fuzzy theory. This model represents the relations among four parameters, "job load", "ability", "stress" and "concentration allocation".

The failure possibility[8] and the error possibility[9] have been proposed in the analysis of technical component reliability and in that of human reliability, respectively. These concepts are based on consideration that all one can reasonably estimate is the possibility or the plausibility of an event taking place, given the information that you can have on hand or can reasonably assemble[6]. The failure possibility and the error possibility are fuzzy sets on the interval [0,1]. These possibilities are subjective measures and can be regarded as the same measure in the reliability analysis[10]. The error possibility can be combined with the failure possibility in the reliability analysis of a man-machine system. On the other hand the error rate and the failure rate should not be regarded as the same measure. It is meaningless to combine these rates. The comparison between the result of the human reliability analysis by the use of the error possibility and that by the use of the error rate has been performed and the validity of the fuzzy reliability analysis has been shown[11].

This paper discusses the derivation of these possibilities from not only the failure or the error rate but also estimate of many factors which affect reliability. Estimate of the factor is also dependent on the engineering judgement and the experience. So the given information is imprecise. The derivation of possibilities is based on the qualitative relation between reliability and each factor. The fuzzy reasoning[12] plays an important role to derive possibilities. The reliability analysis is performed by the use of the possibility obtained by the present method.

This paper also discusses the sensitivity analysis which evaluates what extent the change of estimate of each factor has an influence on reliability of a man-machine system. The important factors to be amelirated are shown through the sensitivity analysis.

Hereafter the failure possibility and the error possibility are treated together as the fuzzy reliability.

2. Fuzzy Reliability

Let us consider a fuzzy set on the interval [0,1] with a possibility distribution such as

$$F(x) = \frac{1}{1 + 20 \times |x - x_0|^m}, \qquad (1)$$

where $m = m_L$ when $x \leqq x_0$ and $m = m_U$ when $x \geqq x_0$.

The parameter x_0 gives the maximal grade of F(x) and the parameter m is related to fuzziness. F(0) implies the degree of a possibility that a technical component does not break down absolutely or a human operator does not fail absolutely. On the other hand F(1) implies the degree of a possibility that the technical component breaks down certainly or the human operator fails certainly. Eq. (1) means that even if x_0 is small, $F(x) > 0$ for all $x \in [0,1]$, i.e., there is a possibility that the technical component breaks down or the human operator fails.

2.1 Derivation of Fuzzy Reliability from Failure or Error Rate

Let $[P_L, P_M, P_U]$ be the triplet of the failure or the error rate (hereafter the failure and the error rates are treated together as the rate), where P_M is the recommended value of the rate, P_L is its lower bound and P_U is its upper bound.

1) x_0 is derived from P_M.

$$x_0 = f(P_M) = \frac{1}{1 + (K \times \log(1/P_M))^3}, \qquad P_M \neq 0 \qquad (2)$$

where f(0) = 0 and K is a constant.

Table 1 Classification of x_0

Class	Bounds of x_0	Representative Value of x_0
C_1	1.0	-
C_2	0.9 - 1.0	0.95
C_3	0.7 - 0.9	0.8
C_4	0.5 - 0.7	0.6
C_5	0.3 - 0.5	0.4
C_6	0.2 - 0.3	0.25
C_7	0.1 - 0.2	0.15
C_8	0.05 - 0.1	0.075
C_9	0.0 - 0.05	0.025
C_{10}	0.0	-

Logarithmic function in Eq. (2) is used in order to fit the very small rate to our feeling. Eqs. (1) and (2) imply that even if the rate is estimated to be very small from the viewpoint of reliability, there is a possibility that the technical component breaks down or the human operator fails. The parameter K means the safety criterion[8]. Table 1 shows the classification of x_0.

2) m is derived from $[P_L, P_M, P_U]$.

i) Define $k_L = P_M/P_L$ and $k_U = P_U/P_M$. Those k_L and k_U are treated together as k.

ii) Four uncertainty bounds are defined, such as $k \leq 3$, $3 < k \leq 5$, $5 < k \leq 10$ and $10 < k$.

iii) In the class C_5, define m = 2.0 for $k \leq 3$, m = 2.5 for $3 < k \leq 5$, m = 3.0 for $5 < k \leq 10$ and m = 3.5 for $10 < k$.

iv) In each class the representative value of x_0 is defined as shown in Table 1. The representative value of x_0 is the middle point of the bounds of x_0 in each class.

Let $F_i(x)$ be the fuzzy reliability in the class C_i and x_{0i} be the representative value of x_0 in the class C_i, i.e., $F_i(x_{0i}) = 1$ (i = 2, 3, ---, 9).

v) Within the same uncertainty bounds m is obtained so as to satisfy

$$F_i(x_i) = F_5(x_5), \qquad (3)$$

where $x_i = f(10 \times P_{Mi})$ when m_U is obtained, $x_i = f(P_{Mi}/10)$ when m_L is obtained, and $x_{0i} = f(P_{Mi})$.

The value of m in each class is compared with that of m in the class C_5 in the sense of Eq. (3).

The fuzzy reliability in the class C_1 is defined as

$$F_1(x) = \begin{cases} 1, & x = 1, \\ 0, & x \neq 1, \end{cases} \qquad (4)$$

and that in the class C_{10} is defined as

$$F_{10}(x) = \begin{cases} 0, & x \neq 0, \\ 1, & x = 0. \end{cases} \qquad (5)$$

2.2 Derivation of Fuzzy Reliability from Estimate of Many Factors

Technical component reliability and human reliability are affected by many factors, e.g., the environment in which a machine is operated, the psychological stress of a human operator, etc. In this section the effect of these factors on reliability is considered. It may be easy to express the relation between these factors and reliability qualitatively. For example, with respect to technical component reliability,

(T1-1) If quality of environment is good, then component reliability is high.
(T1-2) If quality of environment is bad, then component reliability is low.
(T2-1) If quality of maintenance is good, then component reliability is high.
(T2-2) If quality of maintenance bad, then component reliability is low.

With respect to human reliability,

(H1-1) If quality of work environment is good, then human reliability is high.
(H1-2) If quality of work environment is bad, then human reliability is low.
(H2-1) If degree of competence of a human operator is high, then human reliability is high.
(H2-2) If degree of competence of a human operator is low, then human reliability is low.
(H3-1) If quality of man-machine interface is good, then human reliability is high.
(H3-2) If quality of man-machine interface is bad, then human reliability is low.
(H4-1) If degree of fatigue is low, then human reliability is high.
(H4-2) If degree of fatigue is high, then human reliability is low.
(H5-1) If degree of stress is optimum, then human reliability is high.
(H5-2) If degree of stress is low, then human reliability is slightly low.
(H5-3) If degree of stress is high, then human reliability is low.

Terms "good", "bad", "high", "low" and "slightly low" are expressed by fuzzy sets on the interval [0,1]. Fig. 1 shows the above expressions by the use of fuzzy sets. In Fig. 1

$$x^* = f(P_M), \qquad (6)$$

where P_M is the recommended value of the rate,

and

$$x' = \frac{x^* + 1}{2}. \qquad (7)$$

The parameter x_0 in Eq. (1) is obtained by the

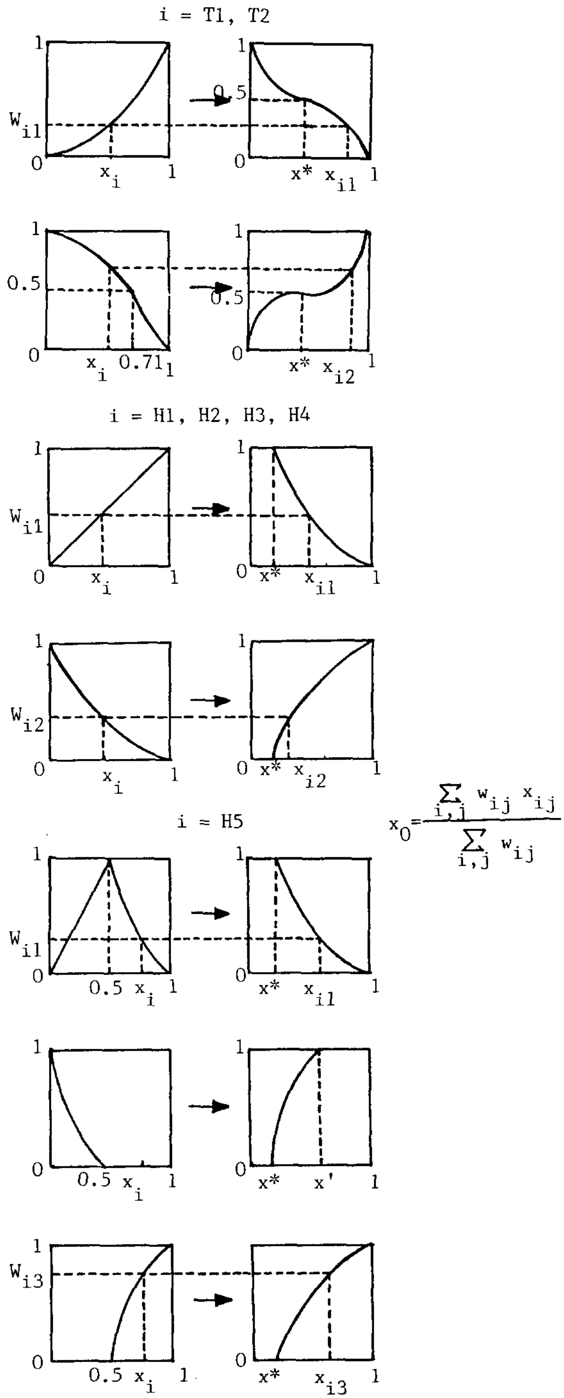

Fig. 1 Relation between Reliability and Estimate of Factor

fuzzy reasoning when estimate of each factor is given. Fig. 1 also illustrates the calculation sequence at estimate of each factor, i.e., x_i (i = T1, T2, H1, H2, ---, H5). The calculation sequence[13] is described in details as follows.

Let $h_{ij}(x)$ and $g_{ij}(x)$(j = 1, 2 when i = T1, T2, H1, ---, H4 and j = 1, 2, 3 when i = H5) be the membership functions of fuzzy sets which express the "if part" and the "then part", respectively.

1) Calculate

$$w_{ij} = h_{ij}(x_i). \tag{8}$$

Each w_{ij} means the degree of satisfaction of the premise.

2) Find x_{ij} such as

$$w_{ij} = g_{ij}(x_{ij}). \tag{9}$$

3) Calculate

$$x_0 = \frac{\sum_{i,j} w_{ij} \times x_{ij}}{\sum_{i,j} w_{ij}}. \tag{10}$$

As the parameter m in Eq. (1), the numerical values, which are derived from the triplet of the rate, are used. That is to say, the fuzzy reliability derived from the rate and estimate of each factor is obtained by the parallel translation of the fuzzy reliability which is derived from only the triplet of the rate.

3. Reliability Analysis Using Fuzzy Reliability

In this section the failure of a technical component and the failure in a human task are called as the event. It is assumed that two events are independent of each other.

3.1 Logical Connectives

3.1.1 AND Connective

It is assumed that if two events happen, then

$$H(x, y) = \frac{1}{1 + (((1-x)/x)^{1/3} + ((1-y)/y)^{1/3})^3}, \tag{11}$$

where $0<x,y\leq 1$ and $H(0,y)=H(x,0)=0$.

an accident occures. The fuzzy reliability of the total system is obtained by the function H and the extension principle[14].

3.1.2 OR Connective

It is assumed that if at least one of two events happens, then an accident occures. The

$$G(x, y) = \frac{((x/(1-x))^3 + (y/(1-y))^3)^{1/3}}{1 + ((x/(1-x))^3 + (y/(1-y))^3)^{1/3}}, \tag{12}$$

where $0\leq x,y<1$ and $G(1,y)=G(x,1)=1$.

fuzzy reliability of the total system is obtained by the function G and the extension principle.

3.1.3 Depenedence between Two Events

It is assumed that if the event A happens, then the event B is liable to happen. Let F_A be the fuzzy reliability of the event A, F_B be that of the event B and R be the degree of the dependence between two events A and B. F_B', which is the fuzzy reliability of the event B influenced by the occurrence of the event A, can be estimated by "F_A AND R". The fuzzy reliability of the system with dependence is found in the following steps.

1) The case that the occurrence of the event A influences that of the event B.

F_B' is the fuzzy reliability of the total system, i.e.,

$$F_B' = H(F_A, R). \tag{13}$$

2) The case that the occurrence of the event A does not influence that of the event B.

As far as the dependence between two events is not complete dependence, the occurrence of the event A does not always influence that of the event B. The portion of the fuzzy reliability of the event A which does not influence the occurrence of the event B is obtained by

$$F_A = G(F'_A, F'_B), \tag{14}$$

where F'_A is this portion.

That is to say, the occurrence of the event A influences that of the event B (F'_B) or not(F'_A). The fuzzy reliability of the total system F' in the case 2) is obtained by

$$F' = H(F'_A, F_B). \tag{15}$$

F' implies the fuzzy reliability that the event A occures and the event B occures not influenced by the occurrence of the event A.

3) The fuzzy reliability F as a whole is obtained by

$$F = G(F', F'_B). \tag{16}$$

The fuzzy reliability F is obtained by taking two cases into consideration: the occurrence of the event B is influenced by that of the event A (F'_B) or not influenced (F'). Eqs. (13) through (16) are calculated by the extension principle.

3.1.4 Evaluation

A fuzzy reliability F is evaluated from four points of view. Let $(F)_\alpha = (x1(\alpha), x2(\alpha))$ be α-cut of F.

1) x_0 which gives the maximal grade of F.

$$J1 = x_0. \tag{17}$$

2) potentiality for failure or error

Define

$$J2 = \frac{\int_0^\beta (x2(\alpha) - 0.5)\alpha d\alpha}{\int_0^1 (1 - 0.5)\alpha d\alpha}, \tag{18}$$

where $x2(\beta) = 0.5$.

J2 is evaluated when J1 < 0.5. J2 is interpreted as the potentiality for failure or error since the part of the fuzzy reliability such as $x2(\alpha) \geqq 0.5$ for $\alpha \in [0, \beta]$ is evaluated by Eq. (18). It can be considered that the larger J2 becomes, the higher the potentiality for failure or error becomes, even if x_0 is evaluated to be small.

3) fuzziness of reliability

Define

$$J3 = \frac{\int_0^1 (x2(\alpha) - x_0)\alpha d\alpha}{\int_0^1 (1 - x_0)\alpha d\alpha}, \tag{19}$$

where $x2(\alpha) \geqq x_0$ for $\alpha \in [0,1]$.

The fuzziness of reliability is evaluated by Eq. (19). It can be considered that if J3 is large, J1 is not evaluated with confidence.

4) the relative potentiality and the relative fuzziness

Define

$$J2' = \frac{\int_0^\beta (x2(\alpha) - 0.5)\alpha d\alpha}{\int_0^{\beta'} (xs2(\alpha) - 0.5)\alpha d\alpha}, \tag{20}$$

where $xs2(\beta') = 0.5$,

and

$$J3' = \frac{\int_0^1 (x2(\alpha) - x_0)\alpha d\alpha}{\int_0^1 (xs2(\alpha) - x_0)\alpha d\alpha}. \tag{21}$$

The denominators in Eqs (20) and (21) are the evaluations of the standard fuzzy reliability F_S in the class which x_0 belongs to. Let $(F_S)_\alpha = (xs1(\alpha), xs2(\alpha))$ be α-cut of F_S. The standard fuzzy reliability has a possibility distribution such as

$$F_S(x) = \frac{1}{1 + 20 \times |x - x_0|^m}, \tag{22}$$

where x_0 equals to the evaluation J1 and m is the numerical value for $3 < k \leqq 5$ in the class which x_0 belongs to.

Eqs (20) and (21) imply the relative evaluation in the class which x_0 belongs to.

3.2 Sensitivity Analysis

The change of estimate of the i-th factor in the n-th event may have an influence on the change of the fuzzy reliability of the total system. It is important to evaluate what extent the change of estimate of the factor has an influence on the fuzzy reliability of the total system from the viewpoint of the reliability assessment since the important factors to be ameliorated are shown by this evaluation. This evaluation corresponds to the sensitivity analysis.

Let F_n be the fuzzy reliability of the n-th event and F_T be that of the total system. Define

$$S(F) = \int_0^1 (x1(\alpha) + x2(\alpha))\alpha d\alpha, \tag{23}$$

where $(F)_\alpha = (x1(\alpha), x2(\alpha))$ is α-cut of a fuzzy reliability F,

and

$$J4(F_{ni}) = \frac{S(F_T + \Delta F_T) - S(F_T)}{S(F_{ni} + \Delta F_{ni}) - S(F_{ni})}, \tag{24}$$

where ΔF_{ni} is the change of the fuzzy reliability owing to the change of estimate of the i-th factor in the n-th event, and ΔF_T is that of the fuzzy reliability of the total system.

The larger J4 becomes, the more important the factor becomes. If $J4(F_{ni})$ is large and estimate of the i-th factor in the n-th event is low, then it is necessary to ameliorate the condition of this factor. On the other hand if $J4(F_{ni})$ is large and the estimation of the i-th factor in the n-th event is good, it is necessary to keep up the condition of this factor.

4. Example

4.1 Outlines of Example

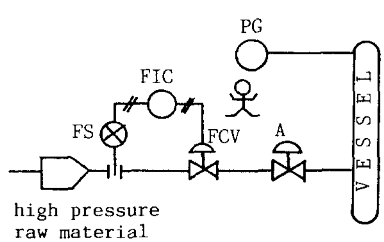

Fig. 2 Simplified Schema of Plant

Fig. 2 shows the simplified schema of the plant. The state of the plant is held steady. An operator is instructed to increase the flow rate of the high pressure raw material by controlling valves. The operation procedures are as follows.
(1) The operator holds the flow control valve(FCV) the specified amount of valve opening through the flow indicating controller(FIC) reading the flow indicator. The amount of the FCV opening should be fit for the increase of the flow rate of the high pressure raw material.
(2) The operator moves. He holds the valve A the specified amount of valve opening manually reading the pressure gage(PG).
The failure of the technical component and the operator's failure in his task are expressed qualitatively as follows.
i) The failure of the flow sensor(FS) or the FIC (the part of the indicator) and the operator's failures in reading the FIC and in controlling the FIC or the failure of the FIC (the part of the controller) or the FCV lead to the failure in the task (1).
ii) The failure of the FS or the FIC (the part of the indicator) influences the operator's failure in reading the FIC. It is assumed that the operator has competence for the task. So there is a possibility that the operator becomes aware of the failure of the FS or the FIC. The dependence between the failure of the FS or the FIC and his failure is assumed to be medium dependence.
iii) The operator's failure in reading the FIC leads to his failure in controlling the FIC. The dependence between these tasks is assumed to be complete dependence.
iv) The failure of the PG and the operator's failure in reading PG and in controlling the valve A or the failure of the valve A lead to the failure of the task (2).
v) The failure of the PG influences the operator's failure in reading the PG. However the dependence between them is assumed to be medium dependence as mentioned in ii).
vi) The operator's failure in reading the PG leads to his failure in controlling the valve A. The dependence between them is assumed to be complete dependence.
vii) The failures in the task (1) and in the task (2) lead to the break down of the vessel.

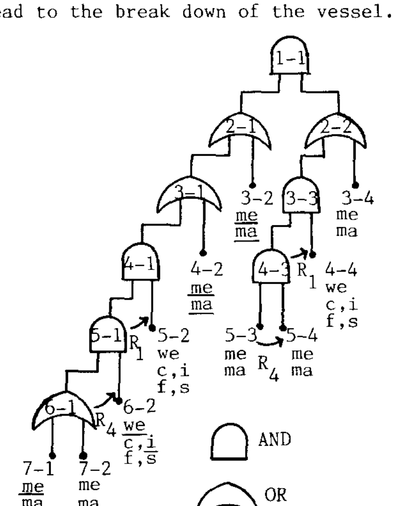

Fig. 3 Fault Tree of Break Down of Vessel

Fig. 3 shows the fault tree of the break down of the vessel. Fig. 4 shows the membership func-

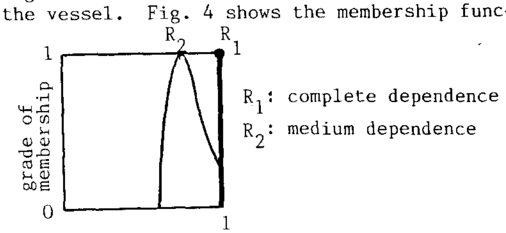

Fig. 4 Membership Functions of Degree of Dependence

tions of complete dependence and medium dependence. In this example the following factors are con-

Table 2 Rate, Parameters K and m, and Estimate of Each Factor

Failure (Event No.)	Rate me,ma or we,c,i,f,s	K (m_U, m_L)
FS (7-1)	8-4,1.752-3,1-2* 0.6,0.8	$1/\log(1/P_4)$ (3.1, 2.5)
FIC (7-2) (Indicator)	2-2,4.06-2,6-2 0.6,0.8	$1/\log(1/P_1)$ (2.0, 2.0)
FIC (4-2) (Controller)	2-2,3.57-2,5-2 0.6,0.8	$1/\log(1/P_1)$ (2.0, 2.0)
FCV (3-2)	8-4,5.782-3,2-2 0.6,0.8	$1/\log(1/P_3)$ (1.7, 4.6)
PG (5-3)	1-1,1-2,3-2 0.5,0.9	$1/\log(1/P_2)$ (3.0, 2.0)
A (3-4)	1-3,5-3,1-2 0.6,0.8	$1/\log(1/P_3)$ (2.5, 2.0)
Reading FIC (6-2)	1-3,3-3,1-2 .5,.85,.55,.55,.8	$1/\log(1/P_3)$ (3.5, 2.0)
Controlling FIC (5-2)	1-4,5-4,1-3 .5,.85,.55,.55,.8	$1/\log(1/P_4)$ (2.0, 3.5)
Reading PG (5-4)	1-3,3-3,1-2 .5,.85,.55,.55,.8	$1/\log(1/P_3)$ (3.5, 2.0)
Controlling A (4-4)	1-4,5-4,1-3 .5,.85,.55,.55,.8	$1/\log(1/P_4)$ (2.0, 3.5)

* reads as 1×10^{-2}.

$P_1 = 5\times10^{-2}$. $P_2 = 10^{-2}$. $P_3 = 5\times10^{-3}$. $P_4 = 10^{-3}$.

sidered. With respect to the technical component, environment(me) and maintenace(ma) are considered. On the other hand with respect to the operator, work enviornment(we), competence for the task(c), man-machine interface(i), fatigue(f) and psychological stress(s) are considered. Let the relation between these factors and reliability be the one as mentioned in section 2.2.

Table 2 shows the failure or the error rate, the parameters K and m, and estimate of each factor.

4.2 Results of Analysis

Fig. 5(a) shows the fuzzy reliability of the total system. This figure shows good reliability as the total system. Fig. 5(b) shows the fuzzy reliability of the task (1). This figure does not necessarily show good reliability since J1 is greater than 0.5 and F(1) is greater than F(0). There is a high possibility that the operator fails in the task (1). The important factors,

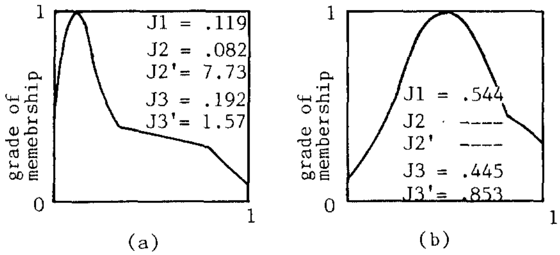

Fig. 5 Results of Analysis I

which relate to the task (1), are chosen to be ameliorated from the result of the sensitivity analysis. These factors are underlined in Fig. 3. Environment factors and maintenance factors in the events (4-2) and (3-2) are chosen since the failures of the event (3-2) or (4-2) leads to the failure in the task (1). None of factors in the event (5-2) are chosen since the dependence between the events (5-1) and (5-2) is complete dependence. The work environment factor and the man-machine interface factor in the event (6-2) are chosen since the degree of dependence between the events (6-1) and (6-2) is not so high as complete dependence and estimate of the work environment factor and that of the man-machine interface factor are low. The environment factor and the maintenance factor in the event (7-1) are chosen but those in the event (7-2) are not, since the event (6-1) happens when the event (7-1) or (7-2) happens and reliability of the event (7-1) is estimated to be lower than that of the event (7-2). It is assumed that the environment factor with respect to the technical component is not ameliorated in spite of large J4 since amelioration of this factor is not easy. As the result of amelioration, the condition of each factor which is chosen is estimated at the best, i.e., 1. Fig. 6

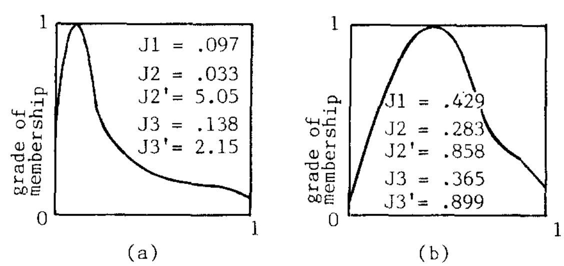

Fig. 6 Results of Analysis II

shows the computed result after the amelioration of factors. Fig. 6(a) shows the fuzzy reliability of the total system. Comparing Fig. 5(a) and Fig. 6(a), Fig. 6(a) shows higher reliability than Fig. 5(a). Fig. 6(b) shows the fuzzy reliability of the task (1). Comparing Fig. 5(b) and Fig. 6(b), it is found that J1 in Fig. 6(b) is smaller than that in Fig. 5(b) and that F(1) in Fig. 6(b) is smaller than that in Fig. 5(b). As a result of the amelioration of factors which is chosen through the sensitivity analysis, reliability of the total system become higher.

5. Conclusions

This paper is based on consideration that all one can reasonably estimate is the possibility or the plausibility of an event taking place, given the information that you can have on hand or can reasonably assemble. Estimate of the failure and the error rates can not help being dependent on engineering judgement because of the lack of precise and complete data. The fuzzy set would seem more appropriate for the representation of reliability rather than the failure rate and the error rate, which have been used in the conventional reliability analysis. Moreover reliability of technical component and human reliability are affected many factors. The relation between reliability and these factors are well expressed qualitatively rather than quantitatively. This paper expresses reliability by the use of the failure possibility and the error possibility which are fuzzy sets on the interval [0,1]. It becomes possible to analyze reliability of a man-machine system including human reliability by the use of these possibilities. This paper discusses the method to derive these possibilities from not only the failure rate or the error rate but also estimate of the factor which affects reliability.

This paper also discusses the sensitivity analysis which evaluates what extent the change of estimate of the factor influences reliability of a man-machine system. The important factors to be ameliorated are chosen through the sensitivity analysis. The example shows that the present method is useful.

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