

Jiliang TU  
Chengli SUN  
Xiangyang ZHANG  
Hongliang PAN  
Ruofa CHENG

## MAINTENANCE STRATEGY DECISION FOR AVIONICS SYSTEM BASED ON COGNITIVE UNCERTAINTY INFORMATION PROCESSING

### DECYZJA W ZAKRESIE STRATEGII UTRZYMANIA RUCHU UKŁADU ELEKTRONIKI LOTNICZEJ W OPARCIU O PRZETWARZANIE INFORMACJI ZWIĄZANYCH Z NIEPEWNOŚCIĄ KOGNITYWNA

*Proper maintenance schedule is required to improve avionics systems reliability and safety. A decision approach to maintenance strategy remains a longstanding challenge in avionics system. With regard to fault diagnosis and equipment maintenance of avionics system, in which the equipment fault information are complex and uncertainty, a multi criteria of decision making method for avionics system based on cognitive uncertainty information processing is proposed to be used in the maintenance strategy decision. Firstly, vague set with three-parameters is introduced to make up for the shortage of the original vague set in expressing fuzzy information, a linguistic variables describing the qualitative indexes into three parameter vague of interval number is proposed. At the same time, due to risk psychological factors of maintenance policymakers that cause cognitive uncertainty are introduced into the maintenance decision process, and a prospect value function of three parameters vague interval value is defined based on prospect theory and the formula for measuring the distance between vague interval value, and a non-linear model of equipment maintenance policies can be established. The implementing process of maintenance policy decision for avionics system based on cognitive uncertainty information processing is given in this paper, and a ranking of the maintenance alternatives is determined. Finally, A specific example of decision of maintenance strategies in avionics system with the application of the proposed method is given, showing that the reliability centered maintenance strategy is the most suitable for avionics system.*

**Keywords:** *The avionics system, Vague sets, Prospect theory, Maintenance strategy, multi criteria decision making*

*Doskonalenie niezawodności i bezpieczeństwa układów elektroniki lotniczej wymaga odpowiedniego harmonogramu działań obsługowych. Podejście decyzyjne do strategii utrzymania ruchu od dawna pozostaje wyzwaniem w systemach awioniki. W odniesieniu do diagnozy uszkodzeń i konserwacji urządzeń systemów elektroniki lotniczej, w których informacje o usterkach urządzeń są złożone i obciążone niepewnością, zaproponowano metodę wielokryterialnego podejmowania decyzji opartą na przetwarzaniu informacji związanych z niepewnością kognitywną, którą można stosować przy podejmowaniu decyzji dotyczących strategii utrzymania ruchu. Po pierwsze, wprowadzono nieostry zbiór trzech parametrów, które pozwalają na wyrażenie wartości liczbowej zaproponowanych zmiennych lingwistycznych opisujących wskaźniki jakościowe, jako wartości z przedziału nieostrego. Jednocześnie, do pojęcia procesu decyzyjnego dotyczącego utrzymania ruchu wprowadzono pojęcie ryzyka związanego z powodującymi niepewność poznawczą czynnikami psychologicznymi kierującymi osobami podejmującymi decyzje obsługowe. Zdefiniowano także funkcję oceny dla wartości z przedziału nieostrego trzech parametrów na podstawie teorii perspektywy i wzór do pomiaru odległości między wartościami z przedziału nieostrego, oraz ustalono nieliniowy tryb polityki konserwacji sprzętu. W artykule zaprezentowano proces implementacji decyzji w zakresie polityki konserwacji układów elektroniki lotniczej w oparciu o przetwarzanie informacji związanych z niepewnością kognitywną, stworzono też ranking dostępnych alternatyw w zakresie utrzymania ruchu. Na koniec, zaprezentowano konkretny przykład decyzji w zakresie strategii konserwacji układów elektroniki lotniczej z zastosowaniem proponowanej metody, pokazując, że strategia utrzymania ruchu oparta na niezawodności jest najbardziej odpowiednia dla układów awioniki.*

**Słowa kluczowe:** *układ elektroniki lotniczej, zbiory nieostre, teoria perspektywy, strategia utrzymania ruchu, wielokryterialne podejmowanie decyzji*

#### 1. Introduction

Avionics system is an important part of aircraft, being safe, fast and environmentally friendly, whose failures are among the top five reasons that caused aircraft on ground (AOG) as Seidenman and Spanovich stated [20]. Air Wisconsin and Jet Age Airline claimed

that nearly 50% and 30% of AOG (Aircraft On Ground) incidents were related to avionics (particularly to interconnected equipments). Maintenance-related failures have been associated with up to 15% of major aircraft accidents [19]. Despite this seemingly small percentage, but Vassilis Tsagkas [25] found that maintenance related failures are the second leading cause of fatal accidents in aviation exceeded

only by pilot error. In that sense, the importance of maintenance activity has increased due to its key role on improving system availability, performance efficiency, safety and reliability, etc. Thus in order to improve avionics considerations in general, maintenance managers (MM) should take decisions about the maintenance strategies to be implemented as well as the necessary resources to satisfy avionics system performances and requirements.

Satisfactory performance of an aircraft depends up on the continued reliability, security, features enhancements of avionics system. Reliability is proportional to amount of maintenance received and knowledge of men who performed such maintenance [13, 17]. Now, an avionics system may comprise a large number of components, and efficient maintenance strategy is required to improve the reliability of relevant functions and to reduce high maintenance cost. For a long time, both home and abroad have to take preventive tests and routine maintenance to ensure the safe operation of avionics system [7]. According to Tan & Kramer et al. study, the high cost of maintenance is an important factor in business operations, accounting for approximately 20-50% of the total operating budget of process systems [22]. Thus cost-effective maintenance strategies for avionics system equipment are required. Avionics system maintenance work includes pre-flight checks, post-flight inspection and scheduled maintenance. According to statistics, only 60% of the aircraft total failure can be found with ground inspection, while 40% of the fault is exposed during flight [5]. It is obvious that the integrity of the aircraft with a high rate is difficult to guarantee only with the ground inspection, but due to bad maintenance such as frequent power-on check or ineffective removal of equipment will cause the equipment to reduce the inherent reliability and waste the human and financial resources.

Recent literature in aircraft maintenance safety tends to accept that deviations, uncertainties and surprises are inherent and to a large extent inevitable in maintenance operations [10,23,4]. In the process of avionics systems equipment maintenance, some judgments from maintenance experts or engineers may not be (fully) compatible due to lack of knowledge of the actual use and maintenance of the equipment. In fact, the factors of maintenance strategy are also related to maintenance economic, environmental, social influence and other human factors, there are different degrees of cognitive uncertainty, so the avionics communications systems equipment maintenance program is actually a complex decision problems, involving many factors based on uncertain information processing multiple attribute decision making problems (MADM) [27]. For example, Bevilacqua M. describes an application of the Analytic Hierarchy Process (AHP) for decision the best maintenance strategy for an important Italian oil refinery (an Integrated Gasification and Combined Cycle plant)[23]. In this decision model, when the number of experts on the different levels of equipment maintenance program to make decisions, often difficult to avoid the qualitative, imprecise, incomplete and uncertain information. Over the past years, there have been a number of researchers tempted to develop techniques involving fuzzy set theory to complement conventional system maintenance decision-making [21, 2, 18, 1], where uncertain and imprecise judgments of decision makers are translated into fuzzy numbers. However, in the existing methods, it is seldom considered that attribute value and aspiration-level are in the form of interval numbers. In the real world, the attribute values of alternatives are often uncertain due to estimation inaccuracies and errors in measurement and it is also difficult for the MM to provide a clear aspiration-level. Interval numbers can usually be used to describe uncertain and inaccurate attribute values or aspiration-levels in practical MADM problems [6]. Solve the above problems are in need of repair or engineering technician expert judgment, MM are often at risk for a maintenance program on subjective preferences, then mostly also showed varying degrees of knowledge based on experience and knowledge uncertainty, but the existing methods sufficiently consider the important role of the aspiration-level in decision analysis.

Fortunately, a powerful tool, vague sets theory [8] is available and it has been extensively adopted in the fields of decision making. It is emerging as an efficient tool in managing uncertainty, incomplete and imprecise information. For the sake of characteristic with the vague set of membership have the two aspects of information, which makes the vague set have more advantages than traditional fuzzy sets in the treatment of cognitive uncertainty information. Jue Wang and Wei Xu [14] provides a soft and expansive way to help the decision maker in NSFC to make his decision based on vague set theory. They also introduced a family of intersection and union aggregation operators for vague values. In choosing a maintenance plan of engineering practice, maintenance experts often base on different decision criteria for maintenance scheme judgment when using language form to give its personal preference information. The use of vague sets and the concept of interval numbers can well express the MM's fuzzy decision-making process. Because of the decision-making problems for maintenance strategy are usually risky and uncertain, it is necessary to consider the MM's psychological behavior in decision analysis. Therefore, it is urgent to investigate the risk decision analysis methods considering human behavior for the purpose of providing effective decision support to the MM in maintenance strategy. Tversky and Kahneman [24] put forward the prospect theory, which can more accurately reflect the risk when facing maintenance plan decision preference psychological characteristics, through the value function and the decision weighting function to calculate the comprehensive prospects of different maintenance schemes under different criteria values to prioritize. Each maintenance scheme allows the theory to a more scientific description of uncertainty in the actual circumstances experts or engineering technical personnel in the maintenance scheme decision-making behavior. The objective of this paper is to develop a method based on the research of vague set and prospect theory to solve the MADM problem considering aspiration-levels. The paper combines the two theories in cognitive uncertainty information processing advantages, and builds a kind of based on Vague language variables of three parameter sets to describe the maintenance decision makers in the criteria weights information incomplete solution under the circumstance of the fuzzy interval value.

The rest of this paper is arranged as follows. Section 2 gives a brief introduction to vague set and prospect theory. Section 3 provides a brief introduction on avionics and its hierarchy structure. Section 4 describes the formulation and the resolution procedure of the maintenance strategy decision problem considering aspiration-levels based on vague set. In Section 5, a decision making example is given to illustrate the specific implementation process of the proposed method for verify its validity and rationality. The outcomes of the research and future research recommendations are presented in the final section.

## 2. Concept of Vague Sets and Prospective Theory

In practice, interval number is often used to present uncertainty information. The basic concept of vague set theory is as follows [8]. Let a set  $X$  be a finite universe of discourse, then a fuzzy set  $A = \{ \langle x, \mu_A(x) \rangle \mid x \in X \}$  defined by Zadeh is characterized by a membership function  $\mu_A : X \rightarrow [0,1]$ , where  $\mu_A$  denotes the membership degree of the element  $x$  to the set  $A$ .

**Definition 1.** Concerning the domain  $X = \{x_1, x_2, \dots, x_n\}$ , Vague set  $A$  by true membership function and false membership function is described.  $t_A : X \rightarrow [0,1]$ ,  $f_A : X \rightarrow [0,1]$ , which is the recognition by the evidence of  $x_i \in X$  membership degree lower bound, by against  $x_i \in X$  negative membership degree and lower bounds of the evidence, and  $0 \leq t_A + f_A \leq 1$ . Elements  $x_i$  in Vague set  $A$  of membership degree by the interval  $[0,1]$  show as follows:  $A = \{ \langle x, t_A(x), 1 - f_A(x) \rangle \mid x \in X \}$ .

**Definition 2.** (three parameters of Vague set )  $\forall x \in X$ ,  $\tilde{t}_A = \frac{1-f_A+t_A}{2} + \gamma \cdot (1-f_A-t_A)$  is called for x relative to A maximum likelihood measurement, known as the nucleus of Vague set, where  $|\gamma| \leq 0.2$ . By the known, x relative to A subordinate situation should adopt three-dimensional parameter interval  $[t_A, \tilde{t}_A, 1-f_A]$ .

**Definition 3.**  $\forall x, y \in X$ , if  $x = [t_A, \tilde{t}_A, t_A^*]$ ,  $y = [t_B, \tilde{t}_B, t_B^*]$ , where  $t_A^* = 1-f_A, t_B^* = 1-f_B$ . Now we consider the distance measurement between Vague A and vague B is given as follows:

$$d_\lambda(A, B) = \lambda|t_A - t_B| + \lambda|t_A^* - t_B^*| + (1 - 2\lambda)\left| \tilde{t}_A - \tilde{t}_B \right| \quad (1)$$

The parameter  $\lambda$  representing the weight of decision interval value, namely the importance of three parameters interval Vague left and right endpoint and the maximum degree of membership. In this paper, the three parameter importance degree are the same equal, where  $\lambda = 1/3$ .

Due to human thinking is fuzzy, the cognitive uncertainty and complexity of the decision-making problem, experts in maintenance of maintenance schemes under different decision criteria to determine the language form is given preference information is universal and convenient. Experts in maintenance give their judgments on criteria of alternatives in linguistic terms. Therefore, the linguistic variables of judgments on criteria are inconsistent, and the complexity of this issue will be increased. In order to simplify the treatment of judgments expression, a unified set of linguistic variables is predetermined in this paper, which can be used to evaluate every criterion from the satisfaction perspective. The general linguistic term set used in the questionnaires consists of the following seven terms, i.e. very low (VL), low (L), relatively low (RL), medium (M), relatively high (RH), high (H), and very high (VH). To get the quantitative evaluation of value, the linguistic term can be quantified with three parameters interval numbers in definition (2). The way to determine the vague values of linguistic variables are various, but all of these methods basically ignore the impact of possible degree [26].

Table 1. The scale of linguistic variables and the corresponding vague interval numbers

linguistic variables	$t_A$	$f_A$	$\tilde{t}_A$	$1-f_A$	Three parameters interval Vague $\gamma = 0.1$
(VL)	0	0.9	0.06	0.1	[0, 0.06, 0.1]
(L)	0.1	0.75	0.19	0.25	[0.1, 0.19, 0.25]
(RL)	0.25	0.55	0.37	0.45	[0.25, 0.37, 0.45]
(M)	0.45	0.45	0.51	0.55	[0.45, 0.51, 0.55]
(RH)	0.55	0.25	0.67	0.75	[0.55, 0.67, 0.75]
(H)	0.75	0.1	0.84	0.9	[0.75, 0.84, 0.9]
(VH)	0.9	0	0.96	1	[0.9, 0.96, 1]

In this paper, a linguistic assessment set of ideas for quantitative is provided, the reference value of truth-membership  $t_A$  of each linguistic variable is per-determined, and the false-membership degree  $f_A$  is given with linguistic judgment. In the end, the membership of maximum possible degrees  $\tilde{t}_A$  is also determined by the definition (2). So the three parameters interval Vague of seven level language variables in this paper is established, the process is seen in Table 1.

## 2.2. Concept of prospect theory

According to prospect theory, a decision process consists of two phases: the editing phase and the evaluation phase. In the editing phase, outcomes of alternatives are coded as gains or losses relative to a reference point. In the evaluation phase, the edited prospects are evaluated by a value function and a weighting function, and the prospect of highest value is chosen.

We suppose a gamble is composed of n potential monetary outcomes  $x_1, x_2, \dots, x_n$  with probabilities  $p_1, p_2, \dots, p_n$ , where  $x_i$  is potential outcome and  $p_i$  is the probability of potential outcome, Thus, the prospect is defined as the ordered pair  $f$  and the prospect value of the gamble is given by [28].

$$V(f) = \sum_{i=1}^n \pi(p_i) v(x_i) \quad (2)$$

where  $v(x_i)$  is the value of potential outcome  $x_i$ ,  $\pi(p_i)$  is the decision weight for the value of potential gain or loss  $x_i$ .  $v(x_i)$  can be represented by [28]:

$$v(x_i) = \begin{cases} x^\alpha, & x \geq 0; \\ -\theta(-x)^\beta, & x < 0. \end{cases} \quad (3)$$

Where  $\alpha$  and  $\beta$  quantify the degree of diminishing sensitivity for gain and loss,  $\theta$  quantifies the degree of loss aversion. It has been widely recognized that loss-aversion factor  $\theta$  should be greater than 1, which indicates that individuals are more sensitive to losses than gains [15].

**Definition 4.** Suppose  $v_A = [t_A, \tilde{t}_A, t_A^*]$  and  $v_B = [t_B, \tilde{t}_B, t_B^*]$  denote the two Vague set by use of three parameter interval number respectively, if the interval number as a reference point, then the prospect value with interval number is given below:

$$V(d_\lambda(v_A, v_B)) = \begin{cases} (d_\lambda(v_A, v_B))^\alpha, & v_A \geq v_B; \\ -\theta(d_\lambda(v_A, v_B))^\beta, & v_A < v_B. \end{cases} \quad (4)$$

## 3. Hierarchy of Avionics System

To clearly describe the avionics maintenance strategy decision problem, we first define avionics system hierarchy structure. Avionics System can be divided into three system levels, system, subsystem and component, which are involved in this paper. The three system levels can be defined as follows [19]: (1) a system is a combination of subsystems that complete a task together, (2) a subsystem consists of components, which can perform a specific function of the system, and (3) a component is an operating part of the subsystem. Taken a domestic avionics as an example (see Fig.1), the avionics system can be divided into seven subsystems according to their functions and operational characteristics, which is made up of subsystems including flight control subsystem, engine control subsystem, cockpit control-display subsystem, energy control subsystem, fuel and LG(landing gear) control subsystem, cabin control subsystem and airborne network subsystem. These subsystems can be further broken down to components. For example, the flight control subsystem contains three FCGC (flight control and guidance computer) and three FCSC (flight control secondary computer), and the airborne network subsystem involves ES

(end system) and switches. The others abbreviations note: AC–Air Conditioning; ACR–Avionics Communication Router; ADIRU–Air Data Inertial Reference Unit; CDIS–Cabin Data Intercommunication System; EEC–Engine Electronic Control; ELM–Electrical Load Management; FM–Flight Management; IPCU–Ice Protection Control Unit; IRDC–Intelligent Remote Data Concentrator. Due to the complexity, the avionics contractor usually subcontracts the avionic subsystems and even components to several subcontractors for further design and manufacturing.

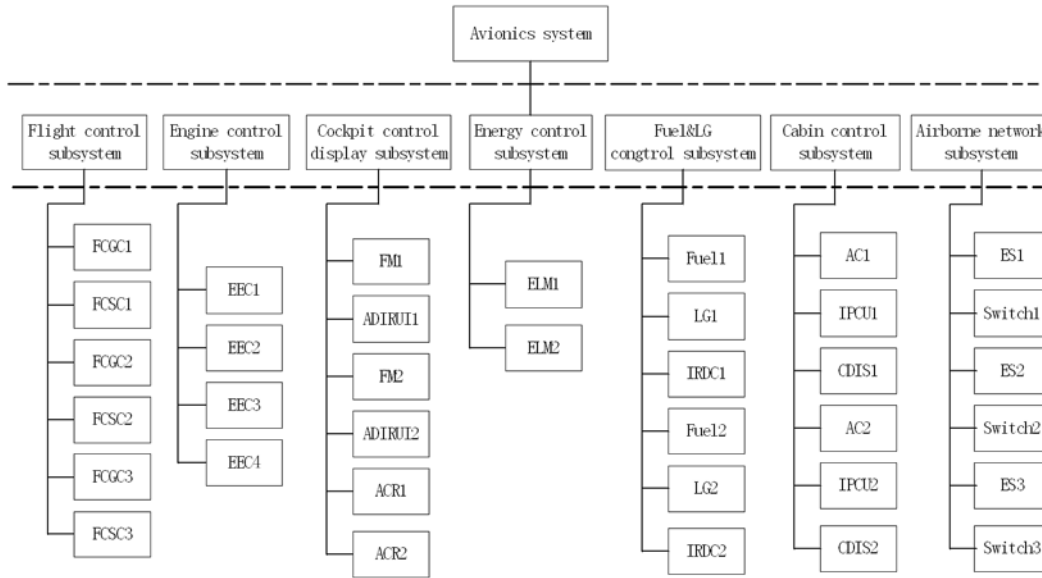


Fig. 1. The hierarchy of Avionics system

On the original organic basis, the system expands the scope of monitoring to improve the data collection, storage, distribution, and uses the data link to send the data package to data processing terminal in the ground station. Nowadays, avionic subsystems and components are interconnected through an airborne network consist of the air-ground access devices and the air-ground communication transmission system, via which both the information and the function integrations are realized. The air-ground access devices are responsible for information acquisition, information composition, information decomposition, information encoding, information decoding, and information transmission security mechanism. For example, the engine data captured by the engine control subsystem must be transmitted to the cockpit control-display subsystem, and then the pilot can receive the engine information for further decision making. The data transmission plays a key role in the avionic system, and one or more data transmission used to complete a specified function (e.g. reception of the engine data, display the atmospheric pressure) is defined as a mission. This can guarantee a safe, reliable and real-time information transmission. It is obvious that the maintenance strategy decision of avionics is a multi-mission problem.

## 4. The implementing process of the proposed approach

### 4.1. Prepare the maintenance plan and decision attribute

Subsystems with unacceptable risks are identified after risk evaluation. Equipment in these subsystems is regarded as high risk equipment. Proper maintenance plans should be performed to reduce the equipment failure probability. In this paper, a general maintenance decision-making strategy is proposed by considering both avionics

systems degradation and hierarchy structure. The maintenance effect in the follows was considered to be perfect, though it is always imperfect in practice [11]. Periodic preventive maintenance (PM) is applied to some key equipment. Corrective maintenance (CM) and PM are considered to be imperfect maintenance, since they generally only repair failed or faulty components; Condition-based maintenance (CBM), shortly described, is maintenance when need arises. This maintenance is performed after one or more indicators show that equipment is going to fail or that equipment performance is deteriorating [16]. This concept is

applicable to mission critical systems that incorporate active redundancy and fault reporting. First and most important of all, the initial cost of CBM can be high. It requires improved instrumentation of the equipment. To reduce the economic risk due to unexpected failures, the risk-based maintenance (RBM) strategy is applied to determine the proper interval of periodic PM for each piece of equipment at a cost of probably low maintenance expenditure. According to the reliability limits, the interval of periodic PM for key equipment was obtained under the condition that the default maintenance effect is perfect. Reliability Centered Maintenance (RCM) analysis provides a structured framework for analyzing the functions and potential failures for a physical asset (such as an airplane, a manufacturing production line, etc.) with a focus on preserving system functions, rather than preserving equipment. RCM is used to develop scheduled maintenance plans that will provide an acceptable level of operability, with an acceptable level of risk, in an efficient and cost-effective manner.

Probabilistic approaches constitute the most reasonable way to deal with the various uncertainties inherent to this task. Several indicators have been proposed during recent years to represent the time dependent structural performance of deteriorating structures [9]. Once the future condition of the device estimated effectively applying probability forecasting model, the equipment failure rate at a certain time, reliability function, or residual life distribution function has been obtained. A maintenance decision model can be established in accordance with the economy, equipment availability, risk and other criteria, and the optimal strategy [12].

Probabilistic approaches constitute the most reasonable way to deal with the various uncertainties inherent to this task. Several indicators have been proposed during recent years to represent the time dependent structural performance of deteriorating structures [9]. Once the future condition of the device estimated effectively applying probability forecasting model, the equipment failure rate at a certain time, reliability function, or residual life distribution function has been obtained. A maintenance decision model can be established in accordance with the economy, equipment availability, risk and other criteria, and the optimal strategy [12].

### 4.2. Flowchart of maintenance strategy decision

According to the above research content in this paper, the maintenance policy decision for avionics system based on cognitive uncertainty information processing can be description as follows, the implementing process of this proposed approach in this paper is shown by flow chart in Fig. 2 and details process are given here after.

#### Step 1: Collected the maintenance records and historic failure data

First step of the technique is the information extraction phase in which information is extracted from various sources. Information in the form of system components' failure rates and repair times are extracted from various sources such as historical maintenance records, reliability databases, system reliability expert opinion, etc. In decision-making process, based on the fault information provided by the

diagnosis and prediction program, the decision is made according to if the faulty equipment is needed to be repaired and when to be repaired, and analysis accounting about maintenance costs and repair working time calculation.

**Step 2: ascertain the range of attribute weights**

Decision making problem in avionics system equipment maintenance, maintenance experts often according to their own maintenance experience and skills, for maintenance scheme under different criteria values are formed certain risk forecast, such expectations can be considered as maintenance decision makers with reference to the risk behavior characteristics of the formation of the reference point, so

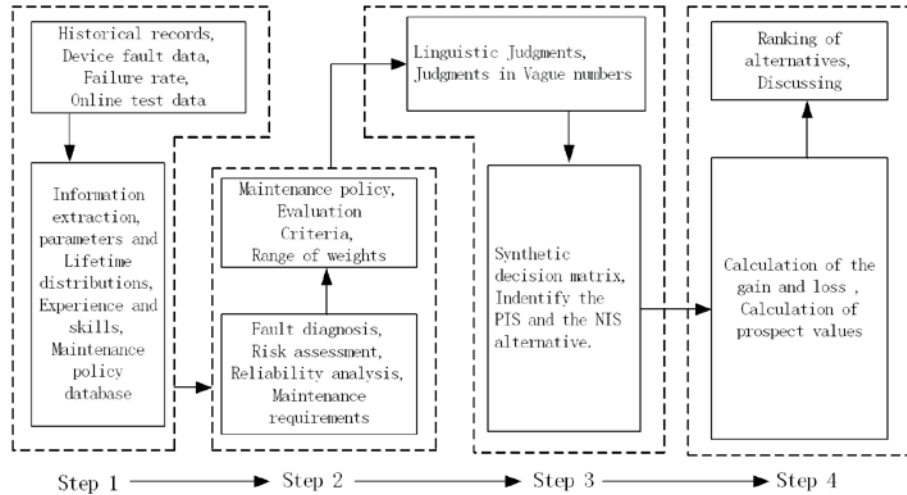


Fig. 2. The flowchart of the proposed approach

the maintenance plan is called a reference. According to the reference service solutions can measure the maintenance of gains and losses. Because 5 set of evaluation index are efficiency index, which requires the bigger is the better. Each attribute weight is not entirely sure, but its range of decision attribute weights for avionics system be set as follows :

$$H : \{0.25 \leq w_1 \leq 0.32, 0.25 \leq w_2 \leq 0.3, 0.15 \leq w_3 \leq 0.2, 0.18 \leq w_4 \leq 0.22, 0.06 \leq w_5 \leq 0.15\} \quad (5)$$

And all weight must be meet the requirement:  $w_1 + w_2 + w_3 + w_4 + w_5 = 1$ . Under the condition of above-mentioned cognitive uncertainty information to determine each strategy of the equipment maintenance plan set A sorting, which choice satisfies the requirement of decision-making of maintenance plan.

**Step 3 : Express the corresponding vague interval numbers of each maintenance policy**

MMs give their judgments on criteria of alternatives in linguistic terms. Vague set theory is used to give styles of judgments and transform linguistic judgments into vague numbers. The original judgment information is in the form of linguistic variable. In general, linguistic variables are pre-determined. We can set to equipment maintenance plan, as norm constraint set, and assumes that plan under rule constraint set values are given in the form of language variable, by maintenance specialist again by definition vague converts it to three parameters interval number 2, can be represented as:

$$a_i = \{a_{i1}, \dots, a_{i5}\} = \left\{ (c_1, [t_{i1}, \tilde{t}_{i1}, t_{i1}^*]), (c_2, [t_{i2}, \tilde{t}_{i2}, t_{i2}^*]), \dots, (c_5, [t_{i5}, \tilde{t}_{i5}, t_{i5}^*]) \right\} \quad (6)$$

When choosing positive and negative ideal solution maintenance, relatively Vague interval number nuclear first, think scheme is optimal, the greater the second comparison, two Vague interval number and the same, if you have more scoring function, also value the bigger the better. Based on the positive ideal solution (PIS) and negative ideal solution (NIS) as a reference for maintenance plan, get:

$$\left. \begin{aligned} G &= (G_1, \dots, G_5) = ([t_1^+, \tilde{t}_1^+, t_1^{*+}], [t_2^+, \tilde{t}_2^+, t_2^{*+}], \dots, [t_5^+, \tilde{t}_5^+, t_5^{*+}]) \\ B &= (B_1, \dots, B_5) = ([t_1^-, \tilde{t}_1^-, t_1^{*-}], [t_2^-, \tilde{t}_2^-, t_2^{*-}], \dots, [t_5^-, \tilde{t}_5^-, t_5^{*-}]) \end{aligned} \right\} \quad (7)$$

**Step 4: Maintenance plan decision based on Prospect theory**

**(1) Calculation of the gain and loss for maintenance policy**

According to the definition of Vague distance calculation formula for each maintenance scheme for degree to the positive and negative ideal solution (distance),

$$d(a_i, G) = \{d(a_{i1}, G_1), d(a_{i2}, G_2), \dots, d(a_{i5}, G_5)\},$$

$$d(a_i, B) = \{d(a_{i1}, B_1), d(a_{i2}, B_2), \dots, d(a_{i5}, B_5)\}$$

According to definition (4), maintenance solution can be got under the rule of the value of future utility value function:

$$v(a_{ij}) = \begin{cases} (d(a_{ij}, B_j))^\alpha, & B_j \in B \\ -\theta(d(a_{ij}, G_j))^\beta, & G_j \in G \end{cases} \quad (8)$$

**(2) Calculation of the prospect values of each maintenance plan**

To maintenance scheme for the reference point is ideal, the maintenance plan is inferior to ideal solution, maintenance for decision makers, is facing losses, the policy makers to pursue risk right now, will plug in formula (3), can get it:

$$v^-(d(a_{ij}, G_j)) = -\theta(d(a_{ij}, G_j))^\beta \quad (9)$$

Take Negative ideal maintenance plan as a reference point in this paper, because of the repair scheme  $a_i$  is better than negative ideal repair scheme, so the decision makers are faced with profit, MMs will avoid the risk at this time according to prospect theory. For the situation that attribute value and aspiration-level are in the form of interval numbers, we give the following formula:

$$v^+(d(a_{ij}, B_j)) = (d(a_{ij}, B_j))^\alpha \quad (10)$$

In summary, by Equation (8) and (9), the calculation formula of gain for Positive  $V^+$  and negative  $V^-$  prospect matrix is expressed by:

$$V_i = \sum_{j=1}^5 v(a_{ij})^+ \pi^+(w_j) + \sum_{j=1}^5 v(a_{ij})^- \pi^-(w_j) \quad (11)$$

Where,  $\pi^+(w_j)$ ,  $\pi^-(w_j)$  denote the weighting functions of maintenance strategy for gains and losses, respectively, and they are given by formula (11) and (12).

$$\pi^+(w_j) = \frac{w_j^{\gamma^+}}{(w_j^{\gamma^+} + (1-w_j)^{\gamma^+})^{1/\gamma^+}} \quad (12)$$

$$\pi^-(w_j) = \frac{w_j^{\gamma^-}}{(w_j^{\gamma^-} + (1-w_j)^{\gamma^-})^{1/\gamma^-}} \quad (13)$$

where,  $\gamma^+$ ,  $\gamma^-$  are model parameters,  $\pi^+(w_j)$  and  $\pi^-(w_j)$  are monotonic and exhibit inverse S-shapes for  $\gamma^+ > 0.27$ ,  $\gamma^- > 1$ . They are adequate for average decision-making behavior (i.e., overweight the outcomes with low probabilities and underweight the outcomes with moderate and high probabilities)

### (3) Ranking alternatives and discussion

In order to more accurately determine the advantages and disadvantages of various maintenance scheme of quantitative evaluation, decided in the comprehensive prospect calculate each maintenance plan value, must come from the same criteria weight vector set

$W = \{w_1, w_2, w_3, w_4, w_5\}$ . The weight of each criterion maintenance schemes decision value can be selected according to expert experience or through the analytic hierarchy process. In this paper, combined with the calculation process in prospect theory value show that calculation criterion weight should guarantee comprehensive prospect value of all maintenance scheme sets is optimal. Therefore, based on this point, based on the above theoretical analysis process, the maintenance scheme decision optimization model is established in this paper as follows:

$$\begin{aligned} \max V &= \sum_{i=1}^5 \sum_{j=1}^5 v(a_{ij})^+ \pi^+(w_j) + \sum_{i=1}^5 \sum_{j=1}^5 v(a_{ij})^- \pi^-(w_j) \\ S.T. \quad &\sum_{i=1}^5 w_i = 1, w_i \geq 0, w \in H. \end{aligned} \quad (14)$$

According to the maintenance decision-making model, criterion weights of the optimal solution  $w^* = \{w_1^*, w_2^*, w_3^*, w_4^*, w_5^*\}$  can be got. Then according to the formula (10) – formula (12), the maintenance scheme  $a_i$  can be got comprehensive value outlook. Then according to the size of the prospect of comprehensive value, and can carry on the order maintenance plan of all set, to determine the optimal maintenance plan. Obviously, the greater overall prospect value  $V$  is, the better Maintenance scheme  $A$  will be. Therefore, based on the overall prospect values, we can determine the ranking of response actions and select the most desirable action for reducing the consequent negative effect of maintenance scheme.

## 5. Case Analysis

In order to validate the proposed based on the cognition of uncertain information processing Aeronautical wireless communication system decision making method, the feasibility and effectiveness of equipment maintenance in front of the parking preventive test for the maintenance scheme decision-making system equipment. In order to guarantee the correctness of the decision, before the decision by the engineering and maintenance personnel for each equipment testing and reliability evaluation system, check the equipment operation

records report, again through the laboratory test data of the equipment operation, field testing and other testing methods, the results were not found abnormal, can be used after the maintenance strategy. The decision-making process is as follows:

**Step 1:** Parameters of the failure distribution and maintenance effect are estimated from maintenance records. The two-parameter Weibull distribution is a general distribution widely used to model processes such as failure due to aging and wear. Maintenance records from different observation periods are collected together to obtain more accurate estimation. Parameter uncertainty often implies that maintenance should be performed more frequently, especially if the parameter uncertainty constitutes a large fraction of the total uncertainty and if preventive maintenance costs are low. The more frequent maintenance actions ensure that costly failures are unlikely to occur. An immediate consequence, however, is that hardly any failure data will be collected, sustaining the uncertainty. If one aims to reduce this uncertainty, maintenance actions should be postponed or, if this is undesirable, tests should be performed in a controlled setting.

**Step 2:** By the on-line monitoring at any time of avionics system, through equipment fault diagnosis system and state trend forecasting system, we can diagnose the avionics system facilities of latent fault and its development trend. From a macro point of view, based on the implementation of the avionics system at home and abroad widely used to CBM, PM, CM, RBM and RCM, 5 kinds of maintenance policy can be referred to as follows:

$$A = \{a_1, a_2, a_3, a_4, a_5\} \quad (15)$$

where,  $a_1$  is CBM,  $a_2$  is PM,  $a_3$  is CM,  $a_4$  is RBM,  $a_5$  is RCM.

Avionics systems equipments of safety indicators characterizing the influence of the equipment fault on the person, other related equipment and operating environment adversely; Reliability can measure the ability of the equipment to accomplish the required task in conditions within the prescribed time and under the provisions; Maintainability said occurred in the time of equipment failure, the provisions ability which can back to the specified function within the time specified under the maintenance condition equipment, while maintenance cost is considered as another indicators related to the economy (e.g. spare parts' costs, external party services, financial penalties) and the availability is considered as a local objective related to the maintenance efficiency, reinstall the removed and inspect it. (Restart the task). So, a multi-attribute maintenance decision-making model based on multiple attribute value theory is proposed to give an overall objective to determine the optimal maintenance policy. The attribute set are shown as follows:

$$C = \{c_1, c_2, c_3, c_4, c_5\} \quad (16)$$

where,  $c_1$  is indicator of system safety,  $c_2$  is Reliability,  $c_3$  is Maintainability,  $c_4$  is maintenance economy,  $c_5$  is availability.

**Step 3:** maintenance organization are maintenance countermeasures of each set of linguistic variables set, get the corresponding evaluation index of language variable, then in turn according to Table 1 for conversion method due to Vague language variables set with corresponding three parameters interval number. According to the reference solution definition, determine the positive and negative ideal scheme, the data are shown in Table 2.

**Step 4:** According to prospect theory, we firstly regard aspiration-levels as reference points. Then, gains and losses of alternatives are calculated by measuring perceived differences of attribute values from reference points (aspiration-levels).

Table 2. The corresponding vague interval numbers of each maintenance policy

Alternatives	$c_1$	$c_2$	$c_3$	$c_4$	$c_5$
$a_1$	[0.55,0.67, 0.75]	[0.1, 0.19, 0.25]	[0.25,0.37, 0.45]	[0.25,0.37, 0.45]	[0.1, 0.19, 0.25]
$a_2$	[0.75, 0.84, 0.9]	[0.45,0.51, 0.55]	[0.25,0.37, 0.45]	[0.25,0.37, 0.45]	[0.45,0.51, 0.55]
$a_3$	[0.75, 0.84, 0.9]	[0.55,0.67, 0.75]	[0.45,0.51, 0.55]	[0.55,0.67, 0.75]	[0.45,0.51, 0.55]
$a_4$	[0.55,0.67, 0.75]	[0.55,0.67, 0.75]	[0.25,0.37, 0.45]	[0.25,0.37, 0.45]	[0.55,0.67, 0.75]
$a_5$	[0.9, 0.96, 1]	[0.55,0.67, 0.75]	[0.55,0.67, 0.75]	[0.55,0.67, 0.75]	[0.55,0.67, 0.75]
$G$	[0.9, 0.96, 1]	[0.55,0.67, 0.75]	[0.45,0.51, 0.55]	[0.55,0.67, 0.75]	[0.55,0.67, 0.75]
$B$	[0.55,0.67, 0.75]	[0.1, 0.19, 0.25]	[0.25,0.37, 0.45]	[0.25,0.37, 0.45]	[0.1, 0.19, 0.25]

(1) To determine the maintenance plan and the distance of the positive and negative ideal solution (degree), calculated value function as follows:

$$d(a_1, G) = \{d(a_{11}, G_1), d(a_{12}, G_2), \dots, d(a_{15}, G_5)\} = \{0.297, 0.477, 0.147, 0.3, 0.477\},$$

$$d(a_2, G) = \{d(a_{21}, G_1), d(a_{22}, G_2), \dots, d(a_{25}, G_5)\} = \{0.123, 0.153, 0.147, 0.3, 0.153\},$$

$$d(a_3, G) = \{d(a_{31}, G_1), d(a_{32}, G_2), \dots, d(a_{35}, G_5)\} = \{0.123, 0, 0, 0, 0.153\},$$

$$d(a_4, G) = \{d(a_{41}, G_1), d(a_{42}, G_2), \dots, d(a_{45}, G_5)\} = \{0.297, 0, 0.147, 0.3, 0\},$$

$$d(a_5, G) = \{d(a_{51}, G_1), d(a_{52}, G_2), \dots, d(a_{55}, G_5)\} = \{0, 0, 0.153, 0, 0\},$$

$$d(a_1, B) = \{d(a_{11}, B_1), d(a_{12}, B_2), \dots, d(a_{15}, B_5)\} = \{0, 0, 0, 0, 0\},$$

$$d(a_2, B) = \{d(a_{21}, B_1), d(a_{22}, B_2), \dots, d(a_{25}, B_5)\} = \{0.173, 0.323, 0, 0, 0.323\},$$

$$d(a_3, B) = \{d(a_{31}, B_1), d(a_{32}, B_2), \dots, d(a_{35}, B_5)\} = \{0.173, 0.477, 0.147, 0.3, 0.323\},$$

$$d(a_4, B) = \{d(a_{41}, B_1), d(a_{42}, B_2), \dots, d(a_{45}, B_5)\} = \{0, 0.477, 0, 0, 0.477\},$$

$$d(a_5, B) = \{d(a_{51}, B_1), d(a_{52}, B_2), \dots, d(a_{55}, B_5)\} = \{0.297, 0.477, 0.3, 0.3, 0.477\}.$$

The above calculation results fed into formula (9) and formula (10) to obtain the prospects of each maintenance scheme under different criterion utility value. According to the experimental results given by Tversky and Kahneman [15], the value of the function of each parameter is given as follows:

$$\alpha = \beta = 0.88, \theta = 2.25, \text{ therefore:}$$

$$v^-(d(a_{ij}, G_j)) = -2.25(d(a_{ij}, G_j))^{0.88}$$

$$v^+(d(a_{ij}, B_j)) = (d(a_{ij}, B_j))^{0.88}$$

(2) According to the above results, by the calculation formula (9) and (10), gain matrix  $V^+$  and loss matrix  $V^-$  are constructed, respectively, i.e.,

$$V^- = \begin{bmatrix} -0.773 & -1.173 & -0.416 & -0.779 & -1.173 \\ -0.356 & -0.192 & -0.416 & -0.779 & -0.192 \\ -0.356 & 0.0000 & 0.0000 & 0.0000 & -0.192 \\ -0.773 & 0.0000 & -0.146 & -0.779 & 0.0000 \\ 0.0000 & 0.0000 & -0.192 & 0.0000 & 0.0000 \end{bmatrix}$$

$$V^+ = \begin{bmatrix} 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.214 & 0.370 & 0.000 & 0.000 & 0.370 \\ 0.214 & 0.521 & 0.185 & 0.347 & 0.370 \\ 0.000 & 0.521 & 0.000 & 0.000 & 0.521 \\ 0.344 & 0.521 & 0.347 & 0.347 & 0.521 \end{bmatrix}$$

(3) Calculate the overall prospect value of each alternative and confirm the ranking order of alternatives according to the obtained overall prospect values. The prospect of plus or minus value matrix into the horizon optimization model (14), at the same time, according to the formula (12) and formula (13). Many scholars had paid great attention to the parameter estimation of weighting function. Tversky and Kahneman estimated parameters using median data which suggested the median values of  $\gamma^+ = 0.61, \gamma^- = 0.69$  [15]. Their estimation results were reasonably close to each other. The essential characteristics of weighting function (i.e., underweighting of high probabilities and inflation of small probabilities) were the same, and the degrees of distortion were almost the same.

The optimal criteria weight vector  $w^* = \{0.28, 0.25, 0.16, 0.2, 0.11\}$  can be convenient deprived from the nonlinear optimization programming by using matlab 7.0 software. According to the formula (12) and formula (13), the each decision maintenance policy of the profit and loss probability weighting function can be obtained:

$$\pi^+(w_j) = \{0.308, 0.291, 0.234, 0.261, 0.195\},$$

$$\pi^-(w_j) = \{0.314, 0.293, 0.225, 0.257, 0.18\}.$$

Further, using the formula (11), The overall prospect value of each maintenance policy can be obtained, i.e.,

$$V(a_1) = -1.091, V(a_2) = -0.4964 + 0.2457 = -0.251,$$

$$V(a_3) = -0.1463 + 0.4235 = 0.277, V(a_4) = -0.4758 + 0.2532 = -0.223,$$

$$V(a_5) = -0.0432 + 0.5309 = 0.488.$$

Finally, MM select the maintenance strategy with the highest prospect value in evaluation phase. Therefore, according to the overall prospect value of maintenance strategy, a ranking order of the five alternatives is  $a_5 > a_3 > a_4 > a_2 > a_1$ , obviously, RCM policy can be as the basis of schedule avionic system equipment maintenance, the decision results conform to the avionic system in maintenance of actual engineering standards. With this information managers could easily focus where to put efforts: on the implementation of a maintenance strategy, on the implementation of redundancy, in optimizing the spare of stocks, etc.

## Conclusions

Maintenance strategy plays a key role in reducing cost, minimizing equipment downtime, improving quality, increasing safety and providing reliable equipment and as a result achieving organizational goals and objectives for avionic system. The purpose of this paper is to present an approach for deciding on an appropriate maintenance strategy decision for avionics system. The issue of avionic system maintenance strategy decision is not just a cost-oriented issue, and it should be consider safety, reliability, cost, and other quality aspects. This paper has presented a method based on vague sets and prospect theory to solve maintenance strategy decision problems considering aspiration-levels under cognitive uncertainty information circumstance. It can deal with DM's vague and uncertain judgment where uncertain and imprecise judgments of decision makers are translated into vague interval numbers with three parameters. From definition in Section 2, it can be concluded that vague set theory is superior to fuzzy set theory in dealing with cognitive uncertain and vague information in decision-making. Compared with the traditional behavioral economics theories, prospect theory is more conform to the characteristics of human behavior, providing an appealing way to understand individual attitudes under risk and uncertainty. The parameterized prospect theory, involved the MM's risk attitudes of maintenance policy choice behavior, was simple and effective to evaluate alternative policy under dynamic maintenance information. According to prospect theory, MM's aspiration-levels are regarded as the reference points. By measuring

the perceived difference between the attribute value and the reference point, gain and loss of each alternative are assessed, and the prospect value of each alternative is calculated. Ranking result of alternatives can be determined according to the prospect values. In the proposed method, it is a valuable attempt to incorporate prospect theory and vague set into maintenance policy decision analysis.

As demonstrated by this case study, our method proposed in this paper is a simple and effective tool for tackling the uncertainty and imprecision associated with MADM problems of maintenance decision for avionics system, which might prove beneficial for plant maintenance managers to define the optimum maintenance strategy for each piece of system or subsystem equipment.

## Acknowledgements

*Authors gratefully acknowledge the financial support provided by the National Natural Science Foundation of China (Grant No. 51167013), Natural Science Foundation of Jiangxi Province (Grant No. 20142BAB207002) and Aeronautical Science Foundation of China (Grant No.20142056005), especially the research fund for the doctoral program of higher education of NCHU, Jiang Xi, China (Project No.EA201304348). The authors would also like to express their grateful appreciation to the anonymous referees for their helpful comments to improve the quality of this paper.*

## References

1. Al-Najjar B, Alsyouf I. Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making. *International Journal of Production Economics* 2003;84:85-100, [http://dx.doi.org/10.1016/S0925-5273\(02\)00380-8](http://dx.doi.org/10.1016/S0925-5273(02)00380-8).
2. Azizollah Jafari, Mehdi Jafarian, Abalfazl Zareei. Using Fuzzy Delphi Method in Maintenance Strategy Selection Problem. *Jouranal of Uncertain system* 2008; 2(4): 289-298.
3. Bevilacqua M., Braglia M. The analytic hierarchy process applied to maintenance strategy selection. *Reliability Engineering and System Safety* 2000;70(1):71-83, [http://dx.doi.org/10.1016/S0951-8320\(00\)00047-8](http://dx.doi.org/10.1016/S0951-8320(00)00047-8).
4. Bram de Jonge, Warse Klingenberg, Ruud Teunter, Tiedo Tinga. Optimum maintenance strategy under uncertainty in the lifetime distribution. *Reliability Engineering and System Safety*, 2015;133(2):59-67, <http://dx.doi.org/10.1016/j.res.2014.09.013>.
5. Dehuang Chen, Xiaowei Wang, Jing Zhao. Aircraft Maintenance Decision System Based on Real-time Condition Monitoring. *Procedia Engineering* 2012;29 (1): 765 – 769, <http://dx.doi.org/10.1016/j.proeng.2012.01.038>.
6. Echefske Chris K, Wang Zheng. Using fuzzy linguistics to select optimum maintenance and condition monitoring strategies. *Mechanical Systems and Signal Processing* 2003;17(2): 305-316, <http://dx.doi.org/10.1006/mssp.2001.1395>.
7. Elix C Go'mez de Leo'n Hijes, JOSE' Javier Ruiz Cartagena. Maintenance strategy based on a multicriterion classification of equipments. *Reliability Engineering and System Safety* 2006, 91:444-451, <http://dx.doi.org/10.1016/j.res.2005.03.001>.
8. Gau, W.L., Buehrer, D.J. Vague sets. *IEEE Transactions on Systems, Man and Cybernetics* 1993; 23 (2): 610-614, <http://dx.doi.org/10.1109/21.229476>.
9. Giorgio Barone, Dan M.Frangopol. Life-cycle maintenance of deteriorating structures by multi-objective optimization involving reliability, risk, availability, hazard and cost. *Structural Safety* 2014;48 (3): 40-50, <http://dx.doi.org/10.1016/j.strusafe.2014.02.002>.
10. G. Medina-Oliva,P.Weber, B.lung.Industrial system knowledge formalization to aid decision making in maintenance strategies assessment. *Engineering Applications of Artificial Intelligence* 2015;37(1):343-360, <http://dx.doi.org/10.1016/j.engappai.2014.09.006>.
11. Haijun Hua, Guangxu Cheng, Yun Li, Yiping Tang. Risk-based maintenance strategy and its applications in a petrochemical reforming reaction system. *Journal of Loss Prevention in the Process Industries* 2009;22 (2): 392-397, <http://dx.doi.org/10.1016/j.jlp.2009.02.001>.
12. Hai Canh Vu, Phuc Do, Anne Barros, Christophe Bérenguer. Maintenance grouping strategy for multi-component systems with dynamic contexts. *Reliability Engineering and System Safety* 2014;132(1):233-249, <http://dx.doi.org/10.1016/j.res.2014.08.002>.
13. Hobbs A. An overview of human factors in aviation maintenance. *ATSB safety report, aviation research and analysis report AR 2008;55(1):234-242*.
14. Jue Wang, Wei Xu, Jian Ma, Shouyang Wang. A vague set based decision support approach for evaluating research funding programs. *European Journal of Operational Research* 2013; 230 (1): 656-665, <http://dx.doi.org/10.1016/j.ejor.2013.04.045>.
15. Kahneman D,Tversky A. Prospect theory: An analysis of decision under risk. *Economic* 1979; 47(2): 263-291, <http://dx.doi.org/10.2307/1914185>.
16. Lee J, Ramji A, Andrews KSJ, Darning L, and Dragan B. An integrated platform for diagnostics, prognostics and maintenance optimization. In *Proceedings of Intelligent Maintenance System, Arles, France 2004*;15-17.
17. Nicolai RP, Dekker R. Optimal maintenance of multi-component systems: a review In: *Complex system maintenance handbook*. London: Springer 2008:263-86, [http://dx.doi.org/10.1007/978-1-84800-011-7\\_11](http://dx.doi.org/10.1007/978-1-84800-011-7_11).
18. R.R. Yager. Uncertainty representation using fuzzy measures. *IEEE Trans Systems, Man, and Cybernetics, Part B*, 2002;32 (1):13-20, <http://dx.doi.org/10.1109/3477.979955>.



19. Ruiying Li, Jingfu Wang, Haitao Liao, Ning Huang. A new method for reliability allocation of avionics connected via an airborne network. *Journal of Network and Computer Applications* 2013;34(2):678-682.
20. Seidenman P, Spanovich DJ. Avionics integrity. *Aircraft Technology Engineering & Maintenance* 2011;6:29–31.
21. Sharma, R.K., D.Kumar, and P. Kumar. FLM to select suitable maintenance strategy in process industries using MISO model, *Journal of Quality in Maintenance Engineering* 2005;1 1(2):359-374.
22. Tan, J. S., Kramer, M. A. A general framework for preventive maintenance optimization in chemical process operations. *Computers Chemical Engineering* 1997;21(12):1451-1469, [http://dx.doi.org/10.1016/S0098-1354\(97\)88493-1](http://dx.doi.org/10.1016/S0098-1354(97)88493-1)
23. Tangbin Xia, Lifeng Xi, Xiaojun Zhou, Jay Lee. Dynamic maintenance decision-making for series parallel manufacturing system based on MAM-MTW methodology. *European Journal of Operational Research* 2012;221 (1) 231-240, <http://dx.doi.org/10.1016/j.ejor.2012.03.027>.
24. Tversky, A., Kahneman, D. Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty*, 1992;5(4):297–323, <http://dx.doi.org/10.1007/BF00122574>.
25. Vassilis Tsagkas, Dimitris Nathanael, Nicolas Marmaras. A pragmatic mapping of factors behind deviating acts in aircraft maintenance. *Reliability Engineering and System Safety* 2014;130(1);106–11, <http://dx.doi.org/10.1016/j.res.2014.05.011>.
26. Xiuli Geng, Xuening Chu, Zaifang Zhang. A new integrated design concept evaluation approach based on vague sets. *Expert Systems with Applications* 2010;37 (3): 6629–6638, <http://dx.doi.org/10.1016/j.eswa.2010.03.058>.
27. Y. Liu. H. Z. Huang. Optimal selective maintenance strategy for multi-state systems under imperfect maintenance. *IEEE Transactions on Reliability* 2010;59(2): 356-367, <http://dx.doi.org/10.1109/TR.2010.2046798>.
28. Zhi-Ping Fan, Xiao Zhang, Fa-Dong Chen, Yang Liu. Multiple attribute decision making considering aspiration-levels: A method based on prospect theory. *Computers & Industrial Engineering* 2013; 65 (1) 341–350, <http://dx.doi.org/10.1016/j.cie.2013.02.013>.

---

**Jiliang TU**  
**Chengli SUN**  
**Xiangyang ZHANG**  
**Ruofa CHENG**

School of Information Engineering  
Nanchang Hangkong University  
No. 696, Fenghenan Avenue, Honggutan New Zone  
Nanchang, Jiangxi, 330063, China

**Hongliang PAN**  
Magnetic Suspension Traffic Engineering Technology Research  
Center of Tongji University  
Shanghai, 201804, China

E-mails: [tjl1980@nchu.edu.cn](mailto:tjl1980@nchu.edu.cn), [395229630@qq.com](mailto:395229630@qq.com)

---