The Aeronautical Journal (2025), 1–23
doi:10.1017/aer.2024.125

ROYAL AERONAUTICAL SOCIETY

RESEARCH ARTICLE

Fighter optimal selection based on sequential multi-criteria decision-making with uncertainty measurement

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Received: 1 April 2024; **Revised:** 10 August 2024; **Accepted:** 10 October 2024

Keywords: Fighter optimal selection; Multi-criteria decision-making; Sequential decision making; Effectiveness evaluation; Intuitionistic fuzzy numbers (IFNs)

Abstract
Rapid and comprehensive fighter optimisation is an important part of modern combat decision-making. However, due to the numerous influencing factors, it is difficult for decision-makers to consider comprehensively and specify the optimal decision, and it is highly subjective, which leads to different decision conclusions from person to person. Therefore, to solve the above deficiencies in fighter selection, this paper proposes a sequential decision-making framework that comprehensively considers the effectiveness, maintenance, support capability and health status of the fighter aircraft. Based on the multi-dimensional state, it provides comprehensive and credible auxiliary support for commanders. The sequential decision-making framework (called GRA-VIKOR-IFNs) uses the combination of equation and fuzzy multi-criteria decision-making (FMCDM) to evaluate the effectiveness, support capability and health in turn, to complete the step-by-step selection of fighter models, troops and sorties. The evaluation equation is for the effectiveness evaluation and a hybrid method using the extended grey correlation analysis (GRA) and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method based on intuitionistic fuzzy numbers (IFNs) is for the support capability and health evaluation. The proposed strategy is in line with the logic and demand of actual combat and training decision-making and takes into account the influence of uncertain factors. Finally, a comparison with some classical methods is carried out, such as the full consistency method (FUCOM), the technique for order of preference by similarity to ideal solution (TOPSIS) and so on. The GRA-VIKOR-IFNs method is consistent with the results of other methods and the result sort resolution is 0.0619 and at least 40% higher than other methods, which can lead the commanders to a more reliable and clear decision.

Nomenclature

MCDM	multi-criteria decision-making
FMCDM	fuzzy multi-criteria decision-making
GRA	grey correlation analysis
VIKOR	VlseKriterijumska Optimizacija I Kompromisno Resenje
IFN	intuitionistic fuzzy numbers
GRA-VIKOR-IFNs	the sequential optimal selection framework this paper proposed
FUCOM	the full consistency method
LBWA	the level-based weight assessment
OPA	ordinal priority approach
TOPSIS	technique for order of preference by similarity to ideal solution
MABAC	multi-attributive border approximation area comparison
MAIRCA	multi-attributive ideal-real comparative analysis

ρ	resolution coefficient in GRA
ω	the decision weight in MCDM problem
S	group effect value in VIKOR
R	individual regret value in VIKOR
Q	comprehensive evaluation value in VIKOR
v	decision-making mechanism coefficient in VIKOR
RSC	the average head-on radar reflection interface
Sw	the area of wing
L_{all}	the full length of the fighter
P_{SEP}	the remaining power per unit weight
$n_{y,cir}$	the maximum hover overload of fighter
T_R	thrust-weight ratio of the fighter
Ma	maximum speed of the fighter
H_{pc}	service ceiling of the fighter

1.0 Introduction

With the advancement of technology, modern warfare is gradually evolving in the direction of informatisation and intelligence. The war under the new situation presents the characteristics of a complex environment, fierce confrontation, agile decision-making, information coupling and state diversification [1]. The factors that commanders need to consider when making decisions are becoming increasingly complex, with increasing uncertainty and higher requirements for decision-making efficiency. As a common equipment on the battlefield, the optimal selection of fighters is an important issue when commanders make combat decisions, therefore, this paper takes fighter optimisation as the research object to develop an optimisation strategy to assist decision-making.

Battlefield decision-making is a systematic, multi-collaborative process that needs to consider all aspects of the factors influencing it to make a comprehensive and credible decision. For the optimal selection of fighters, commanders need to consider the fighter types, formations, support forces and even specific fighter sorties that will conduct the mission. These decision objects are usually realised when measuring fighter effectiveness, maintenance support capabilities and fighter health [2]. Only from these aspects to ensure that the fighter in the mission execution, and daily exercise process can have the best play. However, no literature systematically considers the above factors to establish a framework for fighter battlefield decision-making but rather examines each of the above decision factors more independently and singularly.

Many studies focus on the selection of fighter models based on the effectiveness evaluation, and these studies are primarily for government procurement. For example, to evaluate nine military fighters for the air forces to select the appropriate aircraft, literature [3] came up with a multiplicative multi-criteria decision-making analysis method and utilised ten criteria to evaluate the fighter effectiveness, such as the maximum takeoff weight, service ceiling and so on. Further, due to the complexity of the situation and the changeable combat status, it is often too limited to use certain numerical values to describe information. Researchers began to explore methods to describe uncertain information in the fighter optimal selection problem. For instance, Ma, Shidong [4] and other scholars use the Cloud model to process uncertain information representing battlefield conditions and realise air combat under fuzzy conditions Threat Level Assessment. Other relevant research results in fighter optimal selection can be found in the literature [5, 6] and their references.

When it comes to the research in the evaluation of support capability and health status of fighters, the application mainly focuses on the optimal maintenance schemes. For instance, literature [7] presented a multi-objective decision-making model to get the optimal maintenance scheme for the aircraft. Pedersen and Vatn [8] proposed an optimisation method based on expected utility theory to calculate the maintenance cost and provide optimal maintenance alternatives to commanders.

However, the fighter optimal selection decision-making is a decision-making process of a hierarchical and progressive system, and its task is not only to select a fighter model as most literature does but also

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the troops and the sorties based on the performance of the fighter, the support capability, the battlefield situation and other multi-dimensional information [2].

To solve the above problems, this paper establishes a sequential decision-making system of performance evaluation, support evaluation and health evaluation, which can comprehensively consider various factors affecting equipment performance, support capability and equipment health status, so as to complete the step-by-step selection of fighter model, troops and sorties.

The problem of considering multiple criteria and making decisions based on them is called the multi-criteria decision-making (MCDM) problem [9]. Therefore, MCDM is suitable for solving the fighter optimal selection problem which requires the consideration of multiple and complex factors, and this paper adopts a MCDM method. Moreover, there are often some criteria that are difficult to characterise by precise values, so the fuzzy theory is often applied to MCDM problems [10], such as triangular fuzzy number, interval fuzzy number, etc.

According to the characteristics of the three types of evaluation decision-making information, and referring to the relevant literature research [11, 12], the evaluation equation method and the fuzzy MCDM method are respectively determined to evaluate the effectiveness based on exact values and the support and health assessment based on uncertain information.

For the fuzzy MCDM method, this paper proposes a combination of an extended grey correlation analysis (GRA) [13] and VIseKriterijumska Optimizacija I Kompromisno Resenje(VIKOR) [14], which is based on the intuitionistic fuzzy numbers (IFN) [15]. The extended GRA method is for the weight calculation, which is objective and is more suitable for the small amount of decision information in the context of fighter optimal selection. VIKOR method is an improvement of the technique for order of preference by similarity to ideal solution (TOPSIS) [16], and VIKOR not only keeps the advantage of TOPSIS but also better considers the hesitation and contradiction of decision makers and is more reasonable. IFN introduces the concept of non-membership degree, which can further realise the effect of expressing neither this nor that, which is more in line with the actual situation of people's voting in reality, and can better describe uncertainty. Therefore, IFN is chosen to represent decision information in this study. To sum up, the contributions of this paper can be listed as follows.

1. This paper designs a sequential framework to solve the fighter optimal selection in the battle and training decision-making and by analysing the actual demand and existing research, we designed a comprehensive index system based on the sequential decision-making criteria. Through this optimal selection framework, the commander can realise the selection decision from the fighter model to the execution team and then to the specific sortie, which makes the decision form a system and conforms to the decision logic of combat and training.
2. This paper proposes a novel fuzzy MCDM method to support and health evaluation in the fighter optimal selection, utilising IFN and VIKOR to consider the uncertainty hesitation and contradiction. The alternative confliction and fuzzy decision information quantification can be better resolved, which is more in line with the complex battlefield decision characteristics.
3. Comprehensive model validation and comparison with classic methods in MCDM are carried out. The influence of the resolution coefficient and the decision-making mechanism coefficient on the decision-making result is determined. In comparing with various existing research methods, this research method gets the decision results consistent with most classical methods and gets the highest decision identification degree, which verifies that the proposed decision method is applicable, effective and reliable.

The remaining sections of the paper are organised as follows: Section 2 reviews some related concepts about the extended GRA method, VIKOR based on IFN. In Section 3, a new optimal selection MCDM framework is proposed. In Section 4, a case about fighters is used to demonstrate the feasibility of the proposed method. Through comparison and analysis in Section 5, we conclude the advantages of our work.

2.0 Preliminaries

In this section, we briefly introduce the basic theory about an extended GRA method and VIKOR based on IFN.

2.1 The extended GRA method used to obtain the weights

Grey correlation analysis is a derivative method based on grey system theory [13] and has little requirements on the sample size and is suitable for the problem of a small sample with, a scarce amount of information, which is difficult to be solved by fuzzy mathematics. Therefore, it is more suitable for determining the attribute weight based on a small amount of decision information in the context of equipment optimal selection.

Literature [17] proposes an extended GRA method of interval triangular fuzzy numbers. The single membership degree of the traditional fuzzy set can express the degree of support and further obtain the degree of opposition [18], but it cannot express the degree of neither support nor opposition. Intuitionistic fuzzy number introduces the concept of non-membership degree [15], and is more in line with the actual situation of people's voting in reality. In this paper, Zhang's method is extended to intuitionistic fuzzy numbers with the following steps:

Step 1: Determining the ideal sequence.

The ideal sequence is generally consisting of the best value of each attribute of each alternative. In this paper, we use the maximum (or minimum) of the intuitionistic fuzzy number as the ideal sequence. Whether the maximum or minimum value is used depends on whether the decision target is the best or the worst.

The ideal sequence is denoted as:

$$R_0 = \{r_{01}, r_{02}, \ldots, r_{0n}\}, r_{0j} = (1, 0, 0) \; or \; (0, 1, 0), j = 1, 2, \ldots, n \tag{1}$$

Step 2: Calculating the distance between the attribute value sequence and the ideal sequence.

The distance between the jth attribute of the ith alternative and the jth attribute of the ideal sequence is calculated as follows:

$$\Delta_{ij} = d(r_{0j}, x_{ij}) = 1/2 \cdot \left(\left|\mu_{r_{0j}} - \mu_{x_{ij}}\right| + \left|\nu_{r_{0j}} - \nu_{x_{ij}}\right| + \left|\pi_{r_{0j}} - \pi_{x_{ij}}\right| \right) \tag{2}$$

where $r_{0j} = (\mu_{r_{0j}}, \nu_{r_{0j}}, \pi_{r_{0j}})$ and $x_{ij} = (\mu_{x_{ij}}, \nu_{x_{ij}}, \pi_{x_{ij}})$ are intuitionistic fuzzy numbers, and μ, ν and π represent the degree of membership, the degree of non-membership and the degree of hesitation in the intuitionistic fuzzy number.

Step 3: Calculating the grey relational coefficient.

Step 4: Constructing a multi-objective programming equation.

Since the alternative with a greater grey correlation degree with the ideal sequence is closer to the ideal sequence, the multi-objective programming equation which is constructed with the grey correlation degree as the programming objective is as follows:

$$\begin{cases} \max \gamma_i = \sum_{j=1}^{n} \omega_j \xi_{ij}, i = 1, 2, \ldots, m. \\ s.t.: \sum_{j=1}^{n} \omega_j = 1, \omega_j \geqslant 0, j = 1, 2, \ldots, m. \end{cases} \tag{3}$$

where ξ_{ij} represents the grey relational coefficient between the jth attribute of the $i$thalternative and the jth attribute of the ideal sequence.

Step 5: Transforming the equation and solving the equation.

Considering that there is no preference relationship between alternatives and fair competition, the problem can be transformed into a single-objective programming problem by taking the sum of the grey

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correlation degrees of each alternative as the planning objective. The conditional extremum is obtained by the Lagrange multiplier method, and the weight expression is finally obtained:

$$\omega_j = \sum_{i=1}^{m} \xi_{ij} \Big/ \sum_{i=1}^{m} \sum_{j=1}^{n} \xi_{ij} \tag{4}$$

2.2 The VIKOR method used on IFN

VIKOR method [14] is a compromise ranking method based on ideal points. It is more suitable for situations where the decision maker cannot express the preference accurately, the measurement units used are different, or there is a conflict between evaluation criteria. In addition, VIKOR method can obtain a compromise solution with priority, which can provide decision-makers with more comprehensive and accurate decision aids.

The steps of VIKOR based on intuitionistic fuzzy numbers are as follows:

Step 1: Determining the positive ideal solutions and negative ideal solutions.

The two represent the most and least expected solutions, respectively. They can be denoted as r^+ and r^-.

Step 2: Calculating group effect value and individual regret value.

The group effect value S and individual regret value R of the ith alternative is calculated using the following formula:

$$S_i = \sum_{j=1}^{n} \omega_j (r_j^+ - r_{ij}) \big/ (r_j^+ - r_j^-), i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{5}$$

$$R_i = \max_j \omega_j (r_j^+ - r_{ij}) \big/ (r_j^+ - r_j^-), i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{6}$$

where j represents the jth attribute. r_j^+, r_j^-, r_{ij} are intuitionistic fuzzy numbers, so subtracting two intuitionistic fuzzy numbers means calculating the distance between them:

$$\alpha - \beta = d(\alpha, \beta) = 1\big/2 \cdot (\left|\mu_\alpha - \mu_\beta\right| + \left|\nu_\alpha - \nu_\beta\right| + \left|\pi_\alpha - \pi_\beta\right|) \tag{7}$$

Step 3: Calculating comprehensive evaluation value Q.

Step 4: Sorting the alternatives.

S, R and, *Q* are sorted in ascending order respectively, and the final alternative is determined according to the evaluation criteria.

3.0 Methodology

This chapter first investigates the characteristics of actual decision-making in the use of military battle and training. It provides a basis for the hierarchical decision-making mode in battle and training decision-making and finally determines the sequential optimal selection model. Then, according to the hierarchical relationship and the current research, a universal decision-making index system is constructed. Finally, based on the sequential framework and index system, the equipment optimal selection model is determined, and the selection process is explained in detail.

3.1 Criteria

Tactics for a battlefield commander include not only the planning of weapons and equipment but also the planning of various resources such as troops and maintenance resources [2].

At present, excluding the temporary formation, the equipment of the forces of various countries is in the minimum operational formation, such as flying squadrons, missile battalions, naval formations,

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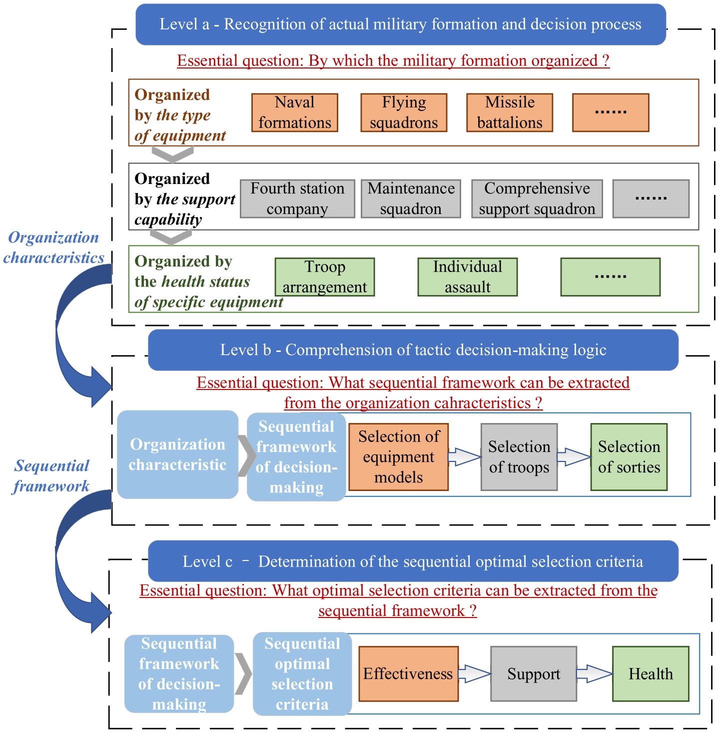

Figure 1. *The logic of the determination of the sequential criteria.*

etc., and the equipment for different purposes is usually composed of only one type of equipment. In the combat organisation, in addition to the combat equipment to carry out combat tasks, there are also support forces to meet support needs, such as the fourth station company of the flying squadron, the maintenance squadron, the combat support battalion, and the comprehensive support battalion in the missile brigade, etc. In addition to the selection of models and support forces, the commander also needs to carry out the planning of troop arrangements and individual assaults.

To sum up, this paper adopts the sequential decision-making method to construct an intelligent optimal selection system. Firstly, the model selection should be completed through effectiveness evaluation to determine the equipment model for the combat mission. Then, in the units equipped with this type of equipment, the support capacity of each unit is evaluated to determine the troops to carry out the combat mission. Finally, when it comes to specific equipment, it is necessary to determine it in the selected troops based on the state of the equipment through health assessment. The determination logic of sequential evaluation criteria is shown in Fig. 1.

3.2 Index

The three types of evaluation all need to establish a corresponding index system for evaluation calculation. This section determines the index system by analysing the characteristics of each evaluation.

Without considering the enemy factors, the combat effectiveness of model selection is mainly affected by the equipment's performance, useability, survivability and other aspects. Therefore, the indicators can be divided into the performance parameters and geometric parameters of the equipment. For example, performance parameters such as thrust-weight ratio and maximum flight speed of fighter aircraft will affect the performance and use of aircraft, while geometric parameters such as wing length and head-on radar reflection area will affect the survivability of fighter aircraft [19]. However, studies involving

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Table 1. Common indexes in effectiveness and support evaluation

Criteria	Index	Details
Effectiveness	Performance index	Aircraft: thrust-weight ratio, maximum flight speed [19], maximum takeoff mass operational range [6] and so on. Missile: warhead type, mass, range and so on [21].
	Geometric index	Aircraft: wing length, head-on radar reflection area and so on. Missile: missile scale [21], length and so on.
Support capability	Support personnel index	Training, assembility [21], team and so on.
	Support facilities index	Spare parts [20], facilities, resources [20] and so on [22].
	Support management index	Maintenance activities [20], management system and so on [11].
	Support design index	Maintenance plan, cost [23], equipment downtime [23] and so on.

maintenance strategies and support schemes [7, 20] usually only focus on the selection of maintenance support schemes and support resources of equipment, which are often separated from the optimal selection of equipment in practical use.

The implementation of safeguards requires a decision based on the specific circumstances of the support force in which the equipment is located. The common indexes in effectiveness and support evaluation can be seen in Table 1. To sum up, support capability can be generally summarised as support personnel index, support facilities index, support management index and support design index.

For health assessment, the data of each sub-system of the equipment is tested by sensors and other detection devices according to concepts such as health state-based maintenance (CBM) [8] and fault diagnosis prediction and health management (PHM) [24]. Data is transmitted back to the management system for condition monitoring, fault diagnosis and life prediction to determine when and how equipment should be repaired. Simplifying the above ideas, use language evaluation which is given by the experts according to the test data of each subsystem as the decision information for the health evaluation of equipment optimal selection.

The final general index system of sequential decision-making is shown in Fig. 2. As it is based on multi-faceted research on the optimal models of typical equipment in various fields such as fighters, missiles and so on, the index system is applicable for not only fighter optimal selection but can be transformed to other equipment optimal selection quickly. For fighters, with the central maintenance computer architecture for reference, the fighter's key systems can be divided into: engine systems, aircraft health monitoring facilities by recording analysis mechanical and electrical systems (fuel, power supply, hydraulic, environmental control system) and avionics system (such as navigation, communication, weather radar system) of the state information [25].

3.3 Decision-making with uncertainty

The indicators of support evaluation generally need to be given according to the actual situation of the formation, which often has complexity and uncertainty and is difficult to express by a definite value. In this paper, the attribute value is obtained by the language evaluation method given by experts. In health evaluation, in order to reduce the algorithm complexity and improve the decision-making efficiency, this paper adopts the same method to get the attribute value. Therefore, for support assessment and health

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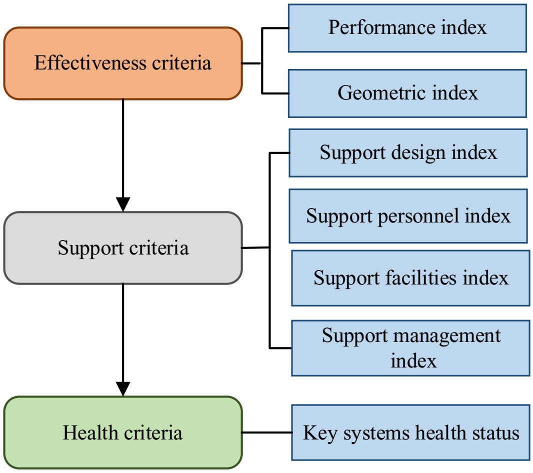

Figure 2. *The general index system.*

assessment, this paper uses the hybrid MCDM method based on IFNs. The process of the hybrid MCDM method is shown in Fig. 3.

Step 1: the support index of each support force and the health index of each piece of equipment will be evaluated by experts in a seven-level system. The relations between linguistic variables and IFNs are shown in Table 2 [26].

Step 2: It is transformed into intuitionistic fuzzy numbers according to Table 2, and the attribute value matrix composed of intuitionistic fuzzy numbers is obtained.

Step 3: The attribute value matrix was substituted into the extended GRA model to obtain the attribute weight.

Step 4: The attribute weight and attribute value matrix are brought into the VIKOR method to obtain the evaluation ranking results of each alternative, and finally the result scheme is obtained.

3.4 Sequential decision-making framework

Based on the determined index system and sequential decision-making method, the universal decision model is constructed as follows:

(1) Integrated decision-making model

$$Optimization = sequential(E, Support, Health).$$

E represents the evaluation result of combat effectiveness, $Support$ represents the evaluation result of support capability and $Health$ represents the evaluation result of health status.

Equipment optimal selection needs to be carried out sequentially by efficiency evaluation, support evaluation and health evaluation. Input the decision information of the three types of evaluation, and the comprehensive evaluation results of the three can be obtained, to complete the optimal selection from model level, to support force level and then to specific equipment level.

(2) Effectiveness evaluation model

The efficiency evaluation equation is used for effectiveness evaluation, as the research on performance evaluation has a history of several decades, and the theory and application have been more comprehensive and reliable.

$$E = efficiency(Per, Geo).$$

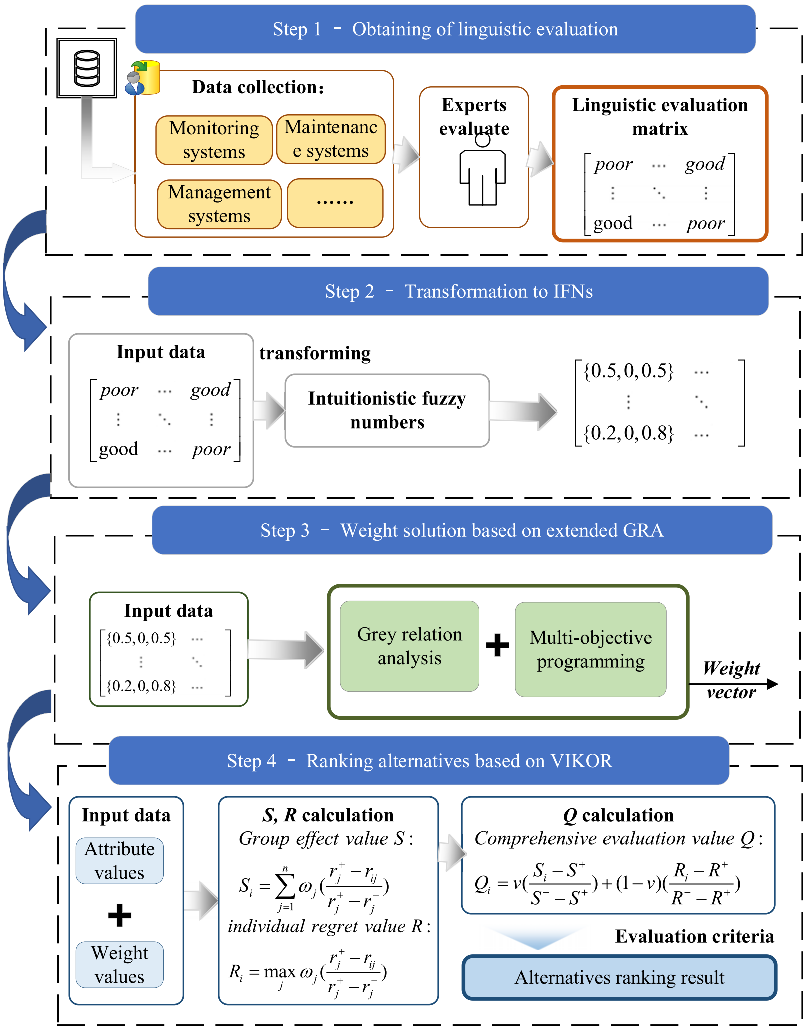

Figure 3. *Steps of the hybrid MCDM method.*

In efficiency evaluation, the parameters of equipment performance index *Per* and geometric index *Geo* should be taken as input. After normalisation, the evaluation results are calculated by the evaluation equation, and the sorting is completed to obtain the final selected equipment model.

In this paper, the composite index *E* of the survivability *Geo* and the performance index *Per* is used to measure the effectiveness of fighter aircraft. The calculation equation is as follows [27–29]:

$$Geo = \omega_{s1} \cdot (5/RCS)^{0.25} + \omega_{s2} \cdot (Sw \times L_{all})^{-1} \tag{8}$$

$$Per = \omega_{B1} \cdot P_{SEP} + \omega_{B2} \cdot n_{y,cir} + \omega_{B3} \cdot T_R + \omega_{B4} \cdot Ma + \omega_{B5} \cdot H_{PC} \tag{9}$$

$$E = \omega_{E1} \cdot Per + \omega_{E2} \cdot Geo \tag{10}$$

where *RSC* represents the average head-on radar reflection interface, *Sw* represents the area of wing, L_{all} represents the full length of the fighter. P_{SEP} indicates the remaining power per unit weight, $n_{y,cir}$ indicates the maximum hover overload, T_R is the thrust-weight ratio, *Ma* is maximum speed, H_{pc} is service ceiling.

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Table 2. *The relations between linguistic variables and IFNs*

Linguistic variables	Intuitionistic fuzzy numbers
Very poor	(0.15, 0.80, 0.05)
Poor	(0.25, 0.65, 0.10)
Medium poor	(0.35, 0.55, 0.10)
Medium	(0.5, 0.4, 0.1)
Medium good	(0.65, 0.25, 0.10)
Good	(0.75, 0.15, 0.10)
Very good	(0.85, 0.10, 0.05)

According to the literature [27, 29], it can be determined that $\omega_{B1} = 0.35$, $\omega_{B2} = 0.25$, $\omega_{B3} = 0.15$, $\omega_{B4} = 0.15$, $\omega_{B5} = 0.10$. Refers to the comprehensive evaluation of effectiveness, which can determine the main influencing factors of energy based on references. However, since geometric indexes affect the survivability of fighter aircraft, they also have a certain weight [28], so it is determined as $\omega_{E1} = 0.75$, $\omega_{E2} = 0.25$.

(3) Support assessment model

$$Support = support(val, v, \rho).$$

In the sub-model of support evaluation, experts should give the language evaluation *val* of four kinds of support evaluation indexes for the alternative support forces, and input the decision mechanism coefficient v and discrimination coefficient ρ according to the actual decision tendency. In the model, the evaluation value is transformed into the attribute value matrix of intuitionistic fuzzy number, and the weight is obtained by the weight solving algorithm and the optimal result of the final support force is obtained by the scheme ranking algorithm.

(4) Health assessment model

$$Health = health(val, v, \rho).$$

Health assessment requires experts to give the language evaluation *val* of the health status of the subsystem according to the parameter data of each key subsystem for each alternative equipment, and input the decision mechanism coefficient v and discrimination coefficient ρ according to the actual decision tendency. The optimal selection procedure is the same as that of the support evaluation model.

In summary, the overall process of sequential equipment optimal selection can be obtained in Fig. 4.

4.0 Case study and comparison experiments

In this chapter, the effectiveness of the model is verified through a case of fighter aircraft, and the advantages of the proposed method are verified by comparing with other classical combination methods.

4.1 Sensitivity analysis

4.1.1 Resolution coefficient ρ

Resolution coefficient ρ is the coefficient used to measure the resolution ability of the algorithm in grey correlation analysis [30]. Therefore, this paper takes support assessment as an example, and selects several representative values in the interval of [0,1], to observe the change of attribute weight results. The result is shown in Fig. 5.

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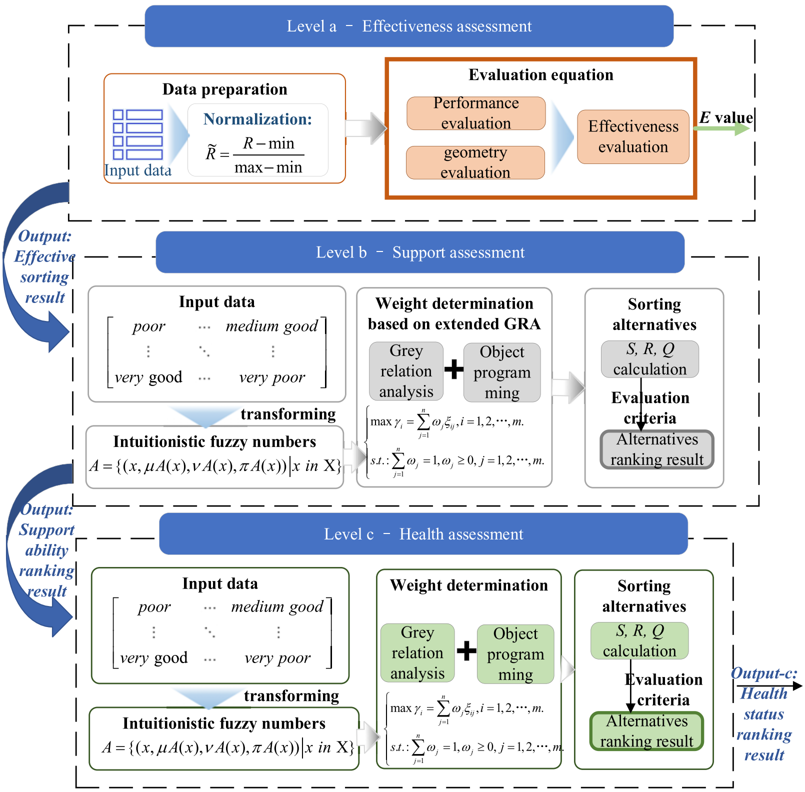

Figure 4. *Steps of sequential MCDM method.*

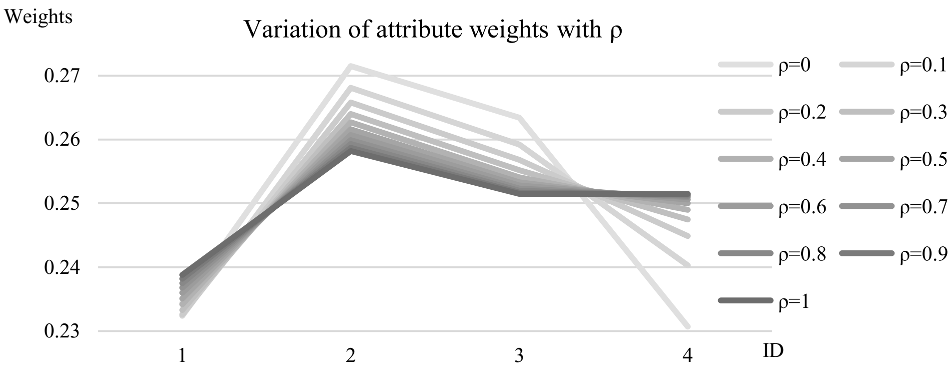

Figure 5. *Sensitivity analysis result of* ρ.

It can be observed from the above figure that the resolution coefficient ρ has a significant influence on the calculated weight. The fluctuation of the weights of different attributes is different. When $\rho = 0$, the weight fluctuation is the largest; when $\rho = 1$, the weight fluctuation is the smallest. Thus, it can be seen that the value of ρ will affect the resolution of the weight, a higher value will lead to a decline in resolution, which means that even if the two sequences are in the worst correlation situation, they will get a higher correlation coefficient, which is inconsistent with people's actual cognition.

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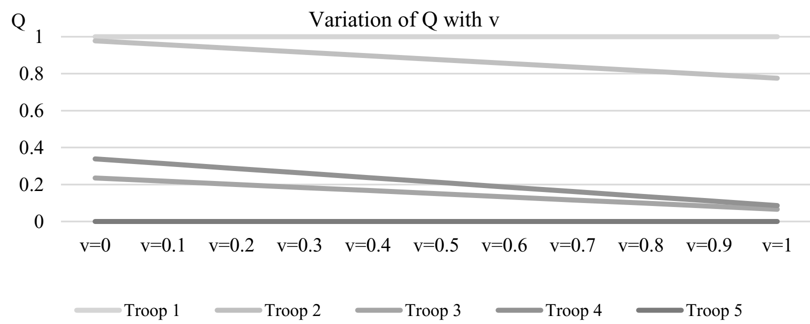

Figure 6. *Sensitivity analysis result of v.*

Referring to the literature [31], according to the '3σ rule', the implementation range can cover 0.95, which can be regarded as a significant result. With the distinguishing coefficient ξ as the benchmark, when the range [0.05, 1] can be obtained, the resolution ability can be considered significant. Literature [31] gives the calculation method to ensure high resolution: when $\Delta_{ij} = \Delta_{\max}$, ξ_{ij} gets the minimum value:

$$\xi_{ij} = (\Delta_{\min} + \rho\Delta_{\max}) \big/ ((1+\rho)\Delta_{\max}) \tag{11}$$

When $\Delta_{\min} = 0$, ξ_{ij} gets the infimum:

$$\inf \xi_{ij} = \rho/(1+\rho) \tag{12}$$

Let $\inf \xi_{ij} = \rho/(1+\rho) = 0.05$, it can be obtained that $\rho = 0.0526$, and because the infimum of ξ_{ij} is increasing with ρ, it is obtained that when $\rho \leq 0.0526$, the resolution is strong. In the decision-making, the commander can take $\rho = 0.0526$, to ensure that the final weight of the solution results relative gap is larger and more realistic.

4.1.2 Decision-making mechanism coefficient v

The decision-making mechanism coefficient v in the VIKOR method represents the degree of emphasis of decision-makers on group effect and individual regret. In this paper, several representative values are selected in the interval of [0, 1] to observe the change in ranking results. Since the ranking of the compromise value itself can approximately represent the ranking result of the scheme, the two criteria are not considered in the analysis, and the compromise value is used as the ranking basis.

It can be observed in Fig. 6 that the comprehensive evaluation value Q will change significantly with the value change of v. Sometimes it may even influence the result of the plan ranking. It can be seen that the value of the decision-making mechanism coefficient also has a significant impact on the ranking results. When the decision-maker focuses on maximising the group effect, it can make $v > 0.5$; when the decision-maker focuses on minimising individual regrets, it can make $v < 0.5$; when decision-makers want to balance group effect and individual regret, they can make $v = 0.5$.

4.2 Example of the application of sequential MCDM method

4.2.1 Effectiveness assessment

Ten typical models in service are taken as alternative fighter aircraft for model selection (letters A-J are used to represent actual models in this paper), and their performance indexes and geometric indexes are shown in Tables 3 and 4, with data from the literature [19].

Step 1: Normalising the attribute value, and denote the normalised decision matrix obtained as $\widetilde{R} = (\widetilde{r}_{ij})_{m \times n}$.

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Table 3. *Performance indexes*

The plane model	P_{SEP} (m/s)	$n_{y,cir}$	T_R	Ma (km/h)	H_{pc} (m)
A	310	9	1.1	2,877	18,000
B	235	3.2	0.74	3,464	20,600
C	300	7.3	1.19	2,815	18,300
D	265	7.5	0.88	2,815	17,000
E	305	9	1.03	2,387	18,000
F	290	9	0.88	2,387	18,000
G	245	6	0.87	2,203	15,240
H	238	8.6	0.82	2,693	18,000
I	255	9	0.86	2,693	18,000
J	180	5.5	0.7	2,570	15,000

Table 4. *Geometric indexes*

The plane model	RSC (m^2)	Sw (m^2)	L_{all} (m)
A	9.1	38	17.32
B	12.8	61.6	22.7
C	11.3	56.5	19.43
D	12.7	56.5	19.43
E	4.9	27.87	15.04
F	4.9	27.87	15.04
G	7.1	37.16	17.07
H	5.8	41	14.36
I	5.8	41	14.36
J	11.7	30	16.72

Step 2: The normalised attribute values are substituted into Equation (8), Equation (9), Equation (10) for calculation, and the ranking results of efficiency are shown in Fig. 7. According to the results, the effectiveness of model E fighter is the best.

4.2.2 Support assessment

Step 1: Assuming that the E-type aircraft obtained in the optimal selection of the previous level has five alternative support forces, the language evaluation of each alternative force is given by the experts according to the indicators, and the language evaluation matrix is shown in Table 5.

Step 2: The support evaluation model transforms the input language variable matrix into the attribute value matrix composed of intuitionistic fuzzy numbers, as shown in Table 6.

Step 3: Input the value matrix in Step 2 into the weight solving model and the weights were obtained:

$$\omega = [0.2351, 0.2616, 0.2533, 0.2500],$$

where the resolution coefficient ρ is chosen as 0.5.

Step 4: Input the attribute weight and attribute value matrix into the VIKOR model, select the decision mechanism coefficient v as 0.5, and the obtained values S, R, and Q are respectively:

$$S = [0.6989, 0.5927, 0.2573, 0.2669, 0.2262],$$

$$R = [0.2153, 0.2125, 0.1176, 0.1308, 0.0875],$$

$$Q = [1.0000, 0.8765, 0.1506, 0.2125, 0].$$

The visualisation of the sorted results is shown in Fig. 8.

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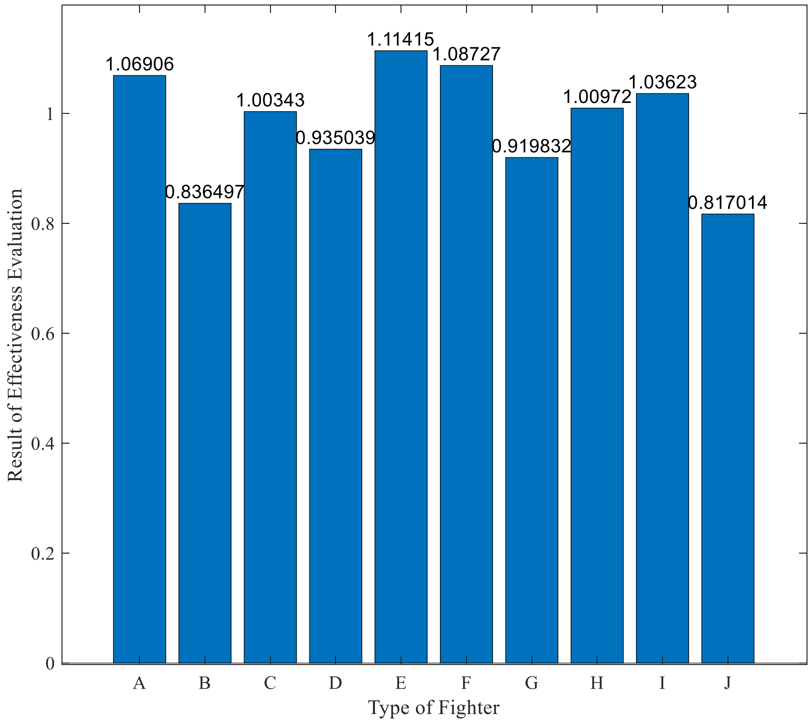

Figure 7. *Result of effectiveness assessment.*

Step 5: According to the acceptable advantage criterion, and the acceptable stability criterion, there are three schemes in the compromise scheme set, and the compromise alternative scheme set is finally obtained *{troop5, troop3, troop4}*.

4.2.3 Health assessment

Step 1: Assuming that the *troop5* obtained in the optimal selection of the previous level has seven alternative aircrafts, the language evaluation of each alternative force is given by the experts according to the key system test data of each alternative sortie, and the language evaluation matrix is shown in Table 7.

Step 2: The health evaluation model transforms the input language variable matrix into the attribute value matrix composed of intuitionistic fuzzy numbers, as shown in Table 8.

Step 3: Input the value matrix in Step 2 into the weight solving model and the weights were obtained:

$$\omega = [0.1187, 0.1396, 0.1191, 0.1133, 0.1215, 0.1358, 0.1258],$$

where the resolution coefficient ρ is chosen as 0.5.

Step 4: Input the attribute weight and attribute value matrix into the VIKOR model, select the decision mechanism coefficient v as 0.5, and the obtained values S, R, and Q are respectively:

$$S = [0.4419, 0.4363, 0.4179, 0.6494, 0.6195, 0.5727, 0.4609],$$

$$R = [0.1069, 0.0963, 0.0771, 0.1154, 0.1069, 0.1154, 0.0947],$$

$$Q = [0.4413, 0.2902, 0, 1.0000, 0.8247, 0.8344, 0.3220].$$

The visualisation of the sorted results is shown in Fig. 9.

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Table 5. *Linguistic evaluation of support forces*

Alternatives	Support design	Support personnel	Support facilities	Support management
Troop 1	Very poor	Poor	Very poor	Medium good
Troop 2	Poor	Very good	Medium poor	Very poor
Troop 3	Medium	Very good	Very good	Good
Troop 4	Very good	Medium	Good	Very good
Troop 5	Very good	Good	Very good	Medium good

Table 6. *Attribute value matrix of support forces*

Alternatives	Support design	Support personnel	Support facilities	Support management
Troop 1	[0.15, 0.80, 0.05]	[0.25, 0.65, 0.10]	[0.15, 0.80, 0.05]	[0.65, 0.25, 0.10]
Troop 2	[0.25, 0.65, 0.10]	[0.85, 0.10, 0.05]	[0.35, 0.55, 0.10]	[0.15, 0.80, 0.05]
Troop 3	[0.50, 0.40, 0.10]	[0.85, 0.10, 0.05]	[0.85, 0.10, 0.05]	[0.75, 0.15, 0.10]
Troop 4	[0.85, 0.10, 0.05]	[0.50, 0.40, 0.10]	[0.75, 0.15, 0.10]	[0.85, 0.10, 0.05]
Troop 5	[0.85, 0.10, 0.05]	[0.75, 0.15, 0.10]	[0.85, 0.10, 0.05]	[0.65, 0.25, 0.10]

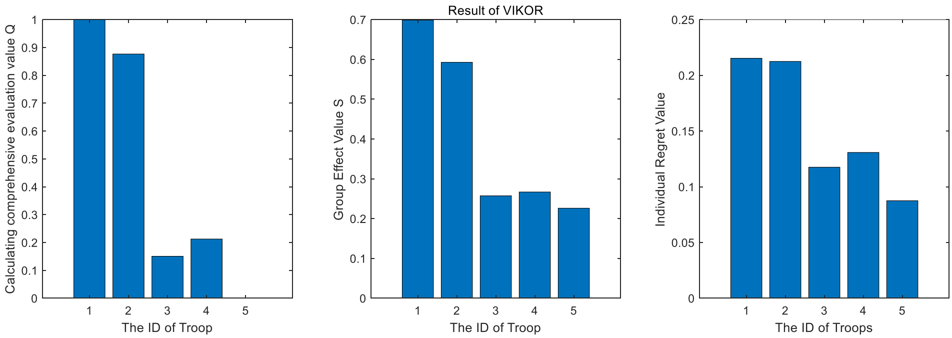

Figure 8. *Sorting result of support assessment.*

Step 5: According to the acceptable advantage criterion, and the acceptable stability criterion, the VIKOR ranking results of the health assessment are in line with the judgement criteria 1 and 2, and the fighter with the optimal health status of *Fighter3* can be directly obtained.

4.3 Comparison analysis

4.3.1 Comparison experiment

Due to the complexity of the GRA-VIKOR-IFNs method, this paper mainly performs the comparison experiment of this method. The comparison experiments are conducted from both qualitative and quantitative perspectives and are divided into two parts, attribute weight solving methods and sort methods. For the former, five methods are selected including the full consistency method (FUCOM) [32, 33], the level-based weight assessment (LBWA) [34], ordinal priority approach (OPA) [35], and entropy weight method [36]. Table 9 shows a qualitative comparison of the above methods. According to the analysis, the objective empowerment method process is much simpler and does not require subjective knowledge input, and expert knowledge collection. The extended GRA method is applicable for the small simple scenario which is in line with the research scenario of this paper.

Further, a quantitative comparison is made in this paper. Since subjective assignment methods require human subjective input and are not easily accessible, this paper compares two objective assignment

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Table 7. *Linguistic evaluation of alternative aircraft*

Alternatives	Engine system	The fuel system	Power supply system	Hydraulic system	Environmental control system	Navigation system	Avionics system	Weather radar system
Fighter 1	Poor	Medium Poor	Good	Very Good	Good	Medium Good	Good	Very Poor
Fighter 2	Very Good	Good	Medium Poor	Very Poor	Medium Poor	Good	Medium	Good
Fighter 3	Medium Poor	Medium Good	Medium	Medium	Medium	Medium	Very Good	Good
Fighter 4	Poor	Medium	Very Poor	Medium	Poor	Very Poor	Very Poor	Very Good
Fighter 5	Poor	Very Good	Very Poor	Very Poor	Medium Good	Poor	Medium	Very Poor
Fighter 6	Medium Good	Medium Poor	Medium	Medium Poor	Poor	Very Good	Very Poor	Medium Poor
Fighter 7	Medium	Good	Good	Poor	Medium Good	Poor	Very Good	Poor

Table 8. *Attribute value matrix of support forces*

Alternatives	Engine system	The fuel system	Power supply system	Hydraulic system	Environmental control system	Navigation system	Avionics system	Weather radar system
Fighter 1	[0.25, 0.65, 0.10]	[0.35, 0.55, 0.10]	[0.75, 0.15, 0.10]	[0.85, 0.10, 0.05]	[0.75, 0.15, 0.10]	[0.65, 0.25, 0.10]	[0.75, 0.15, 0.10]	[0.15, 0.80, 0.05]
Fighter 2	[0.85, 0.10, 0.05]	[0.75, 0.15, 0.10]	[0.35, 0.55, 0.10]	[0.15, 0.80, 0.05]	[0.35, 0.55, 0.10]	[0.75, 0.15, 0.10]	[0.50, 0.40, 0.10]	[0.75, 0.15, 0.10]
Fighter 3	[0.35, 0.55, 0.10]	[0.65, 0.25, 0.10]	[0.50, 0.40, 0.10]	[0.50, 0.40, 0.10]	[0.50, 0.40, 0.10]	[0.50, 0.40, 0.10]	[0.85, 0.10, 0.05]	[0.75, 0.15, 0.10]
Fighter 4	[0.25, 0.65, 0.10]	[0.50, 0.40, 0.10]	[0.15, 0.80, 0.05]	[0.50, 0.40, 0.10]	[0.25, 0.65, 0.10]	[0.15, 0.80, 0.05]	[0.15, 0.80, 0.05]	[0.85, 0.10, 0.05]
Fighter 5	[0.25, 0.65, 0.10]	[0.85, 0.10, 0.05]	[0.15, 0.80, 0.05]	[0.15, 0.80, 0.05]	[0.65, 0.25, 0.10]	[0.25, 0.65, 0.10]	[0.50, 0.40, 0.10]	[0.15, 0.80, 0.05]
Fighter 6	[0.65, 0.25, 0.10]	[0.35, 0.55, 0.10]	[0.50, 0.40, 0.10]	[0.35, 0.55, 0.10]	[0.25, 0.65, 0.10]	[0.85, 0.10, 0.05]	[0.15, 0.80, 0.05]	[0.35, 0.55, 0.10]
Fighter 7	[0.50, 0.40, 0.10]	[0.75, 0.15, 0.10]	[0.75, 0.15, 0.10]	[0.25, 0.65, 0.10]	[0.65, 0.25, 0.10]	[0.25, 0.65, 0.10]	[0.85, 0.10, 0.05]	[0.25, 0.65, 0.10]

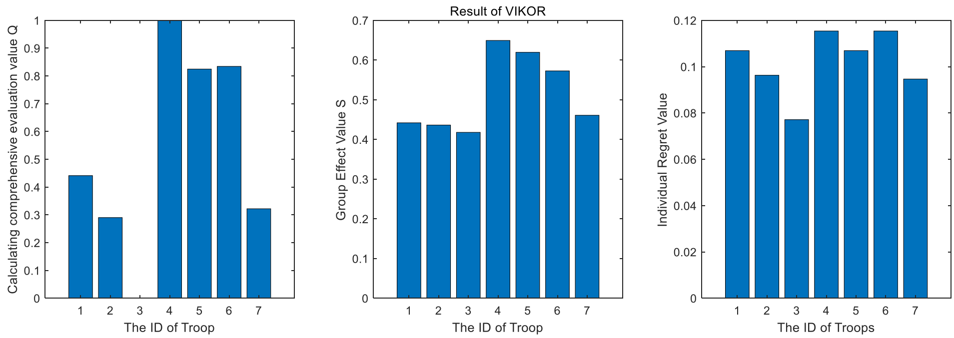

Figure 9. *Sorting result of health assessment.*

methods, entropy weighting method and GRA method. This paper indirectly evaluates the two weight methods by assessing the quality of the decision results obtained using the generated weights, the decision-making method uses the VIKOR method which is applied in this paper, and the quality of the results is expressed using the resolution of the ranked results. The higher the degree of identification between the results, the easier it is for the commander to make a choice based on the ranking results. In Ref. (37), the definition of the sort resolution R_v is given to calculate the discernibility of the sort result. The formula is as follows:

$$R_v = \min_{i,j;i\neq j}\left\{\left|v_i - v_j\right|\right\} \Big/ (\max_i v_i - \min_i v_i) \tag{13}$$

where $v = (v_1, v_2, \ldots, v_n)$ represents the sorting vector, satisfying $v_i \in [0, 1]$, $\sum_{i=1}^{m} v_i = 1$. In this paper, the sorting results of each method are normalised as sorting vectors. The methods are utilised to evaluate and optimise the support force of E-type fighter and the comparison result is shown in Table 10. It can be seen that the decision result of the two methods is consistent and the sort resolution of the extended GRA method is bigger than the entropy weight method, which indicates that the weight method in this paper is effective and can provide more identifiable sorting results. Because the grey correlation analysis method is suitable for solving the problem of 'small data', it has high applicability for the situation where the decision-making needs to be selected from several or more than ten kinds of alternatives.

For the sort method, this paper selects five methods to compare with the utilised VIKOR method in this paper, including TOPSIS method [38], GRA method, multi-attributive border approximation area comparison (MABAC) [39, 40], multi-attributive ideal-real comparative analysis (MAIRCA) [41, 42]. The qualitative analysis is in Table 11. Each method has its characteristics and applicability, and it is impossible to determine which method is the best. For this paper, the VIKOR method was chosen mainly because of its combined consideration of group utility values and individual regret values. For fighter optimal selection, especially in exercise scenarios, commanders sometimes do not consider using the equipment closest to the ideal solution, but rather synthesise conflicting criteria. In this case, the subjective preference of the decision maker can be satisfied by adjusting the coefficients of the decision mechanism, so the VIKOR method is chosen in this paper, which is more suitable for the fighter aircraft preference problem.

As for the quantitative comparison part of the sort methods, this paper utilises the extended GRA method as the weight method. Since MAIRCA requires the generation of weighting results in the form of IFNs for the subsequent calculation of the gap between the theoretical rating matrix and the real rating matrix, this method will not be considered in this part of the comparison. The result is illustrated in Table 12. This paper compares the different methods in terms of two aspects: the validity of the results and the resolution of the results. It is shown that each method gets the same ranking results, which proves that the results have some credibility and validity. According to the sorting resolution, the fuzzy MCDM

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Table 9. *The qualitative comparison of weight methods*

Method	Method type	Method principle
FUCOM	Subjective empowerment approach	Ideal for scenarios needing to ensure consistency of assessment results
LBWA	Subjective empowerment approach	Suitable for use in complex MCDM models with a large number of criteria
OPA	Subjective empowerment approach	Based on ordinal relationships; suitable for attributes that are difficult to quantify
Entropy weight method	Objective empowerment approach	Calculations need only be based on available data; high requirements for data selection
The extended GRA method	Objective empowerment approach	Calculations need only be based on available data; applicable to small samples of information

Table 10. *The comparison results of weight methods*

Method	Weight results	Q result of VIKOR and ranking result	Sort resolution
The entropy weight	[0.2340, 0.2465, 0.2753, 0.2442]	[1.000, 0.795, 0.112, 0.135, 0] $X_5 > X_3 > X_4 > X_2 > X_1$	0.0289
The extended GRA	[0.2351, 0.2616, 0.2533, 0.2500]	[1.000, 0.836, 0.117, 0.162, 0] $X_5 > X_3 > X_4 > X_2 > X_1$	0.0619

Table 11. *The qualitative comparison of sort methods*

Method	Principal	Can deal with fuzzy data
TOPSIS	Calculate the distance between the alternative and the positive and negative ideal solution.	Yes
GRA	Calculate the grey correlation between the alternatives and the reference scenario.	Yes
MABAC	Calculate the distance of the alternative from the boundary proximity area.	Yes
MAIRCA	Calculate the gap between the theoretical rating matrix and real rating matrix.	Yes
VIKOR	Calculate group effect value and individual regret value of the alternatives by combining positive and negative ideal solutions and synthesised into comprehensive evaluation.	Yes

method adopted in this research has a higher sorting resolution and more identifiable sorting results, which can provide more reasonable and reliable decision support for commanders. The VIKOR method can also obtain a compromise solution set when the sorting result is not highly identified, providing more comprehensive and reliable decision support for the commander. Therefore, the research methods used in this paper are more flexible and more applicable than other methods.

Table 12. *The comparison results of sort methods*

Method	Numerical results (grey correlation/ comprehensive evaluation/relative closeness)	Ranking results	Sort resolution
TOPSIS	$D_1 = 0.3682$, $D_2 = 0.4576$, $D_3 = 0.7496$, $D_4 = 0.7410$, $D_5 = 0.7934$	$X_5 > X_3 > X_4 > X_2 > X_1$	0.0202
GRA	$C_1 = 0.5337$, $C_2 = 0.6249$, $C_3 = 0.8740$, $C_4 = 0.8635$, $C_5 = 0.8967$	$X_5 > X_3 > X_4 > X_2 > X_1$	0.0289
MABAC	$S_1 = -0.4164$, $S_2 = -0.1784$, $S_3 = 0.5439$, $S_4 = 0.5285$, $S_5 = 0.6221$	$X_5 > X_3 > X_4 > X_2 > X_1$	0.0148
VIKOR	$Q_1 = 1.000$, $Q_2 = 0.8765$, $Q_3 = 0.1506$, $Q_4 = 0.2125$, $Q_5 = 0$	$X_5 > X_3 > X_4 > X_2 > X_1$	0.0619

Table 13. *Attribute value matrix of support assessment*

Alternatives	Support design	Support personnel	Support facilities	Support management
Troop 1	20	25	15	65
Troop 2	25	80	30	10
Troop 3	50	80	85	75
Troop 4	85	50	75	85
Troop 5	85	70	85	70

4.3.2 Usage of intuitionistic fuzzy numbers (IFNs)

Finally, this paper analyses the necessity of using IFNs by comparing them with the way of expressing decision information by deterministic values. As an example of a support assessment comparison, experts first give the score of each alternative force. The score can be seen in Table 13.

The weight obtained by extended GRA is:

$$\omega = [0.2210, 0.2632, 0.2479, 0.2679].$$

S, *R* and *Q* values obtained by VIKOR method are:

$$S = [0.5063, 0.5490, 0.1412, 0.1331, 0.0770],$$

$$R = [0.1918, 0.2348, 0.0949, 0.1038, 0.0474],$$

$$Q = [0.8401, 1.0000, 0.1948, 0.2099, 0].$$

Visualisation results are shown in Fig. 10.

According to the acceptable advantage criterion, and the acceptable stability criterion, there are three schemes in the compromise scheme set, and the compromise alternative scheme set is finally obtained $\{troop5, troop3, troop4\}$.

The ranking result is: *troop5* > *troop3* > *troop4* > *troop2* > *troop1*, and sort resolution $R_v = (0.0935 - 0.0868) / (0.4455 - 0) = 0.0150$.

In summary, there is a certain difference between the ranking results and the original method when the decision information is expressed by the determined value, and the ranking resolution is less than the multi-criteria decision method based on intuitionistic fuzzy numbers. This is because the determined value will cause problems such as information loss when describing vague information. In addition, experts are more inclined to fill in the language evaluation when performing the scoring, while the hesitation and deviation are greater when filling in the deterministic value. Therefore, the sorting results are not accurate enough and the resolution is low.

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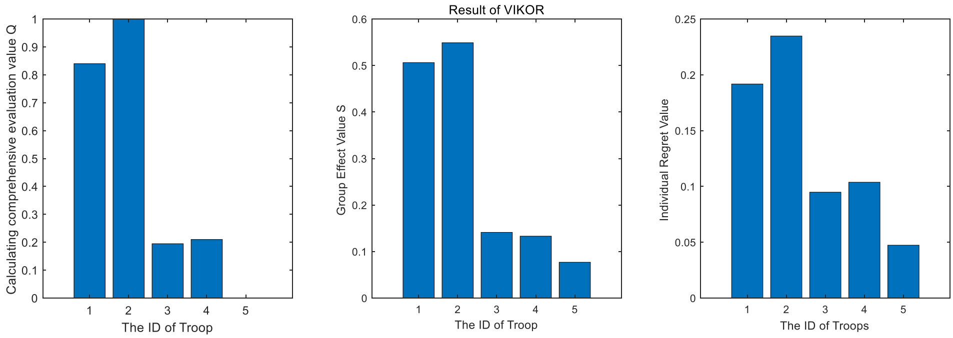

Figure 10. *Sorting result of support assessment.*

5.0 Conclusion and future work

Equipment optimal selection is an indispensable decision-making auxiliary means in daily training and the actual use of equipment. Aiming at the actual combat requirements of troops and the characteristics of equipment optimal selection decision-making, this paper proposes an optimal strategy based on the sequential MCDM method with uncertainty measurement. The methodology we put forward has some strengths as follows:

1. The effectiveness-support-health sequential structure includes the effectiveness index, support index and health index, covering the inherent ability of the equipment, use, maintenance and logistics management of many factors, close to the actual battlefield command decision-making process, more in line with the actual needs.
2. Support and health assessment based on IFN are in line with the actual decision-making habits of decision-makers, which leads to a more accurate result. Compared with the traditional method, the plan of the extended GRA-VIKOR method is more suitable for small sample scheme optimal selection, which can not only obtain higher resolution and more accurate ranking of results but also provide a compromise scheme set when the results of the recommended schemes are similar.
3. The optimal selection system proposed in this paper is universal and can realise the rapid transplantation and utilisation of equipment in aviation, aerospace, marine, land and other fields. It could reduce the research and development cost of the decision-making system and improve the research and development efficiency.

Nevertheless, there are still some limitations of the proposed framework, for which the further work can be completed.

1. At present, this paper proposes an indicator system based on existing knowledge, which cannot ensure that the indicator system can cover all kinds of elements of equipment decision-making. However, the indicator system in this paper has good scalability, therefore, in future use, attention needs to be paid to the object and the use of demand, and the expansion and optimisation, so that the indicator system gradually forms a complete and comprehensive network.
2. This paper does not consider the group decision problem, i.e., modeling the method when having multiple decision-makers, which can be subsequently extended in this direction. For example, various types of methods based on consensus maximisation or subjective methods based on prior knowledge are used to calculate expert weights to represent and aggregate group opinions.
3. The weight solving model in this paper is an objective assignment method, which does not take the subjective preference of decision makers and expert knowledge into consideration, and the

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results are easily affected by the data quality. In the future, we can consider further combining the subjective assignment method, such as FUCOM, LBWA and other models on this basis. Different methods of subjective and objective assignment methods can be synthesised using game theoretic methods, the sum of squares of deviations, etc.

Finally, the proposed MCDM method could have greater potential in different decision-making applications, such as the selection of a component, software, etc. And this also warrants further research on various issues.

Acknowledgments. This study was supported by the National Natural Science Foundation of China (Grant Nos. 72471013, 52472442 and 62103030), National Laboratory of Space Intelligent Control (No. HTKJ2023KL502023), the National Key R&D Program of China under Grant STI 2030 – Major Projects (Grant No. 2021ZD0201300), and the Fundamental Research Funds for the Central Universities.

Competing interests. The authors have no relevant financial or non-financial interests to disclose.

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Cite this article: Suo M., Xing J., Ma K., Xiao D. and Song D. Fighter optimal selection based on sequential multi-criteria decision-making with uncertainty measurement. *The Aeronautical Journal*, https://doi.org/10.1017/aer.2024.125