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Main problems of the evaluation and selection of advanced weapon systems exemplified by a multi-role combat aircraft

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Abstract. This paper presents a selection of issues related to the methods of evaluation and selection of advanced weapon systems for armed forces. The paper's focus is ranking in the form of typical Multidimensional Comparative Analysis Methods, and the AHP method which represents a large group of Multi-Criteria Decision Analysis methods. Both methods were illustrated with a practical computational example related to combat aircraft. The example can help determine the defensive capabilities of friendly forces; it can also support the decision-making process in the acquisition of novel armament, including aircraft, ships, surface-to-air missile defense systems, etc.
Keywords: armament, military aviation, decision making support, multi-criteria analysis, AHP method, ranking
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1. Introduction

A significant part of the operations of certain official authorities, including the national defense department and its subordinate bodies is an analysis of the general defensive capabilities of the state in the context of military threats as they emerge. An analysis of the general defensive capabilities is based on the assessment of current armament at the disposal of national armed forces and related to the decisions (if any) made to acquire new ordnance. The assessments and decisions should be based on impartial premises which help verify the validity of the decisions and confirm that the best options are chosen. Making major strategic decisions or the failure to make them always has concrete consequences. Notably, the consequences can arise in the long term.

It has been proven that human choices and decisions depend on the mechanisms of thinking. It is, however, undisputed that thinking can and should be aided or supported with methods suitable for the task in hand, including decision-making support methods which are acquired with the knowledge and experience of decision makers.

Each decision process is specific. The specificity of decision-making related to the acquisition of military ordnance for national defense and security comprises the following [2]:

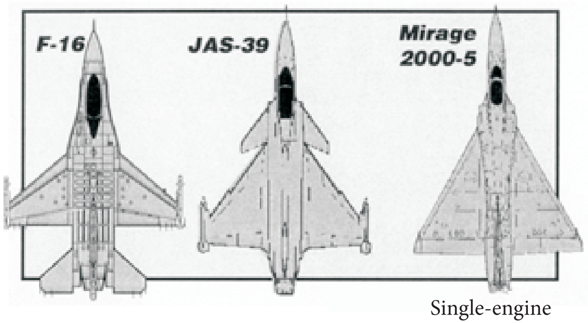
- An evaluation of the existing technical condition of friendly and competitive military ordnance;
- Forecasting the evolution of armament technologies;
- An analysis of the feasibility of meeting the known and notified demands for military ordnance.

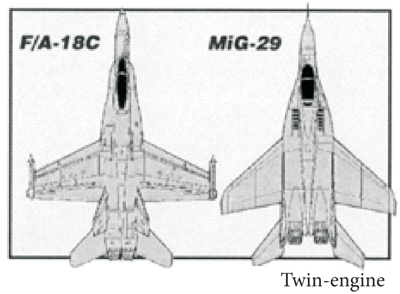
The key decisions related to military ordnance acquisition are made and processed in an extremely formalized manner. The decisions are not rash or quick; they entail much consideration, awareness, and compliance, and, more often than not, they are supported with scientific research and methods [7].

Acquisition of new-generation military aircraft (combat aircraft or helicopter), ship, or a surface-to-air missile defense system is a complex process which entails high costs and liability. The final decision on whether to purchase a selected military platform must be based on a thorough analysis of all activities resulting in the selection of the best option. The said analysis can be focused on systemic, design, technological or organisational criteria described with technical and economic indicators and expressed in certain units; once evaluated, the indicators drive a rational decision. The key argument of decision-making rationality is to select the options which have a proper balance of the positive and negative outcomes of choice [6]. The challenge is to establish the respective criteria and the method for evaluating technical and utility values[7]. It is also difficult to identify the consequences of the chosen option in short and long time frames.

Methods and techniques for supporting decision making processes have been in development for decades[1]. This area of research is shared by multiple scientific disciplines. It has been established that two principal decision support areas exist: Multi Criteria Decision Analysis and Multidimensional Comparative Analysis[4].

[1] So-called decision support method schools exist, including ELECTRE from France, PROMETHEE from Belgium, AHP from the USA, and multiple methods from Poland, including BIPOLAR, GRIP, INSDECAM, WINGS, and MARS.





	F-16 Block 50 52+	JAS 39	Mirage 2000-5	F/A-l8C	MiG-29
• Dimensions					
- Length overall (ft)	49.3	49	48.1	56	56.8
- Wing span (ft)	32.8	27	29.9	40.4	37.3
- Height overall (ft)	16.7	14.8	17.1	15.3	15.5
- Wing area (sq ft)	300	323	441	400	412
• Weight					
- Empty weight w/cannon (lb)	18,917	14920	16616	24745	24280
- Internal fuel tanks JP-8 (lb)	7162	5291	6970	10810	8310
- Maximum TGOW (lb)	48000	28110	37500	51900	44090
- TOGW payload ratio (%)	46	28	37	31	26
• Maximum g-load	9	9	9	7.5	9
• Thrust/weight (at empty weight +50% of fuel capacity)	1.32	1.03	1.06	1.17	1.29

Fig. 1. Basic characteristics of 4th generation multi-role combat aircraft models [1 lb = 1 pound = 0.4535 kg. 1 ft = 1 foot = 30.48 cm] [*source: Lockheed Martin*]

A certain help in practical solving of the decision challenges indicated herein can be provided by **ranking**, which is a typical technique of Multidimensional Comparative Analysis, and **the AHP method** (Analytical Hierarchy Process); both are relatively simple, yet effective methods of Multi Criteria Decision Analysis. Ranking and AHP are the focus of the following sections of this paper. Both ranking and AHP were used to evaluate selected types of multi-role combat aircraft the basic characteristics of which are shown in Fig. 1.

2. Ranking methods and numerical ranks

At present, it is difficult to underestimate the importance and sense of building rankings to evaluate object types. Rankings developed with various comparative techniques evolve into the foundation of major decision processes.

Ranking, or hierarchical organisation, is one of the most frequently used techniques of Multidimensional Comparative Analysis[2]. It consists of a linear organisation of objects from the best to the worst (or vice versa), based on aggregate characteristics. The intended result of the technique is to build a ranking[3].

Here, any attempt at comparison will only make sense if more than one object exists to be analysed, which means $O = \{O_1, O_2, \ldots, O_r\}$, with O being a set of compared objects the number of which is r.

This definition states that a complex technical object[4] can be defined with multiple characteristics (attributes), each of a different nature, different physical form, different standards, and – sometimes – a different value. A certain arrangement of a set of the characteristics (attributes) should leave only the characteristics (attributes) which can be included in the so-called set of diagnostic characteristics. Hence, of all the attributes which describe a technical object, those attributes are determined which, due to the adopted criterion of definition, precisely define the characteristics considered in the evaluation, whereas: $X = \{X_1, X_2, \ldots, X_s\}$, with X being the set of diagnostic characteristics the number of which is s and which are typical for the class of the technical objects being evaluated.

2 The Polish school boasts great contributions to the technique, for it is focused on taxonomic methods, applied mainly in the ranking of objects.

3 A ranking should be construed as an arrangement of objects of evaluation by which the evaluation results of the objects can be arranged in an ascending or descending order.

4 This can be certainly related to modern weapon systems

This provides a two-dimensional square matrix like below [3]:

$$\left[x_{ij}\right]=\begin{bmatrix} x_{11} & x_{12} & \dots & x_{1s} \\ x_{21} & x_{22} & \dots & x_{2s} \\ \dots & \dots & \dots & \dots \\ x_{r1} & x_{r2} & \dots & x_{rs} \end{bmatrix}\cdot\begin{pmatrix} i=1,2,\dots,r \\ j=1,2,\dots,s \end{pmatrix}. \tag{1}$$

It is favourable to classify the diagnostic characteristics in the set being sought in three subsets which are complete. The subsets follow:

— A subset of the characteristics called "stimulants",
— A subset of the characteristics called "de-stimulants",
— A subset of the characteristics called "normal variables".

In simplified terms, stimulants are the attributes (characteristics, parameters, etc.) of a technical object the increase of which should be associated with a positive evaluation of the overall technical object. De-stimulants are variables the increase of which reduces the ranking. Normal variables are the nominal values established according to the circumstances of the evaluation.

References increasingly often replace the terms "stimulants", "de-stimulants", and "normal variables", which are characteristic of Multidimensional Comparative Analysis methods, with equivalent terms of "desirable criteria", "undesirable criteria", and "neutral criteria", respectively[4]. If a comparison between technical objects is attempted, the criteria and their application in the evaluation must be determined.

If the determined diagnostic characteristics are to become evaluation criteria, they must be organised accordingly. The organisation is made by converting the diagnostic characteristic values to homogenize them. This is called „standardization". Standardization of diagnostic characteristics is a critical stage of the evaluation procedure; it provides a total multi-criteria evaluation of the tested technical objects. The converted variables lose their standards and have values of an approximate order. There are several standardization methods. The commonplace standardization formula applied to stimulants is a transformation with the following formula:

$$z_{ij}=\frac{x_{ij}-\min\limits_{i} x_{ij}}{\max\limits_{i} x_{ij}-\min\limits_{i} x_{ij}}, \tag{2}$$

with: z_{ij} — standardised value of diagnostic variable x_{ij}.
De-stimulants are standardised with the following relationship:

$$z_{ij}=\frac{\min\limits_{i} x_{ij}-x_{ij}}{\max\limits_{i} x_{ij}-\min\limits_{i} x_{ij}}, \tag{3}$$

with: z_{ij} — standardised value of diagnostic variable x_{ij}.

In both formulas, the value

$$R\left(X_j\right)=\max_i x_{ij}-\min_i x_{ij}, \tag{4}$$

is the so-called standardised variable range.

The standardised values can be aggregated. An aggregated (synthetic) variable is the foundation on which the ranking structure is built. In the ranking, the technical objects are arranged from the best to the worst by the value of the aggregated variable.

The synthetic variable Q_i can be determined by either of the two alternative formulas:

$$Q_i=\sum_{j=1}^{s} z_{ij} \text{ or } Q_i=\frac{1}{s}\sum_{j=1}^{s} z_{ij} \tag{5}$$

which are the total of standardised variables and the arithmetic mean of standardised variables, respectively.

To include the non-uniform effect of the diagnostic variables on a synthetic variable, systems of weights can be chosen with the help of statistical or expert information. Ultimately, the determination of the synthetic variable value for each of the technical objects under a comparative analysis helps build the ranking of the technical objects, the highest rank of which is the best technical object, and the lowest rank is the worst technical object. If a statistical analysis includes multiple technical objects, a complement to their evaluation can be the assignment of the best technical objects, the moderate technical objects and the worst technical objects along the entire ranking. The assignment is made by determining the constant U from this formula [3]:

$$U=\frac{\max_i Q_i-\min_i Q_i}{3}. \tag{6}$$

The value of U drives the determination of technical object subgroup types:

— the best for $Q_i \in \left(\max_i Q_i - U,\ \ \max_i Q_i\right)$,

— the moderate for $Q_i \in \left(\max_i Q_i - 2U,\ \ \max_i Q_i - U\right)$,

— the worst for $Q_i \in \left(\min_i Q_i,\ \ \max_i Q_i - 2U\right)$.

This way a ranking of the multi-role combat aircraft specified in Fig. 1 was built. To reduce the calculations for the sake of clarity and brevity, the ranking was only built with three parameters of the multi-role combat aircraft[5]. The parameters were: wing area, thrust/weight, and TOGW payload ratio. These were the stimulant diagnostic

[5] In reality, the number of parameters and characteristics to be analysed is much longer.

variables (the higher the value, the better). Having standardised and aggregated the variables with the preceding formulas, the data was derived as shown in Table 1.

TABLE 1

Ranking results

Aircraft	z_{i1}	z_{i2}	z_{i3}	$Q_i = \frac{1}{3}\sum_{j=1}^{3} z_{ij}$	Rank
F-16 Block 50/52+	0	1	1	0.67	**1**
JAS 39	0.16	0.10	0	0.09	**5**
Mirage 2000-5	1	0.55	0.10	0.55	**3**
F/A-18C	0.71	0.25	0.48	0.48	**4**
MiG-29	0.79	0	0.90	0.56	**2**

The highest evaluation result (and the highest) rank was given F-16 Block 50/52+, followed by, in the descending order: MiG-29, F/A-18C, Mirage 2000-5, and JAS 39.

3. AHP method

AHP or **Analytic Hierarchy Process**, was invented in the 1970s by Thomas L. Saaty of the Pittsburgh University. AHP is a Multi-Criteria Decision Analysis method based on the function of utility. AHP is widely accepted and used in the scientific community, and often used as a support tool for complex decisions based on high numbers of criteria. The criteria can be grouped and subgrouped by nature (e.g. technical criteria, operational criteria, service criteria, and economic criteria), while the classification of the criteria by the level of detail provides general criteria and detailed criteria[6]. The basis of AHP is a hierarchical decomposition of evaluation criteria. On the highest hierarchy level, the purpose of decision is established (to buy a combat aircraft); the first lower level features the general criterion or criteria related to the decision problem; the general criterion or criteria can be divided further, down to detailed *k*-criteria[7]. The hierarchy of significance in AHP has a predefined structure for the decision problem. This is a tree of hierarchy, at the top of which is the purpose of decision, with the detailed criteria at the very bottom. The decision maker controls the entire process of AHP by evaluating the possible choice options by the adopted criteria, and the decision maker's knowledge and discretion, based on experience.

6 In an analysis of high-tech weapon systems, the total number of criteria (on all levels and in all groups and subgroups) may reach hundreds of items, which requires dedicated computer applications to handle the computations.

7 In the simplest case, with a low number of criteria, the criteria can be assigned directly to the decision problem without a classification of groups and subgroups.

Each of the detailed criteria has the elements of a preference matrix (or a pairwise comparison matrix) determined by the computation procedure provided by AHP. The elements (numbers) of each column in the matrix are totalled. Next, the pairwise comparison matrix is standardised. In the Saaty's method, the pairwise comparison matrix is standardised in relation to the total values of individual matrix columns[4]. The output is another numerical (and standardised) matrix, the elements of which are used to determine the coefficient of weight, or simply, weights[8]. The next steps of the AHP method computational procedure is to verify the consistency (the correctness of the preference matrix), followed by the determination of a measure which describes compliance of the option with the decision maker's preferences; the determination is made with the totals of the column elements in the pairwise comparison matrix and the corresponding weights (see the computation example below).

A typical AHP implementation procedure for a decision process comprises the four following stages:

Etap 1. Hierarchical organisation of the problem: the objective is to determine and detail the problem [which can be, e.g. the acquisition of a multi-role combat aircraft chosen from the available *n*-offers (or options)] and the decision maker's expectations for compliance with the (general and detailed) criteria which condition a reasonable choice.

Etap 2. Pairwise-comparison-based evaluation of criteria: the decision maker or expert compares the identification parameter of a criterion pairwise by a subjective definition (or preference, or valuation) of the relation between the parameters in the pair. The relations are determined by the 9-point scale by Saaty: 1 — equal value; 3 — slight advantage; 5 — high advantage; 7 — very high advantage; 9 — absolute advantage; 2, 4, 6, 8 — intermediate values. The evaluations in opposite relations are designated with the converse of the integers, i.e. 1/3 — slightly worse, 1/5 — worse, 1/5 — much worse, 1/9 — definitely worse. This stage is finished by building a square matrix for the criterion in question. The square matrix dimensions are *n*x*n*, and the elements are the result of the comparison.

Etap 3. Calculation of the criterion weights and preference validity

Etap 4. Analysis of the computation results and ranking: it is the selection of the best option which suits the preferences.

Not unlike building a ranking, the practical application of AHP relates to the decision process of evaluating the best multi-role combat aircraft of all the options (the offers) shown in Fig. 1. The general criterion, the satisfaction of which will qualify

[8] Several methods are used to determine the weights, e.g. Saaty's method, the right-hand or left--hand eigenvector method, the least squares method, the least absolute weighed error method, and others [3].

the viable aircraft types considered, is the single-engine (the aircraft shall have one engine only). This narrows down the analysis to three multi-role combat aircraft, namely: F-16, JAS 39, and Mirage 2000-5. F/A-18C and MiG-29 are eliminated from the analysis. Hence, there are n=3 decision options.

The next step will be to choose the detailed (criteria) parameters which will enable AHP computations. The criteria will be equivalent (the number of criteria, not unlike in the ranking, was minimised for the sake of clarity hereof).

— **Criterion 1**: wing area
— **Criterion 2**: TGOW payload ratio
— **Criterion 3**: thrust/weight

A comparison of the characteristic values (see Fig. 1) in pairs for each of the criteria gives a pairwise comparison matrix **A** sized $n \times n$, with $n = 3$, the number of decision options in the following form:

$$\mathbf{A} = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix} \tag{7}$$

with: $a_{ij} = 1 \quad \text{dla } i = j$

$$a_{ij} = \frac{1}{a_{ji}} \quad \text{dla } i \neq j$$

A specific characteristic of the matrix is its major diagonal with the main elements equal to 1.

Table 2

The element value matrix for Criterion 1

$A = [a_{ij}]$	F-16C	JAS 39	Mirage 2000-5
F-16C	1	1/3	1/7
JAS 39	3	1	1/5
Mirage 2000-5	7	5	1
$\text{TOTAL}_j \sum_{i=1}^{n} a_{ij}$	11	6.333	1.343

The numerical values of the matrix elements shown in Table 2 are the result of an expert evaluation made with Saaty's scale applied to the data in the table in Fig. 1. The next step is to determine the weight of each criterion separately.

A standardised matrix is built, $\mathbf{B} = [b_{ij}]$, the elements of which are calculated with the following relationship:

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{8}$$

The weights ω_i of each criterion are calculated with the formula:

$$\omega_i = \frac{\sum_{j=1}^{n} b_{ij}}{n} \tag{9}$$

The total of weights shall satisfy the condition: $\sum_{i=1}^{n} \omega_i = 1$

Table 3

Matrix elements and their calculated weights ω_i for Criterion 1

$B = [b_{ij}]$	F-16C	JAS 39	Mirage 2000-5	Weight ω_i
F-16C	0.091	0.053	0.106	**0.083**
JAS 39	0.273	0.158	0.149	**0.193**
Mirage 2000-5	0.636	0.790	0.745	0.724
Total of weights $\sum_{i=1}^{n} \omega_i =$				1

The next step in the AHP computational procedure is to verify the consistency of the pairwise comparison matrix, i.e. the formal validity of the entire method. Expert evaluations (preferences) cannot always be purely impartial; the process flow dictates that the next step is to determine the consistency ratio, *CR*. Ideally, the value of *CR* is zero, which means that the tested matrix is consistent. In practical reality, however, slight deviations at 10% are allowed, up to 15% in some cases [4]. *CR* is determined by the following relationship:

$$CR = \frac{CI}{R} \tag{10}$$

CI (consistency index) is calculated with the following equation:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{11}$$

with: $\lambda_{\max}$ — the highest real eigenvalue of matrix ***A***.
R — the constant dependent on the size of matrix ***A***.

The value λ_{max} of the criterion is calculated from a total of the products of the totals of the column elements in the pairwise comparison matrix **A** and the corresponding weights ω_i. The value *R* is shown in Table 4.

TABLE 4

R-value determination table

n	1	2	3	4	5	6	7	8	9	10	11	12
R	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54

Results of calculation procedures for Criterion 1 are shown in Table 5[9].

TABLE 5

Results for Criterion 1

Aircraft	$TOTAL_j$	Weight ω_i	$\lambda \max_i$
F-16C	11	0.083	0.913
JAS 39	6.333	0.193	1.222
Mirage 2000-5	1.343	0.724	0.972
		$\lambda \max = \sum_i \lambda \max_i$	3.107

The verification of the condition of consistency with the permitted value of *CR* provided the value of CR = 0.103 which satisfies the condition of consistency (CR<0,15). This means that the valuation is correct.

The similar calculations for Criterion 2 and 3 provide a tabulation of weight values (see Table 6), the total of which in each line is a measure Σ_i by which the group of ordnance can be evaluated and the best option chosen (here: the best multi-role combat aircraft).

TABLE 6

Final results of the process of multi-role combat aircraft evaluation

Aircraft	Criterion 1	Criterion 2	Criterion 3	Σ_i	Rank
F-16C	0.083	0.724	0.714	1.521	**1**
JAS 39	0.193	0.083	0.143	0.419	**3**
Mirage2000	0.724	0.193	0.143	1.060	**2**

The numerical values demerited as above enable the determination of evaluation or the preference of choice. The higher the measure Σ_i is, the higher the evaluation

9 The equivalent of the product of two matrices, i.e. $\lambda_{max} = [TOTAL_1\ TOTAL_2\ TOTAL_3] \cdot [\omega_1\ \omega_2\ \omega_3]^T$

of a multi-role combat aircraft is according to the computational procedure shown above. Hence, rank 1 in the ranking generated by AHP means that the best multi--role combat aircraft in the decision process contemplated herein is the F-16C. Rank 2 is the Mirage 2000. Rank 3 is the JAS 39.

Conclusions

The process of evaluating the weapons systems of strategic importance to national security, including aircraft, navy vessels and air defense should be continuous and based on an analysis of the friendly defensive capabilities and the weapon systems operated by other countries. The evaluation of weapons (and their systems) is a classic example of a multi-criteria analysis. The consequence of its process can be decisions on whether to upgrade weapons systems. A symptom of decision making is the selection of a specific solution (option) which is deemed to be the best (most optimal). A synthesis of the problem of supporting these types of decisions leads to the following conclusion: the problem is usually about choosing the best solution from a finite set of options, evaluated with a set of criteria included in operational, technical and servicing, and technical and tactical requirements.

Concerning the acquisition of weapon systems according to the official procedures in Poland [8], the final decision to acquire or not is made as an effect of a feasibility study which presents a description of the analysed ordnance and an assessment of the potential of alternative solutions to satisfy the expectations of the buyer[10].

The decision problem and its calculation example presented herein concerns the evaluation of the 4th-generation multi-role combat aircraft. Given a dynamic evolution of the designs and technologies of weapon systems and the dynamic changes in the levels of threats (and the resulting defense demands), the subjects of the presented analysis may change. The evaluation process suggested herein can be applied to the decision processes in the acquisition of, e.g. 5th-generation combat aircraft (including F-35, Su-57 and J-20), combat helicopters, submarines, air defense missile systems, etc. The methods and problems presented herein will remain useful and timely. A multi-faceted scientific approach to the problem provided the capacity to include custom preferences of the decision maker (by establishing the ranking list) and the capacity of determining impartial measures (see Table 6) which aggregate the attributes of the analysed weapon systems. The foregoing is important to impartial comparisons of the military capabilities of specific weapon systems and making sound decisions in relation to those systems.

[10] The authors hereof believe that this part of the paper should be supplemented with a content focused on the recommended decision support methods and techniques.

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A. KOZAKIEWICZ, M. WRÓBLEWSKI

Podstawowe problemy oceny i wyboru zaawansowanych systemów uzbrojenia na przykładzie techniki lotniczej

Streszczenie. W artykule przedstawiono wybrane zagadnienia związane z metodami oceny i wyboru dla potrzeb sił zbrojnych zaawansowanych technicznie systemów uzbrojenia. Skupiono się na rankingowaniu jako typowej technice wielowymiarowej analizy porównawczej oraz metodzie AHP należącej do licznego grona metod wielokryterialnej analizy decyzyjnej. Obie metody zilustrowano praktycznym przykładem obliczeniowym dotyczącym samolotów bojowych. Przykład ten z jednej strony może służyć do określenia własnego potencjału obronnego, z drugiej zaś może być wykorzystany do wspomagania procesu decyzyjnego związanego z pozyskiwaniem nowego typu uzbrojenia jak np. samoloty, okręty, systemy obrony rakietowej itp.

Słowa kluczowe: uzbrojenie, lotnictwo, wspomaganie podejmowania decyzji, analiza wielokryterialna, metoda AHP, ranking

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