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Classification of Combat Wheeled Vehicles Using Cluster Analysis Methods

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Abstract:

The functionality and purpose of combat wheeled vehicles (CWV) models are determined by both the requirements of the armed forces and the financial and technical capabilities of military equipment manufacturers. This leads to a discrepancy between the technical characteristics of the CWV model and its combat purpose. For the classification of CWV, an approach is proposed that consists of using generalized indicators that characterize the combat properties of CWV models, which allows establishing a correspondence between the technical characteristics of CWV models and their functional purpose, provides an opportunity to develop rational protection options and to justify specific technical solutions to increase the level of survivability of CWV models within groups.

Keywords:

complete link method, dendrogram, single link method, Ward's method, weighted centroid localization method

1 Introduction

The functionality and purpose of combat wheeled vehicle (CWV) models is determined by both the requirements of the armed forces and the financial and technical capabilities of military equipment manufacturers. As a result, there is a discrepancy between the requirements required to perform the tasks assigned to the armed forces and the ability to perform various combat tasks for a particular CWV model, which

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ultimately leads to a discrepancy between the technical characteristics of the CWV model and its combat purpose.

The existing and promising nomenclature of CWV models makes it necessary to generalize them by functional purpose in order to further ensure that the characteristics of CWV models correspond as much as possible to their functional combat purpose.

An ordered and formalized generalization of information can be obtained using classification [1], which provides a determination of the achieved level of CWV models development, reveals the structure in the general population of samples and determines the place of samples in the weapons system [2].

Traditionally, classification is carried out according to individual characteristics [3-5] for CWVs, such as, for example, the purpose, placement of the engine and cab, body type, number of axles, engine location, number of driving and controlled axles, which makes it possible to analyze by design characteristics. However, this classification does not allow establishing a relationship between the technical characteristics of CWVs and their functional purpose, which makes it necessary to develop more advanced methods for classifying CWVs. The most common classification for CWV models is based on the combat mass of the model. However, classification by using the numerical characteristic of the model is not always successful. It is necessary to perform additional transformations or generalizations of characteristics [6].

It is proposed to classify CWV models using cluster analysis methods, which allow combining CWV models into groups with maximum similarity among themselves and significant differences between groups.

2 Methodology for Conducting CWV Models Classification with the Help of Cluster Analysis Methods

For the analysis, the technical specifications of 25 CWV models [7] given in Tab. 1 were used.

Tab. 1 Technical specifications of CWV models

CWV model (producer, year of introduction)	Combat weight [kg]	Wheel arrangement	Payload [kg]	Engine power [kW]	Length [m]	Width [m]	Height [m]	Chassis clearance [m]
Akrep (Otokar, from 1994)	3 600	4 × 4	800	100	4.190	1.91	2.56	0.229
Land Rover D130 (Land Rover, from 1983)	2 400	4 × 4	705	91	3.722	1.79	1.96	0.229
Auverland A4 AVL (Panhard, from 2008)	5 100	4 × 4	1 130	112	4.233	1.96	2.03	0.230
Cobra (Otokar, from 1997)	6 500	4 × 4	1 250	142	5.500	2.22	2.10	0.400
Eagle I (MOWAG, from 1999)	4 500	4 × 4	2 200	119	4.900	2.28	1.75	0.400
Eagle IV (MOWAG, from 2003)	8 800	4 × 4	2 100	186	5.400	2.30	2.30	0.400
AGF (Rheinmetall, from 2002)	3 300	4 × 4	1 000	116	4.880	1.82	1.87	0.400
Dingo 2 (Krauss-Maffei Wegmann, from 2000)	12 500	4 × 4	2 600	163	6.100	2.30	2.50	0.480

CWV model (producer, year of introduction)	Combat weight [kg]	Wheel arrangement	Payload [kg]	Engine power [kW]	Length [m]	Width [m]	Height [m]	Chassis clearance [m]
Cougar (Force Protection, from 2002)	17 200	4×4	2 720	246	5.910	2.74	2.64	0.410
Cougar HE (Force Protection, from 2002)	23 590	6 × 6	5 900	246	7.080	2.74	2.64	0.410
LMV (Iveco, from 2001)	7 100	4×4	2 900	142	4.800	2.20	2.05	0.473
Tiger (GAZ, from 2004)	7 200	4×4	3 100	153	5.700	2.30	2.40	0.400
Stryker (General Dynamics Land Systems, from 2002)	17 200	8×8	4 700	261	6.950	2.72	2.64	0.500
M-ATV (Oshkosh Corporation, from 2009)	14 700	4×4	1 800	276	6.270	2.49	2.70	0.400
HMMWV M1097A2 (AM General, from 1993)	4 672	4×4	1 996	119	4.840	2.18	1.88	0.400
HMMWV M1114 (AM General, from 1993)	5 489	4×4	1 043	142	5.000	2.30	1.90	0.400
HMMWV M1151A1(AM General, from 2006)	6 101	4×4	1 370	142	4.900	2.18	1.82	0.430
RG-32M (BAE Land Systems South Africa, from 2002)	6 700	4 × 4	1 600	137	5.050	2.20	2.31	0.410
RG-31 (BAE Land Systems South Africa, from 2000)	7 280	4×4	2 000	205	6.4	2.47	2.63	0.400
RG-33L(BAE Land Systems South Africa, from 2006)	26 332	6×6	8 762	298	8.5	2.40	2.90	0.360
RG-33(BAE Land Systems South Africa, from 2007)	17 252	4×4	3 768	298	6.7	2.40	2.90	0.360
SPV-3 (GAZ, from 2008)	12 000	4×4	2 000	246	5.900	2.50	2.60	0.500
AMV (Patria, from 2004)	16 000	8 × 8	8 000	405	7.700	2.80	2.30	0.400
ALSV (Chenowth Racing Products, from 1996)	1 600	4 × 4	640	119	4.100	2.11	2.01	0.400
DPV (Chenowth Racing Products, from 1991)	1 600	4×4	681	149	4.090	2.11	2.01	0.400

At the first stage, data analysis was performed using sequential clustering. According to Tab. 1, locus of CWV models is n, each of which is characterized by its corresponding m characteristics, and it can be considered as a point in m-dimensional space. In this regard, the input data of CWV models can be represented by the matrix:

$$X = \begin{pmatrix} x_1^1 & x_1^2 & \cdots & x_1^m \\ x_2^1 & x_2^2 & \cdots & x_2^m \\ \vdots & \vdots & \ddots & \vdots \\ x_n^1 & x_n^2 & \cdots & x_n^m \end{pmatrix} \tag{1}$$

where x_j^i is the value of the i-th characteristics (i equal from 1 to m) of the j-th CWV model (j equal from 1 to n).

The proximity between CWV models of the X locus can be represented as the matrix:

$$D = \begin{pmatrix} 0 & d_{12} & \cdots & d_{1n} \\ d_{21} & 0 & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \cdots & 0 \end{pmatrix} \tag{2}$$

where $d_{j(1\ldots n)}$ is the conditional distance between CWV models in the coordinates of their characteristics.

The Euclidean metric, which determines the conditional distance between CWV models in the coordinates of their characteristics, is used as proximity:

$$d_{j(1\ldots n)} = \sqrt{\sum_{i=1}^{m} \left(x_j^{i\,\mathrm{st}} - x_{j=1\ldots n}^{i\,\mathrm{st}} \right)^2} \tag{3}$$

where $x_{j=1\ldots n}^{i\,\mathrm{st}}$ is the standardized value of the i-th characteristics of the CWV models from j = 1 to n.

Before starting the analysis, the characteristics of CWV models were standardized, which made it possible to eliminate the bias caused by the influence of those features that have a larger range of values [8] in the expression:

$$x_j^{i\,\mathrm{st}} = \frac{x_j^i - \bar{x}}{\sqrt{\frac{1}{n-1} \sum_{j=1}^{n} \left(\bar{x} - x_j^i \right)^2}} \tag{4}$$

where $x_j^{i\,\mathrm{st}}$ is the standardized value of the i-th characteristics of the j-th CWV model; $\bar{x} = \frac{1}{n} \sum_{j=1}^{n} x_j^i$ is the average value of the attribute.

To combine CWV models into a cluster, the complete link method was used, according to which the similarity between CWV models as candidates for inclusion in the cluster and any of its elements (CWV models) must be less than a certain threshold level.

As a result of the analysis, a dendrogram was obtained (the graph is constructed on the basis of the CWV models feature proximity matrix). The Statistica software product was used to build dendrograms [9].

Further clustering was carried out using hierarchical agglomerative methods, the essence of which is that initially each CWV model is a separate cluster, and then the clusters are combined when climbing through the hierarchy. When using the single link method, the distance between two clusters is determined by the distance between the two closest CWV models (closest neighbors) in different clusters. The application of the weighted centroid localization method is to define the distance between two different clusters as the average distance between all pairs of objects in them, and the number of objects contained in the cluster is used as the weighting factor. Ward's method consists in combining the two nearest clusters based on the average values of each characteristic in the cluster and the sum of squared deviations for all samples and for each characteristic of the CWV model.

The rational number of clusters was determined using the iterative k-means clustering method, which distributes CWV models among initially defined clusters, and then moves them between clusters until differences within clusters are minimized and differences between clusters are maximized. Iterative methods provide an optimal solution for any initial separation, if the characteristics of the CWV models have a good structure.

3 Results of CWV Models Classification with the Help of Cluster Analysis Methods

Analysis of a dendrogram based on Tab. 1 data showed that the resulting distribution of CWV models into groups is incorrect, since the groups do not correspond to the combat purpose of CWV models (Fig. 1).

Thus, for example, the group of samples "ALSV, DPV" with high engine power and minimal mass is not distinguished and is a very specific, virtually independent group; the group "Cougar HE, Stryker" combines CWV models with significant differences in characteristics and combat purpose: for patrolling roads and for conducting combat operations.

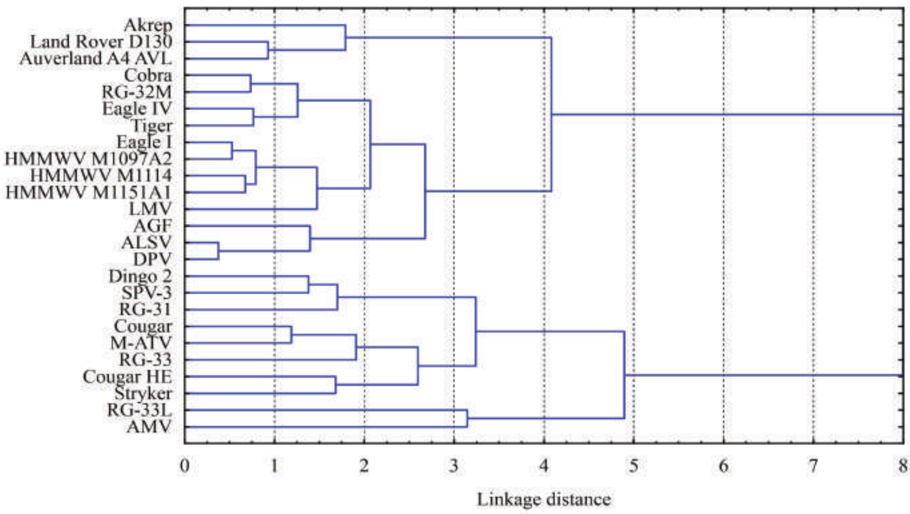

Fig. 1 Dendrogram of the proximity of CWV models features constructed on the CWV models characteristics shown in Tab. 1 with the help of the complete link method

To carry out the most accurate cluster analysis, it is necessary to apply more detailed characteristics of CWV models, namely: mass distribution along the axles, geometric dimensions of the wheels, air pressure in the wheels, specific pressure on the ground and traction force for the characteristics of cross-country ability; stability and handling, smoothness of movement, speed, acceleration and braking characteristics for the characteristics of mobility; protection mass per cubic meter of internal volume for the assessment of protection. However, these characteristics are not fully specified in the technical descriptions for almost all CWV models and can only be determined by examining a specific CWV model. To clarify the classification of CWV models, an approach is proposed that consists in using generalized indicators that characterize the combat properties of CWV models for analysis. Such indicators are: the load on the axle, which together with the properties of the tire characterizes the traction properties, which are the most important components of the Cross-Country ability of the sample; specific power, which determines the traction-dynamic and speed properties and most fully characterizes the mobility of the sample and the mass of the sample divided by a cubic meter of its volume, which characterizes the security of personnel. Generalized characteristics of CWV models are given in Tab. 2. Dendrogram based on Tab. 2 data is shown in Fig. 2.

Tab. 2 Generalized characteristics of CWV models

CWV model	Axle load [t] (A)	Specific power [kW/t] (B)	Sample weight per cubic meter of volume [kg/m^3] (C)
Akrep	1.80	27.76	192.98
Land Rover D130	1.20	37.91	208.11
Auverland A4 AVL	2.55	21.93	341.50
Cobra	3.25	21.80	313.15
Eagle I	2.25	26.51	298.36
Eagle IV	4.40	21.18	372.91
AGF	1.65	35.25	252.76
Dingo 2	6.25	13.01	441.06
Cougar	8.60	14.31	476.31
Cougar HE	7.86	10.43	545.30
LMV	3.55	19.96	426.35
Tiger	3.60	21.23	274.60
Stryker	4.30	15.17	425.17
M-ATV	7.35	18.77	409.38
HMMWV M1097A2	2.34	25.54	299.18
HMMWV M1114	2.74	25.81	318.20
HMMWV M1151A1	3.05	23.22	410.90
RG-32M	3.35	20.48	317.40
RG-31	3.64	28.17	206.51
RG-33L	8.78	11.33	508.18
RG-33	8.63	17.29	422.40
SPV-3	6.00	20.51	387.41
AMV	4.00	25.31	390.59
ALSV	0.80	74.57	114.88
DPV	0.80	93.21	115.16

Fig. 2 analysis shows that at a union distance of 1.5, 6 clusters are defined, the composition of which is given in Tab. 3.

Fig. 3 analysis shows that the sample group also contains 6 clusters, the composition of which is shown in Tab. 3. However, this division is different: 3 groups completely match, one matches, but without one sample (RG-31), two groups are combined into one, and one more group contains one sample (RG-31).

Fig. 4 analysis shows that the sample group also contains 6 clusters, the composition of which is shown in Tab. 3. This division practically coincides with the division by the complete link method, except that one sample (RG-31) is assigned to another group.

Fig. 5 analysis shows that the sample group also contains 6 clusters, the composition of which is shown in Tab. 3. This division coincides with the division by the weighted centroid localization method.

Performing clustering using hierarchical agglomerative methods using the complete link method (Fig. 2), the single link method (Fig. 3), the weighted centroid localization method (Fig. 4) and the Ward's method (Fig. 5) makes it possible to state that there is a clear structure in this data set. At the level of six clusters, there is a clear distribution, with differences in the classification of a single model (RG-31) and in the order of subsequent cluster pairing.

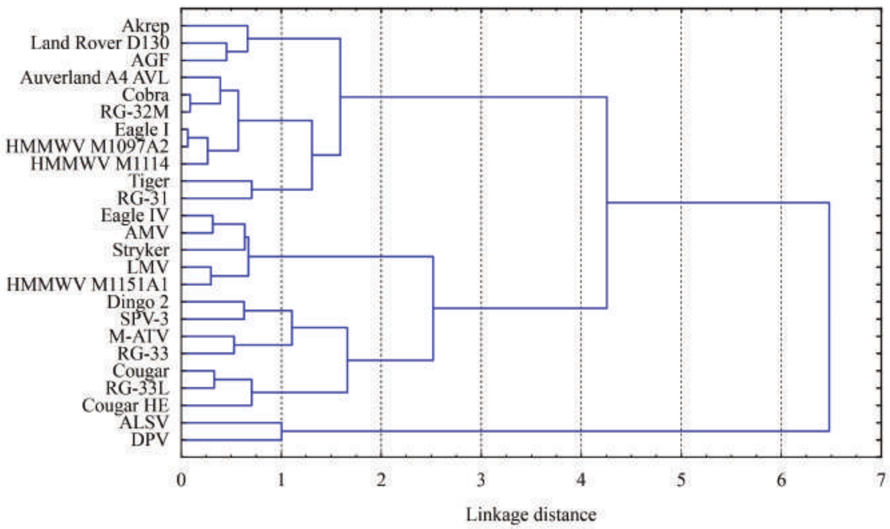

Fig. 2 Dendrogram of the proximity of CWV models features constructed on the generalized CWV models characteristics given in Tab. 2 with the help of the complete link method

When performing clustering using the iterative k-means clustering, the total square deviation of cluster points from their centers is minimized. However, the number of clusters in the CWV models group must be specified. In our case, there are six of them. This number of iterations occurs until the cluster centers become stable (i.e. at each iteration, the same objects will appear in each cluster), the variance within the cluster will be minimized, and between clusters -maximized. The results of dividing samples into six clusters are shown in Tab. 4 and Fig. 6.

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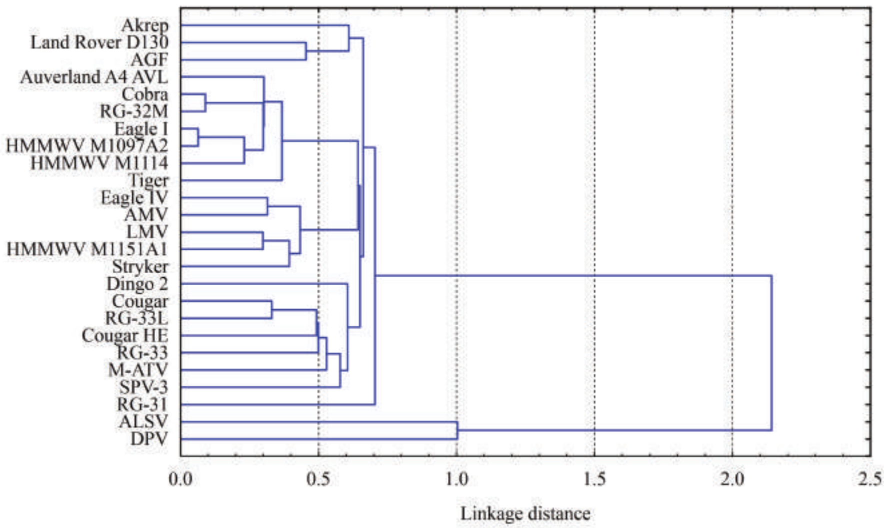

Fig. 3 Dendrogram of the proximity of CWV models features constructed on the generalized CWV models characteristics given in Tab. 2 with the help of the single link method

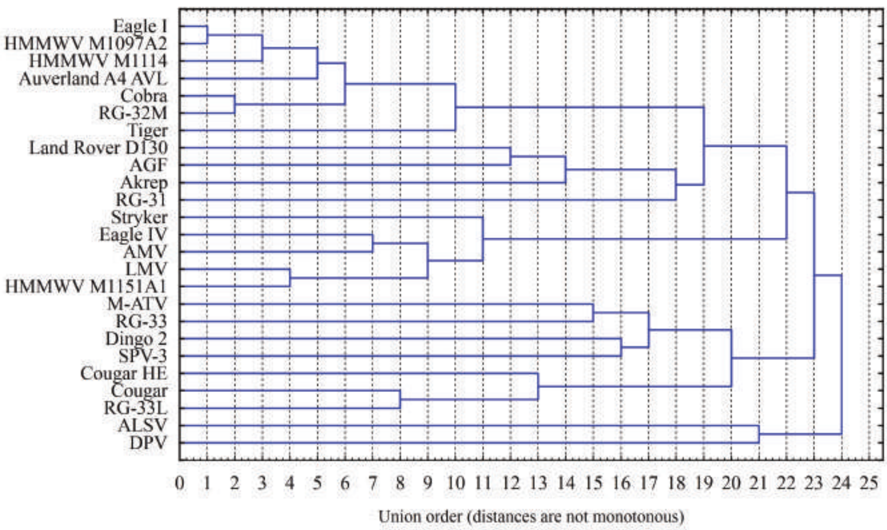

Fig. 4 Dendrogram of the proximity of CWV models features constructed on the generalized CWV models characteristics given in Tab. 2 with the help of the weighted centroid localization method

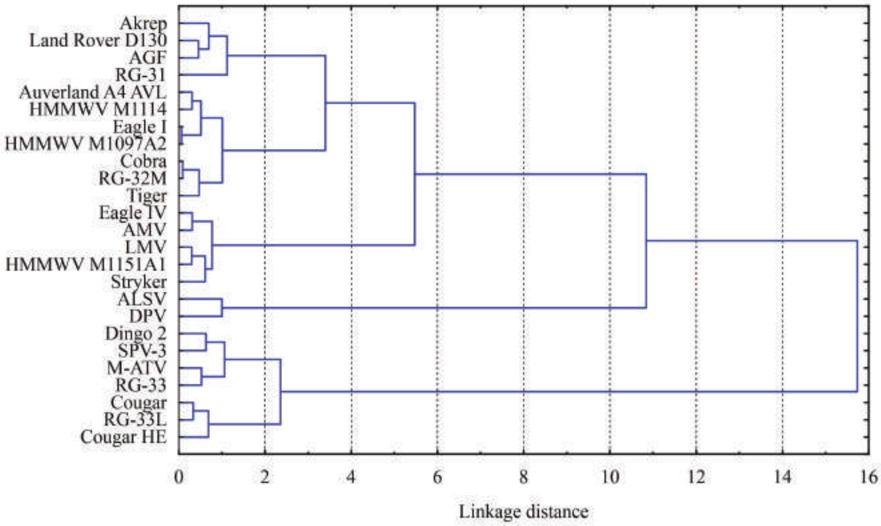

Fig. 5 Dendrogram of the proximity of CWV models features constructed on the generalized CWV models characteristics given in Tab. 2 with the help of the Ward's method

Tab. 3 Composition of CWV models groups

Cluster	Complete link method	Single link method	Weighted centroid localization method	Ward's method
Akrep, Land Rover D130, AGF	+	+	+ with RG-31	+ with RG-31
Auverland A4 AVL, Cobra, RG-32M, Eagle I, HMMWV M1097A2, HMMWV M1114, Tiger, RG-31	+	+ without RG-31	+ without RG-31	+ without RG-31
Eagle IV, AMV, Stryker, LMV, HMMWV M1151A1	+	+	+	+
Dingo 2, SPV-3, M-ATV, RG-33	+	+	+	+
Cougar, RG-33L, Cougar HE	+		+	+
ALSV, DPV	+	+	+	+
RG-31	−	+	−	−

Analysis of cluster center data in Fig. 6 shows that clusters 4 and 5 have very similar values in terms of specific power (B) and sample mass per cubic meter of volume (C) and differ in axis load (A)

Analysis of the CWV models classification results shows that there is a stable structure within the initial data sample, which is manifested by both hierarchical agglomerative methods and iterative ones. The presence of the structure indicates that samples are created to perform a sustainable range of tasks assigned to the Armed Forces. Therefore, increasing the level of partial technical characteristics when creating and improving samples should be carried out within certain groups.

Tab. 4 CWV distribution in the case of six clusters

Cluster name	CWV models	Value intervals in clusters A/B/C	Average values in clusters A/B/C
Light strike CWV	ALSV, DPV	0.8 100-125 114.9-115.2	0.8 112.5 115
Light tactical CWV	Akrep, Land Rover D130, AGF, RG-31	1.2-3.6 37.2-50.8 192.9-252.8	2.1 43.3 215.1
Medium tactical CWV	AVL, Cobra, Eagle I, Tiger, M1097A2, M1114, RG-32M	2.3-3.6 27.5-35.6 274.6-341.5	2.9 31.3 308.9
Heavy tactical CWV	Eagle IV, Stryker, M1151A1, AMV, LMV	3.1-4.4 20.4-33.9 372.9-426.4	3.9 28.1 405.2
High mobility MRAP	Dingo 2, SPV-3, M-ATV	6.0-7.4 17.4-27.5 387.4-441.1	6.5 23.4 412.6
Patrol MRAP	Cougar, Cougar HE, RG-33L, RG-33	7.9-8.8 13.9-23.2 422.4-545.3	8.5 17.9 488.0

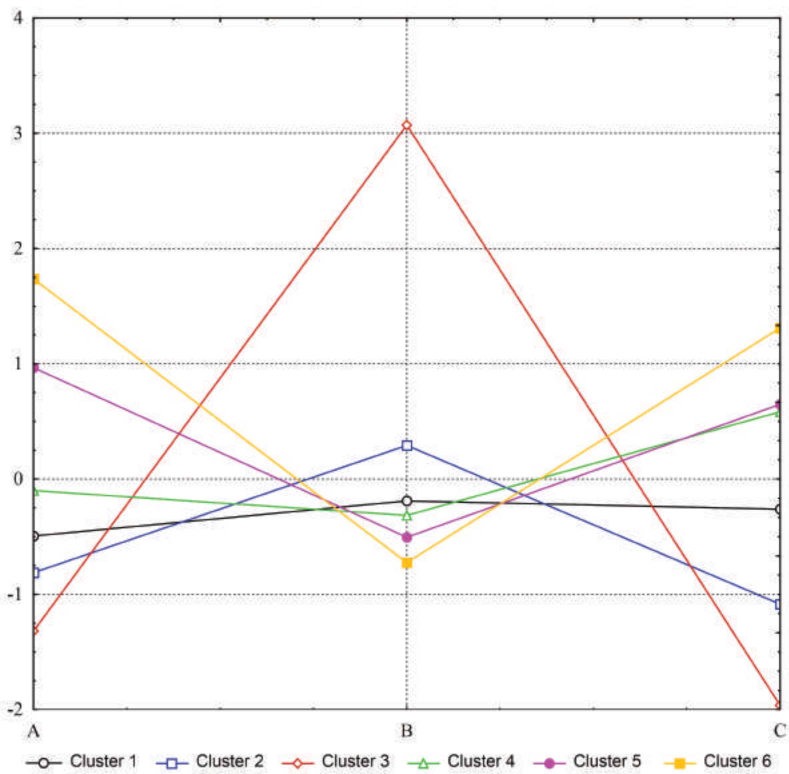

Fig. 6 Average values of cluster metrics

4 Conclusion

The existing classification of CWV models by combat weight neither allows establishing a relationship between the technical characteristics of CWV models and their functional purpose, nor it contributes to the possibility of creating vehicles for various purposes on the chassis of the basic model.

The experience of recent military conflicts, including those in eastern Ukraine, shows a shift in the concept when designing CWV models in the direction of abandoning the design of specialized base chassis to widespread the use of chassis of commercial vehicles (they are time-tested, reliable, and have serviceable components). As a result, new CWV models are being developed rapidly. Since the beginning of the military conflict in eastern Ukraine, the Armed Forces of Ukraine have received more than 15 new CWV models based on the chassis of civilian vehicles. In addition, a significant number of civilian models of vehicles were urgently converted in the field conditions. The proposed method of CWV models classification provides the ability to predict the results of the development of new models of CWV, substantiation of options for building its protection, and specific technical solutions to increase the survivability of CWV models.

The analysis of the technical characteristics of existing and prospective CWV models by sequential clustering showed that the resulting groups do not correspond to the purpose of the models. This is due to significant differences in the technical characteristics of CWV models of the same purpose.

For CWV models classification, an approach is proposed that consists in using generalized indicators that characterize the combat properties of CWV models. Clustering using hierarchical agglomerative methods, the single link method, the weighted centroid localization method, and the Ward's method indicates that there is a clear distribution of samples into 6 groups.

Thus, the developed method of classification of CWV models with the help of specific indicators allows establishing a correspondence between the technical characteristics of CWV models and their functional purpose, provides an opportunity to develop rational protection options and justify specific technical solutions to increase the level of survivability of CWV models within groups, which in general is a way to minimize the cost of providing protection for crews and paratroopers.

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