Assessing the quality level of the technical fabrics intended for protective equipment for firefighters by determining synthetic indicators

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ABSTRACT – REZUMAT

Assessing the quality level of the technical fabrics intended for protective equipment for firefighters by determining synthetic indicators

The paper aims to highlight the quality level of technical fabrics by determining synthetic indicators based on durability and comfort functions, which can subsequently be used for modelling the physico-mechanical properties and selecting the most suitable fabrics to meet the requirements of a specific field of use. The study was conducted on two groups of technical fabrics with different compositions (Kevlar and Nomex), intended to manufacture firefighter protective equipment (jackets). Quality indicators represent numerical expressions of the quality level of a product or the relative expression of a certain characteristic, obtained by comparing it to a reference value (norm, standard, model). Quality indicators are converted into grades $I \in [0,1]$, where conventionally, a grade of 0 represents an inadequate product/non-quality, and a grade of 1 represents a superior quality level. The synthetic indicators determined in this study express the quality level of a product through the prism of categories/subcategories of quality characteristics representative of evaluating the comfort and durability functions specific to the groups of fabrics intended for the manufacture of protective equipment. Based on the values obtained for the synthetic indicators, a ranking of fabric variants is made according to the importance of durability and comfort characteristics. Thus, optimal fabric variants from each group can be highlighted, and solutions for improving the quality level for other variants can be proposed.

Keywords: *synthetic indicators, durability characteristics, comfort characteristics, Nomex fabrics, Kevlar fabrics*

Aprecierea nivelului calitativ al țesăturilor tehnice destinate echipamentelor de protecție pentru pompieri prin determinarea indicatorilor sintetici

Lucrarea și-a propus să evidențieze nivelul calitativ al țesăturilor tehnice, prin determinarea indicatorilor sintetici, pe baza funcțiilor de durabilitate și confort, care pot fi folosiți ulterior pentru modelarea proprietăților fizico-mecanice și pentru selectarea celor mai adecvate țesături privind satisfacerea cerințelor unui anumit domeniu de întrebuințare. Studiul a fost efectuat pe două grupe de țesături tehnice din compoziții diferite (Kevlar și Nomex), destinate confecționării echipamentelor de protecție pentru pompieri (jachete). Indicatorii calității reprezintă expresiile numerice ale nivelului calității unui produs sau expresia relativă a unei anumite caracteristici, obținută prin raportarea la valoarea de referință (normă, standard, model). Indicatorii calității sunt convertiți în calificative, $I \in [0,1]$, unde convențional, prin calificativul 0 se reprezintă un produs necorespunzător/noncalitate, iar prin calificativul 1 se reprezintă nivelul calitativ superior. Indicatorii sintetici determinați în cadrul acestui studiu exprimă nivelul calității unui produs prin prisma unor categorii/subcategorii de caracteristici de calitate reprezentative pentru evaluarea funcțiilor de confort și durabilitate specifice grupelor de țesături destinate confecționării echipamentelor de protecție. Pe baza valorilor obținute pentru indicatorii sintetici se realizează o ierarhizare a variantelor de țesături în funcție de gradul de importanță al caracteristicilor de durabilitate și confort. Astfel, pot fi evidențiate variantele optime de țesături din fiecare grupă și pot fi propuse soluții de îmbunătățire a nivelului calității pentru celelalte variante.

Cuvinte-cheie: *indicatori sintetici, caracteristici de durabilitate și confort, Nomex, Kevlar*

INTRODUCTION

In general, when creating firefighter protective equipment (jackets), fabrics that meet the highest levels of protection and comfort are sought, despite their high costs. Most companies use fabrics made from aramid fibres, which dominate the sector, as they offer high levels of mechanical tensile strength and durability while being completely flame-resistant. For these reasons, a range of technical fabrics necessary for the manufacture of firefighter protective equipment has been developed using blends of the latest meta-aramids and para-aramids with comparable effectiveness and protection at reasonable prices [1–3]. Depending on the application, the choice between Kevlar and Nomex is one of the requirements for comfort and protection, which can be used in the seven layers that make up firefighter protective equipment. Kevlar is much more resistant to abrasion than Nomex and is therefore used in a higher concentration percentage in firefighter protective equipment [4–6]. Nomex is a softer-feeling fibre and is used to a greater extent in everyday clothing articles due to the greater comfort it offers the wearer [7–9]. Simple weave structures such as plain or twill, as well as some of their derivatives like rip-stop and twill, are most commonly used for the outer fabric of firefighter protective equipment due to their exceptional tear resistance and increased tensile strength [10–12]. Nomex provides heat and flame resistance to the protective equipment, while Kevlar offers flexibility, comfort, and breathability [13–15]. Kevlar has been extensively utilized in the production of advanced composites in aerospace, military, marine, and sports sectors due to its mechanical properties, thermal stability, and high energy absorption properties [16–18]. Nomex®, manufactured by DuPont, is made of aramid fibres and is lightweight with high tensile strength and heat resistance (degrading at 480°C) [19–20]. Its high breathability and low water vapour resistance make it suitable for use as an outer layer. Fabrics face complex demands in fire situations [21–26]. The fabric's performance in these situations is related to comfort, time, warmth, durability, and other specific appearance features [27–30]. The performance of firefighter protective clothing is primarily based on the thermophysical properties of the materials used in their construction [31–36].

EXPERIMENTAL PART

Materials and methods

The experimental matrix included twelve samples from two groups of technical fabrics with different compositions, intended for the manufacture of firefighter protective equipment, whose characteristics are presented in table 1.

Group A of fabrics contains six articles, coded K1, K2, K3, K4, K5, and K6, made from yarns composed of Kevlar fibres, balanced in fineness with $Nm_{warp} = Nm_{weft}$ and density $P_{warp} = P_{weft}$, with plain and twill weave structures.

Group B of fabrics contains six articles, coded N1, N2, N3, N4, N5, and N6, made from yarns composed of Nomex fibres, balanced in fineness with $Nm_{warp} = Nm_{weft}$ and density $P_{warp} = P_{weft}$, with plain and twill weave structures.

The fibrous composition, properties of the component fibres, structural parameters of the fabrics, mechanical and physical properties of the yarns, as well as finishing treatments, influence the quality characteristics regarding the durability and physiological comfort of firefighter protective equipment. To highlight the influence of the weave structure on certain surface characteristics of the fabrics in the studies conducted within this work, the weave structure was expressed by the warp floating for the warp yarns F_{warp} and the weft floating for the weft yarns F_{weft}. The intersection between a warp yarn and a weft yarn is called a binding point, so the weave structure contains the set of all binding points with a warp or weft effect in the longitudinal or transverse direction. The floating size, like the binding segment, has a minimum value of $F = 1$, which is specific to the plain weave structure.

Due to its unique properties such as high strength-to-weight ratio and greater modulus, Kevlar fibre has become very popular as reinforcement in composite materials, and its application has increased considerably. Kevlar® is an example of a para-aramid fibre, while Nomex® is considered a meta-aramid. The key difference between meta and para-aramid is that

Table 1

CHARACTERISTICS OF TWELVE SAMPLES OF TECHNICAL FABRICS WITH DIFFERENT COMPOSITIONS

Group/ Composition	Article code	Yarn count $Nm_{warp} = Nm_{weft}$	Technological density, (yarns/10 cm) $P_{warp} = P_{weft}$	Mean flotation F	Type of bonding
Group A/Kevlar	K1	68/2	265	2	Twill $D\frac{2}{2}/$
	K2	54/2	260	2	Twill $D\frac{2}{2}/$
	K3	48/2	290	1.5	Twill $D\frac{2}{1}/$
	K4	60/2	280	1.5	Twill $D\frac{2}{1}/$
	K5	68/2	285	1	Plain
	K6	60/2	275	1	Plain
Group B/Nomex	N1	64/2	270	2	Twill $D\frac{2}{2}/$
	N2	60/2	260	2	Twill $D\frac{2}{2}/$
	N3	48/2	370	1.5	Twill $D\frac{2}{1}/$
	N4	56/2	360	1.5	Twill $D\frac{2}{1}/$
	N5	56/2	355	1	Plain
	N6	68/2	350	1	Plain

meta-aramid has a semi-crystalline molecular structure, while para-aramid is crystalline. Fabrics woven from Nomex® fibres are used in applications requiring good textile properties, good dimensional stability, and excellent heat resistance. Fabrics woven of Nomex® fibre have good resistance to many chemicals and are highly resistant to most hydrocarbons and many other organic solvents.

The database used in this study was obtained by quantifying the physical-mechanical properties of the two groups of fabrics using standardized methods and evaluated through a series of indices determined directly on the measuring apparatus or by calculation.

In determining the synthetic indicators of the two groups of technical fabrics intended for the manufacture of firefighter protective equipment, a series of representative characteristics reflecting durability were selected: tensile strength, *Pr* (daN); fabric tenacity, τ (cN/tex); puncture resistance, *T* (N); work of mechanical deformation at rupture, W_s (N·m); and flexural stiffness, *R* (mg·cm). In determining the synthetic indicators reflecting physiological comfort, the following representative characteristics were selected: air permeability index, *I* (kg/m^2·h); relative elongation at break, ε (%); thermal conductivity coefficient, λ (kcal/m·h·°C); vapour permeability coefficient, μ (g/m^2·h) and fabric mass, *M* (g/m^2).

The representative characteristics used in calculating the synthetic indicators of durability and comfort were selected using the correlation method. Tensile properties tests of the fabrics were conducted on the Honsfield electronic dynamometer, according to SR EN ISO 2062. Analysis of fabric behaviour during wearing indicates that they are subjected to simple or repeated uniaxial or biaxial stretching stresses. The level of these stresses can be close to the breaking limit or may have low, insignificant values, so the designer must anticipate the behaviour under such stresses. This can be appreciated by determining indices derived from the stress-strain diagram. The behaviour under the bending stress of fabrics is structurally determined by the transfer of fibre-yarn-fabric properties, influenced by mechanical and chemical processing processes, and is expressed by the bending length and flexural stiffness. In this study, we used the values obtained for the flexural stiffness of the two groups of fabrics, determined according to the ASTM D1388-18 standard.

Protective equipment for firefighters must be designed to ensure conditions of comfort (being permeable to air and vapours, impermeable to water and toxic substances), of operation (comfortable, resistant, easy to wear), but also to contribute to the prevention of accidents and occupational illnesses.

The mass of the fabrics was determined according to the SR EN 12127:2013 standard, which allows for comparative evaluation, essential for the intended use of the fabric.

Air permeability was determined in accordance with the EN ISO 9237:1995 standard, which for fabrics intended for clothing must ensure comfort conditions during wearer activity.

Experimental values for determining the thermal conductivity coefficient, vapour permeability coefficient, and air permeability index for the two groups of fabrics were obtained through standardized methods, depending on treatment parameters (temperature, pressure, and speed) and material characteristics.

The quality level of the two groups of technical fabrics intended for the manufacture of protective equipment is assessed by determining synthetic quality indicators based on comfort and durability functions.

Quality indicators are numerical expressions of the quality level of a product. A quality indicator must meet a series of conditions:

- it should be simple, so that the calculation method, expression, and meaning are easy to understand;
- it should be relevant to ensure the most accurate description of the actual quality level;
- it should be verifiable so that it can be recalculated anytime based on the method used.

The quality index is a relative expression of a specific characteristic, obtained by comparing it to a reference value (norm, standard, model).

The index can be converted into a rating $I \in [0,1]$, where conventionally, a rating of 0 represents an inadequate product/non-quality, and a rating of 1 represents a superior quality level.

To determine the indices, it is necessary to apply methods for evaluating quality characteristics. Specific methods for the textile industry include:

- measurement with known precision using standardized means;
- expertise conducted through sensory analysis by specialists in the field;
- sociological evaluation based on survey questionnaires addressed to potential users.

In the study, quality characteristics representative of evaluating the comfort and durability functions specific to the groups of fabrics intended for the manufacture of protective equipment were measured. The expertise method was applied to assess the importance of the characteristics expressing the functions of the analysed products. Quality indicators can be simple, synthetic, or global based on the level of complexity. The emphasis of the study was on evaluating the quality level of the analyzed textile surfaces through synthetic and global indicators. The synthetic indicator expresses the quality level of a product through the prism of categories/subcategories of quality characteristics.

The algorithm for calculating the synthetic indicator is as follows:

1. Select representative characteristics.
2. Obtain the sample consisting of representative samples (n).
3. Measure the characteristics using standardized methods.
4. Determine the preferred direction of increase/decrease for each characteristic, depending on the product's purpose.

5. Report the obtained values for each characteristic on a unique scale within the interval [0;1].
6. By reporting, the degree of utility U_i is obtained depending on the preferred direction of increase/decrease of the quality characteristic values, as follows:
   - for the preferred direction of increase in characteristic values (positive characteristic), U_i is calculated using the following relationship:

$$U_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (1)$$

   - for the preferred direction of decrease in characteristic values (negative characteristic), U_i is calculated using the following relationship:

$$U_i = \frac{x_{max} - x_i}{x_{max} - x_{min}} \quad (2)$$

   - the hierarchy of quality characteristics based on the coefficient of significance (degree of importance) is calculated using the following relationship:

$$\gamma_i = \left(100/\sum_{j=1}^{m} R_{ij}\right) / \left(\sum_{i=1}^{n}\left(100/\sum_{j=1}^{m} R_{ij}\right)\right) \quad (3)$$

where R_{ij} = 1 represents the rank assigned to the characteristic considered the most important (with maximum score); R_{ij} = n represents the rank assigned to the characteristic considered the least important (with minimum score); n is the number of characteristics i = 1, ..., n; m is the number of experts j = 1, ..., m.

To establish the significance coefficient, the expertise method was applied. The ranks corresponding to the quality characteristics were evaluated by a team of six specialists in the textile field. Based on the evaluations, the experts fill out survey sheets assigning different ranks to the quality characteristics. The consistency of opinions among experts is verified using the following relationship:

$$W = \sum_{i=1}^{n}\left(\sum_{j=1}^{m} R_{ij} - R_{ij}\right)^2 / \left[m^2 \cdot (n^3 - n)/6\right] \quad (4)$$

where:

$$R_{ij} = \left(\sum_{i=1}^{n}\sum_{j=1}^{m} R_{ij}\right) / 6 \quad (5)$$

The verification of agreement among experts is conducted based on the χ^2 test, where the test statistic is calculated using the following relationship:

$$\chi^2 = W \cdot m(n-1) \quad (6)$$

If $\chi^2_{calc} > \chi^2_{\nu-1,\alpha=0.05}$, it follows that the opinions of the experts are in agreement (W is significant).

For $W \geq 0.8$, the significance coefficient γ_i is determined using the following relationship:

$$\gamma_i = \left(100/\sum_{j=1}^{m} R_{ij}\right) / \left(\sum_{i=1}^{n} 100/\sum_{j=1}^{m} R_{ij}\right) \quad (7)$$

The hierarchy of characteristics is determined based on the criterion of decreasing values of γ_i.The representative values must satisfy the condition $\gamma_i > 1/n$ [37–40]. Calculation of the synthetic indicator using the relationship:

$$Is = \sum_{i=1}^{n} U_i \cdot \gamma_i \quad (8)$$

Synthetic indicators express the quality level of a product through the prism of categories/subcategories of quality characteristics considered to be representative of a product.

RESULTS AND DISCUSSIONS

According to the steps in the workflow algorithm, the following are calculated:

- Synthetic durability indicators $Is_{1-gr.A}$ and $Is_{1-gr.B}$ for Group A and Group B of fabrics, respectively.
- Comfort indicators $Is_{2-gr.A}$ and $Is_{2-gr.B}$ for Group A and Group B of fabrics intended for the manufacture of firefighter protective equipment.

The calculation of the synthetic durability indicator for the fabrics in Group A (Kevlar)

Selection of representative characteristics:

- tensile strength, Pr (daN);
- fabric tenacity, τ (cN/tex);
- puncture resistance, T (N);
- work of deformation at rupture, W_s (N·m);
- flexural rigidity, R (mg·cm).

The average values of durability characteristics for the fabrics in Group A (Kevlar) are presented in table 2.

Table 2

AVERAGE VALUES OF DURABILITY CHARACTERISTICS FOR THE FABRICS IN GROUP A (KEVLAR)

Group/ Composition	Article code	Tensile strength Pr (daN)	Fabric tenacity τ (cN/tex)	Puncture resistance T (N)	Mechanical work W_s (N·m)	Flexural rigidity R (mg·cm)
Group A/ Kevlar	K1	79.03	16.70	1539.72	6.247	52.92
	K2	77.76	16.15	1487.52	6.065	50.86
	K3	72.47	12.00	1224.64	3.287	58.85
	K4	71.59	15.34	1342.78	3.849	54.66
	K5	87.05	20.77	1380.58	6.393	62.44
	K6	85.24	18.60	1420.51	5.919	58.85
Min		**71.59**	**12.00**	**1224.64**	**3.287**	**50.86**
Max		**87.05**	**20.77**	**1539.72**	**6.393**	**62.44**

The preferred direction of variation for durability characteristics has been adopted as follows:

- positive characteristics: *Pr* (daN), τ (cN/tex), *T* (N) and W_s (N·m);
- negative characteristics: *R* (mg·cm).

The values obtained for each characteristic are reported on a single scale in the interval [0;1] as shown in table 3; the degree of utility U_i based on the preferred direction of increase/decrease of the quality characteristic values was determined as follows:

- For the preferred direction of increasing the values of the characteristic (positive characteristic), U_i is calculated using the relationship:

$$U_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (9)$$

- For the preferred direction of decreasing the values of the characteristic (negative characteristic), U_i is calculated using the relationship:

$$U_i = \frac{x_{max} - x_i}{x_{max} - x_{min}} \quad (10)$$

The values of the synthetic durability indicator for the fabrics in Group A (Kevlar) are presented in table 3. To calculate the indicator $Is_{1-gr.A}$, the values of the importance degree of durability characteristics presented in table 4 were required. The importance degree of durability characteristics was evaluated using the expert method (table 5).

The consistency of expert opinions was checked using the relationship:

$$W = \sum_{i=1}^{n}\left(\sum_{j=1}^{m} R_{ij} - \bar{R}_{ij}\right)^2 / \left[m^2 \cdot (n^3 - n)/6\right] = \quad (11)$$

$$= \frac{25960}{36 \cdot \frac{(125-5)}{6}} = 36$$

From a statistical point of view, the agreement of expert opinions is verified using the test, where the χ^2 test statistic is calculated using the relationship:

$$\chi^2 = W \cdot m(n-1) \quad (12)$$

If $\chi^2_{calc} > \chi^2_{\nu-1,\alpha=0.05}$, it follows that the expert opinions are in agreement (*W* is significant). So, from a statistical perspective, $\chi^2_{calc} = 720 > \chi^2_{tab}$, the expert opinions are in agreement (*W* is significant). The ranking of characteristics is based on the criterion of decreasing values of γ_{ij}, as presented in table 5.

The calculation of the synthetic durability indicator for the fabrics in Group B (Nomex)

The average values of durability characteristics for fabrics in Group B (Nomex) are presented in table 6. To calculate the indicator $Is_{1-gr.B}$, the values of the importance degree of durability characteristics presented in table 7 were required. The importance degree of durability characteristics was evaluated using the expert method (table 5).

The ranking of durability characteristics for fabrics in Group B was conducted similarly to fabrics in Group A, according to table 5. This method of calculation allows for drawing direct conclusions based on the quality indicators: the closer the indicator value is to 1, the higher the quality it represents. The synthetic indicator $Is_{1-gr.A}$ includes all the characteristics that are reflected in the durability of the analysed fabrics, as observed from the experimental data for fabrics in Group A (Kevlar). Article K5, characterized by $Nm_{warp} = Nm_{weft}$ = 68/2, $P_{warp} = P_{weft}$ = 285 yarns/10 cm plain weave, with floating *F* = 1, has the highest value of the synthetic indicator $Is_{1-gr.A}$ = 0.889. This is justified by the fact that the utility of positive characteristics for tensile strength, fabric tenacity, and mechanical work of rupture deformation has the maximum value, indicating a higher quality level, except for puncture resistance, which is 0.5. Also, the utility of the negative characteristic for bending stiffness has the maximum value, indicating a higher quality level.

Table 3

VALUES OF THE SYNTHETIC DURABILITY INDICATOR FOR THE FABRICS IN GROUP A (KEVLAR)

Group/ Composition	Article code	Positive	Positive	Positive	Negative	Negative	$Is_{1-gr.A}$
		Pr (daN)	τ (cN/tex)	*T* (N)	W_s (N·m)	*R* (mg·cm)	
Group A/ Kevlar	K1	0.481	0.317	1.000	0.863	0.178	0.553
	K2	0.399	0.357	0.834	0.567	0.000	0.428
	K3	0.057	0.000	0.000	0.106	0.690	0.170
	K4	0.000	0.040	0.375	0.000	0.328	0.160
	K5	1.000	1.000	0.495	1.000	1.000	**0.889**
	K6	0.883	0.994	0.622	0.992	0.690	**0.828**

Table 4

VALUES OF THE IMPORTANCE DEGREE OF DURABILITY CHARACTERISTICS OF GROUP A (KEVLAR)

Degree of importance	*Pr* (daN)	τ (cN/tex)	*T* (N)	W_s (N·m)	*R* (mg·cm)
γ_i	0.19	0.23	0.22	0.15	0.21

Table 5

RANKING OF CHARACTERISTICS OF GROUP A (KEVLAR)						
Characteristics / Experts	Pr (daN)	τ (cN/tex)	T (N)	W_s (N·m)	R (mg·cm)	$\sum_{i=1}^{n} R_{ij}$
E1	5	3	4	2	1	15
E2	4	2	1	5	3	15
E3	1	4	2	3	5	15
E4	2	3	4	5	1	15
E5	1	3	2	4	5	15
E6	2	1	4	5	3	15
$\sum_{j=1}^{m} R_{ij}$	19	15	16	23	17	90
$100/\sum_{j=1}^{m} R_{ij}$	5.26	6.67	6.25	4.35	5.88	28
γ_{ij}	0.19	0.23	0.22	0.15	0.21	1.0
Rank	4	1	2	5	3	15.0
$\sum_{j=1}^{m} R_{ij} - R_{ij,n}$	5041	5625	5476	4489	5329	$\sum_{i=1}^{n}\left(\sum_{j=1}^{m} R_{ij} - R_{ij}\right)^2$

Table 6

AVERAGE VALUES OF DURABILITY CHARACTERISTICS FOR FABRICS IN GROUP B (NOMEX)						
Group/ Composition	**Article code**	Pr **(daN)**	τ **(cN/tex)**	T **(N)**	W_s **(N·m)**	R **(mg·cm)**
Group B/ Nomex	N1	35.05	5.13	674.17	4.068	52.92
	N2	34.89	5.18	642.21	4.039	50.86
	N3	33.27	4.38	538.33	4.051	58.85
	N4	32.86	4.32	524.16	4.04	52.66
	N5	37.24	9.01	706.67	3.339	62.75
	N6	36.58	8.83	716.85	3.348	58.64
Min		**32.86**	**4.32**	**524.16**	**3.34**	**50.86**
Max		**37.24**	**9.01**	**716.85**	**4.07**	**62.75**

Table 7

VALUES OF THE IMPORTANCE DEGREE OF DURABILITY CHARACTERISTICS OF GROUP B (NOMEX)							
Group/ Composition	**Article code**	**Positive**	**Positive**	**Positive**	**Positive**	**Negative**	$Is_{1-gr.B}$
		Pr **(daN)**	τ **(cN/tex)**	T **(N)**	W_s **(N·m)**	R **(mg·cm)**	
Group B/ Nomex	N1	0.500	0.173	0.779	0.960	0.827	0.623
	N2	0.463	0.183	0.613	1.000	1.000	0.624
	N3	0.094	0.013	0.074	0.977	0.328	0.254
	N4	0.000	0.000	0.000	0.962	0.849	0.323
	N5	1.000	1.000	0.947	0.000	0.000	0.628
	N6	0.849	0.962	1.000	0.012	0.346	**0.676**

At Article K4 in Group A, characterized by Nm_{warp} = Nm_{weft} = 60/20, P_{warp} = P_{weft} = 280 yarns/10 cm, diagonal $D\frac{2}{1}/$, with floating F = 1.5, the lowest value of the synthetic indicator $Is_{1-gr.A}$ = 0.160 was obtained. This is justified by the fact that the utility of positive characteristics for tensile strength and mechanical work of rupture deformation has the minimum value. Additionally, fabric tenacity and puncture resistance have values lower than 0.4, closer to the lower limit, indicating a lower quality level. Moreover, the utility of the negative characteristic for bending stiffness has a value lower than 0.4, indicating a lower quality level.

At Article N6 in Group B (Nomex), characterized by Nm_{warp} = Nm_{weft} = 68/2, P_{warp} = P_{weft} = 350 yarns/10 cm, plain weave, with floating F = 1, the highest value of the synthetic indicator $Is_{1-gr.B}$ = 0.676 was obtained. This is justified by the fact that the utility of positive characteristics for tensile strength, fabric tenacity, and puncture resistance, except for the mechanical work of rupture deformation, is close to the maximum value, indicating a higher quality level. However, the utility of the negative characteristic for bending stiffness has a value lower than 0.4, close to the lower limit, indicating a lower quality level.

At Article N3 in Group B, characterized by Nm_{warp} = Nm_{weft} = 48/2, P_{warp} = P_{weft} = 370 yarns/10 cm, diagonal $D\frac{2}{1}/$, with floating F = 1.5, the lowest value of the synthetic indicator $Is_{1-gr.A}$ = 0.254 was obtained. This is justified by the fact that the utility of positive characteristics for tensile strength, fabric tenacity, and puncture resistance is at the minimum value, indicating a lower quality level, except for the mechanical work of rupture deformation. However, the utility of the negative characteristic for bending stiffness is close to the upper limit, indicating a higher quality level.

Among the analysed characteristics, the team of experts considered that fabric tenacity best reflects the durability of the fabrics, assigning it the highest weight for assessing the quality level of fabric assortments needed for the production of firefighting equipment.

Calculating the synthetic physiological comfort indicator for fabrics in Group A (Kevlar)

According to the steps within the algorithm, synthetic comfort indicators $Is_{2-gr.A}$ and $Is_{2-gr.B}$ are calculated for each group of fabrics.

Selection of representative characteristics:

- Air permeability index, I (kg/m^2·h)
- Relative elongation at break, ε (%)
- Thermal conductivity coefficient, λ (kcal/m·h·°C)
- Vapor permeability coefficient, μ (g/m^2·h)
- Fabric mass, M (g/m^2)

The average values of comfort characteristics for fabrics in Group A (Kevlar) are presented in table 8. The preferred direction of variation for physiological comfort characteristics has been adopted as follows:

- positive characteristics: I (kg/m^2·h) and ε (%);
- negative characteristics: λ (kcal/m·h·°C), μ (g/m^2·h) and M (g/m^2).

The values obtained for each characteristic are reported on a single scale in the interval [0;1] in table 9. The degree of utility U_i depending on the preferred direction of increase/decrease of the quality characteristic values was determined as follows:

- for the preferred direction of increasing the values of the characteristic (positive characteristic), U_i is calculated using the relationship:

$$U_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (13)$$

Table 8

AVERAGE VALUES OF COMFORT CHARACTERISTICS FOR FABRICS IN GROUP A (KEVLAR)						
Group/ Composition	**Article code**	**Air permeability index I (kg/m^2·h)**	**Relative elongation at break ε (%)**	**Thermal conductivity coefficient λ (kcal/m·h·°C)**	**Vapour permeability coefficient μ (g/m^2·h)**	**Fabric mass M (g/m^2)**
Group A/ Kevlar	K1	35.4	7.3	0.044	4.28	147
	K2	24.2	6.8	0.047	4.22	160
	K3	34.5	7.6	0.052	4.35	156
	K4	32.8	7.8	0.048	4.42	180
	K5	33.6	5.4	0.053	4.75	162
	K6	34.2	5.6	0.050	4.68	174
Min		**24.2**	**5.4**	**0.044**	**4.22**	**147**
Max		**35.4**	**7.8**	**0.053**	**4.75**	**180**

Table 9

VALUES OF THE SYNTHETIC COMFORT INDICATOR FOR THE FABRICS IN GROUP A (KEVLAR)							
Group/ Composition	**Article code**	**Positive**	**Positive**	**Negative**	**Negative**	**Negative**	**$Is_{2-gr.A}$**
		I (kg/m^2·h)	**ε (%)**	**λ (kcal/m·h·°C)**	**μ (g/m^2·h)**	**M (g/m^2)**	
Group A/ Kevlar	K1	1.000	0.792	1.000	0.887	1.000	**0.939**
	K2	0.000	0.583	0.667	1.000	0.606	0.561
	K3	0.920	0.917	0.111	0.755	0.727	0.694
	K4	0.768	1.000	0.556	0.623	0.000	0.586
	K5	0.839	0.000	0.000	0.000	0.545	**0.296**
	K6	0.893	0.083	0.333	0.132	0.182	0.341

- for the preferred direction of decreasing the values of the characteristic (negative characteristic), U_i is calculated using the relationship:

$$U_i = \frac{x_{max} - x_i}{x_{max} - x_{min}} \tag{14}$$

The values of the synthetic comfort indicator $Is_{2-gr.A}$ for fabrics in Group A (Kevlar) are presented in table 9. For the calculation of the indicator $Is_{2-gr.A}$, the values of the importance degree of comfort characteristics presented in table 10 were required. The importance degree of durability characteristics was evaluated using the expert method (table 11).

The consistency of expert opinions was checked using the relationship:

$$W = \sum_{i=1}^{n}\left(\sum_{j=1}^{m} R_{ij} - R_{ij}\right)^2 / \left[m^2 \cdot (n^3 - n)/6\right] = \tag{15}$$

$$= \frac{25960}{36 \cdot \frac{(125-5)}{6}} = 36$$

From a statistical point of view, the agreement of expert opinions is verified using the test, where the χ^2 test statistic is calculated using the relationship:

$$\chi^2 = W \cdot m(n-1) \tag{16}$$

So, from a statistical perspective, $\chi^2_{calc} > \chi^2_{\nu-1,\alpha=0.05}$, the expert opinions are in agreement (W is significant). The ranking of characteristics is based on the criterion of decreasing values of γ_{ij}, as presented in table 11.

Calculating the synthetic physiological comfort indicator for fabrics in Group B (Nomex)

The average values of physiological comfort characteristics for fabrics in Group B (Nomex) are presented in table 12. The values of the synthetic comfort indicator $Is_{2-gr.B}$ for fabrics in Group B (Nomex) are presented in table 13. For the calculation of the indicator $Is_{2-gr.A}$, the values of the importance degree of comfort characteristics presented in table 10 were required. The importance degree of durability characteristics was evaluated using the expert method (table 11).

The ranking of comfort characteristics for fabrics in Group B was conducted similarly to fabrics in Group A, according to table 4. From the analysis of the values obtained for the synthetic comfort indicators $Is_{2-gr.A}$ and $Is_{2-gr.B}$, the following aspects can be deduced:

- The synthetic indicator $Is_{2-gr.A}$ includes all the characteristics that are reflected in the comfort of the analysed fabrics, as observed from the experimental data for fabrics in Group A (Kevlar). Article K1, characterized by $Nm_{warp} = Nm_{weft}$ = 56/2, $P_{warp} = P_{weft}$ = 365 yarns/10 cm, diagonal $D\frac{2}{2}$/, with floating F = 2, has the highest value of the synthetic indicator $Is_{1-gr.A}$ = 0.939. This is justified by the fact that the utility of positive characteristics for the air permeability index has the maximum value, and the relative elongation at break is close to the upper limit, indicating a higher quality level.

Table 10

VALUES OF THE IMPORTANCE DEGREE OF COMFORT CHARACTERISTICS OF GROUP A (KEVLAR)					
Degree of importance	***I*** **(kg/m²·h)**	**ε (%)**	**λ (kcal/m·h·°C)**	**μ (g/m²·h)**	***M*** **(g/m²)**
γ_i	0.22	0.18	0.19	0.21	0.20

Table 11

RANKING OF CHARACTERISTICS OF GROUP A (KEVLAR)						
Characteristics / Experts	***I*** **(kg/m²·h)**	**ε (%)**	**λ (kcal/m·h·°C)**	**μ (g/m²·h)**	***M*** **(g/m²)**	$\sum_{j=1}^{m} R_{ij}$
E1	1	2	3	4	5	15
E2	3	4	1	5	2	15
E3	4	5	3	1	2	15
E4	1	4	5	2	3	15
E5	2	3	4	1	5	15
E6	5	2	3	4	1	15
$\sum_{i=1}^{n} R_{ij}$	16	20	19	17	18	90
$100/\sum_{j=1}^{m} R_{ij}$	6.25	5.00	5.26	5.88	5.56	28
γ_{ij}	0.22	0.18	0.19	0.21	0.20	1
Rank	1	5	4	2	3	15
$\sum_{j=1}^{m} R_{ij} - R_{ij,n}$	5476	4900	5041	5329	5184	$\sum_{i=1}^{n}\left(\sum_{j=1}^{m} R_{ij} - R_{ij}\right)^2$

Table 12

AVERAGE VALUES OF PHYSIOLOGICAL COMFORT CHARACTERISTICS FOR FABRICS IN GROUP B (NOMEX)						
Group/ Composition	**Article code**	**Air permeability index I (kg/m^2·h)**	**Relative elongation at break ε (%)**	**Thermal conductivity coefficient λ (kcal/m·h·°C)**	**Vapour permeability coefficient μ (g/m^2·h)**	**Fabric mass M (g/m^2)**
Group B/ Nomex	N1	26.30	21.90	0.056	5.45	217
	N2	30.60	22.70	0.054	5.32	214
	N3	28.80	25.30	0.059	5.73	220
	N4	27.40	26.80	0.057	5.66	230
	N5	29.10	17.60	0.063	6.17	292
	N6	32.20	16.30	0.060	5.81	288
Min		**26.30**	**16.30**	**0.054**	**5.32**	**214**
Max		**32.20**	**26.80**	**0.063**	**6.17**	**292**

Table 13

VALUES OF THE SYNTHETIC COMFORT INDICATOR FOR FABRICS IN GROUP B (NOMEX)							
Group/ Composition	**Article code**	**Positive**	**Positive**	**Negative**	**Negative**	**Negative**	**$Is_{2-gr.B}$**
		I (kg/m^2·h)	**ε (%)**	**λ (kcal/m·h·°C)**	**μ (g/m^2·h)**	**M (g/m^2)**	
Group B/ Nomex	N1	0.000	0.533	0.778	0.847	0.962	0.611
	N2	0.729	0.610	1.000	1.000	1.000	**0.870**
	N3	0.424	0.857	0.444	0.518	0.923	0.624
	N4	0.186	1.000	0.667	0.600	0.795	0.630
	N5	0.475	0.124	0.000	0.000	0.000	**0.128**
	N6	1.000	0.000	0.333	0.424	0.051	0.386

Additionally, the utility of the negative characteristics, such as the thermal conductivity coefficient and fabric mass, has maximum values. Moreover, the vapour permeability coefficient has a value greater than 0.8, close to the upper limit, indicating a higher quality level.

- At Article K5 in Group A, characterized by Nm_{warp} = Nm_{weft} = 68/2 and P_{warp} = P_{weft} = 285 yarns/10 cm, plain weave, with floating F = 1, the lowest value of the synthetic indicator $Is_{2-gr.A}$ = 0.296 was obtained. This is justified by the fact that the utility of positive characteristics for relative elongation at break is at the minimum value, indicating a lower quality level. Additionally, the utility of negative characteristics, such as the thermal conductivity coefficient and vapour permeability coefficient, has minimum values. Moreover, the fabric mass has an average value, indicating a lower quality level.
- At Article N2 in Group B (Nomex), characterized by Nm_{warp} = Nm_{weft} = 60/2, P_{warp} = P_{weft} = 260 yarns/10 cm, diagonal $D\frac{2}{2}/$, with floating F = 2, the highest value of the synthetic indicator $Is_{2-gr.B}$ = 0.870 was obtained. This is justified by the fact that the utility of positive characteristics, such as the air permeability index and relative elongation at break, is close to the upper limit, indicating a higher quality level. Additionally, the utility of negative characteristics, such as the thermal conductivity coefficient, vapour permeability coefficient, and fabric mass, has maximum values, indicating a higher quality level.
- At Article N5 in Group B, characterized by Nm_{warp}= Nm_{weft} = 56/2, P_{warp} = P_{weft} = 355 yarns/10 cm, plain weave, with floating F = 1, the lowest value of the synthetic indicator $Is_{1-gr.A}$ = 0.128 was obtained. This is justified by the fact that the utility of positive characteristics, such as the air permeability index and relative elongation at break, is close to the lower limit, indicating a lower quality level. Additionally, the utility of negative characteristics, such as the thermal conductivity coefficient, vapour permeability coefficient, and fabric mass, has minimum values, indicating a lower quality level.
- Among the analysed characteristics, the team of experts considered that the air permeability index best reflects the comfort of the fabrics, assigning it the highest weight for assessing the quality level of fabric assortments needed for the production of firefighting equipment.

CONCLUSIONS

In conclusion, it is noted that the highest values for the synthetic durability indicators of fabrics, both in Group A (Kevlar) and Group B (Nomex), were obtained for fabrics with a plain weave structure,

$Is_{1-gr.A}$ = 0.889, Art. K5 and $Is_{1-gr.B}$ = 0.676, Art. N6, while the lowest values were obtained for fabrics with a diagonal $D\frac{2}{1}/$ structure, $Is_{1-gr.A}$ = 0.160, Art. K4 and $Is_{1-gr.B}$ = 0.254, Art. N3.

The highest values for the synthetic comfort indicators of fabrics, both in Group A (Kevlar) and Group B (Nomex), were obtained for fabrics with a Diagonal $D\frac{2}{1}/$ structure, $Is_{2-gr.A}$ = 0.939, Art. K1 and $Is_{2-gr.B}$ = 0.870, Art. N2 respectively, while the lowest values were obtained for fabrics with a plain weave structure, $Is_{2-gr.A}$ = 0.296, Art. K5 and $Is_{2-gr.B}$ = 0.128, Art. N5.

Fabrics with a Plain weave structure provide better stability of the yarns in the woven structure, regardless of the fibre composition. However, it should be noted that the raw materials used in the production of firefighting equipment must have special characteristics, which Kevlar and Nomex fibres fulfil, thus ensuring the performance of activities involving risk factors of thermal, chemical, biological, mechanical, physical, or electrical nature and have direct influences on the health and life of the individual performing a certain activity.

The values of the synthetic indicators determined based on durability and comfort functions can be used subsequently for modelling the physical-mechanical properties and for selecting the most suitable fabrics to meet the requirements of a particular field of use.

Articles in each group where the value of both the synthetic durability indicator and the synthetic comfort indicator is close to the maximum, indicating a superior quality level, can be considered reference elements. Therefore, articles, where the value of both the synthetic durability indicator and the synthetic comfort indicator is minimal, can have their quality improved by modifying structural parameters (such as fineness, technological density, and weave type), with the high-quality article from each group serving as a reference. This approach allows for finding optimal operating conditions in a short time and with reduced material costs compared to laboratory research.

The choice of raw material for making firefighter suits is a meticulous and rigorous process, considering that this equipment must provide maximum protection under extreme conditions.

By calculating the synthetic durability indicators for the fabrics from Group A (Kevlar), manufacturers can select plain weave fabrics, such as: Art. K5 ($Is_{1-gr.A}$ = 0.889) and Art. K6 ($Is_{1-gr.A}$ = 0.828), to be used in the outer layer of the protective jacket for firefighters, because through their structural characteristics (fineness, technological density, type of weave) and the values of durability assessment properties, they offer good resistance to cuts and abrasions, as well as thermal protection.

Diagonal $D\frac{2}{2}/$ weave fabrics, namely Art. K1 ($Is_{1-gr.A}$ = 0.553) and Art. K2 ($Is_{1-gr.A}$ = 0.428), can be used for the collar and cuff areas. These areas can be reinforced with Kevlar fabric to prevent fire penetration and provide additional protection against heat.

Additionally, $D\frac{2}{1}/$ weave fabrics, namely Art K3 ($Is_{1-gr.A}$ = 0.170) and Art. K4 ($Is_{1-gr.A}$ = 0.160), can be used for the shoulder and elbow areas as an additional layer of protection to provide better protection against impact and heat.

Based on the obtained values of the synthetic comfort indicators for the fabrics from Group A (Kevlar), manufacturers can select Diagonal $D\frac{2}{1}/$, weave fabrics, such as: Art K1 ($Is_{2-gr.A}$ = 0.939) and Art. K2 ($Is_{2-gr.A}$ = 0.561), to be used in the elbow and knee areas in the case of pants, as an additional layer of protection.

Diagonal $D\frac{2}{1}/$ weave fabrics, namely Art. K3 ($Is_{1-gr.A}$ = 0.694) and Art. K4 ($Is_{1-gr.A}$ = 0.586), can be used for the pocket area. This area can be reinforced with Kevlar fabric to prevent the penetration of fire and water, providing additional protection against heat and for the radio/phone.

Plain weave fabrics, namely Art. K5 ($Is_{1-gr.A}$ = 0.296) and Art. K6 ($Is_{1-gr.A}$ = 0.341), can be used for the shoulder and collar areas as an insulation layer to keep heat away and protect against extreme temperatures.

By calculating the synthetic durability indicators for the fabrics from Group B (Nomex), manufacturers can select plain weave fabrics, such as: Art. N6 ($Is_{1-gr.B}$ = 0.676) and Art. N5 ($Is_{1-gr.B}$ = 0.628), to be used in the outer layer of the jacket, providing a barrier against flames and intense heat.

Diagonal $D\frac{2}{2}/$ wave fabrics, namely Art. N1 ($Is_{1-gr.B}$ = 0.623) and Art. N2 ($Is_{1-gr.B}$ = 0.624), can be used for the protective hood, which covers the head, neck, and sometimes shoulders, often made of Nomex to protect these sensitive areas from exposure to fire and heat.

Diagonal $D\frac{2}{1}/$ wave fabrics, namely Art. N3 ($Is_{1-gr.B}$ = 0.254) and Art. N4 ($Is_{1-gr.B}$ = 0.323), can be used for the collar and cuff areas. These areas can be reinforced with Nomex fabric to prevent fire penetration and provide additional protection against heat.

Based on the obtained values of the synthetic comfort indicators for the fabrics from Group B (Nomex), manufacturers can select Diagonal $D\frac{2}{2}/$ weave fabrics, such as Art. N2 ($Is_{2-gr.B}$ = 0.870) and Art. N1 ($Is_{2-gr.B}$ = 0.611), to be used in the making of base clothing, worn under the main suit, which can be made from Nomex to provide additional protection at the skin level.

Diagonal $D\frac{2}{1}/$ weave fabrics, namely Art. N3 ($Is_{1-gr.B}$ = 0.624) and Art. N4 ($Is_{1-gr.B}$ = 0.630), can be used for making full suits to provide complete protection.

Plain weave fabrics, namely Art. N5 ($Is_{1-gr.B}$ = 0.128) and Art. N6 ($Is_{1-gr.B}$ = 0.386), can be used in the inner layers including lining to ensure additional protection and enhance the comfort of the firefighter.

Based on the obtained values of durability and comfort synthetic indicators, manufacturers ensure that the selected materials used in various areas of firefighter protective equipment meet the highest safety and performance standards, thereby protecting the lives of those on the front lines of firefighting efforts.

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