Protective clothing system for interventions in emergency situations

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DOINA TOMA
GEORGETA POPESCU
ALINA POPESCU
SABINA OLARU
ADRIAN SALISTEAN
IONELA BADEA

ABSTRACT – REZUMAT

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Emergency workers are exposed to many different risks at the same time and possible consequences for their safety and health may be manifold. Many emergency workers suffer from accidents and injuries in the course of their jobs, as well as other negative health effects that lead to severe deterioration of their physical and psychological well-being. The use of specific personal protective equipment (PPE) according to the given risks is of great importance in preventing adverse health effects among emergency workers. This research aimed to develop, for emergency workers, a PPE system, in a modular structure consisting of: i) modular layer 1: the inner layer, in contact with the skin/Underwear PPE, with the function of sensorial and thermophysiological comfort and which ensures thermal protection; ii) modular layer 2: the intermediate (basic) layer/Duty uniform – with the function of limited protection to the specific risk factors of an unpredictable intervention action (thermal risks: convection heat, flame; risks from the external environment: liquid splashes; mechanical risks: cutting, abrasion, etc); iii) modular layer 3: the outer layer/specialized PPE, with a function of barrier against specific risk factors for fire intervention missions, extreme weather conditions etc. This modular approach provides some advantages, including preserving comfort and flexibility until the intervention mission requires the use of the next level of protection. This helps ensure that emergency responders are not in the position of choosing between their safety or mission effectiveness.

Keywords: *protection, duty-uniform, mission-specific layers, modular layers, emergency workers*

Sistem de îmbrăcăminte de protecție pentru intervenții în situații de urgență

Lucrătorii în situații de urgență sunt expuși la multe riscuri diferite în același timp și posibilele consecințe pentru securitatea și sănătatea lor pot fi multiple. Mulți lucrători în situații de urgență suferă accidente și vătămări în cursul muncii lor, precum și alte efecte negative asupra sănătății care duc la deteriorarea gravă a bunăstării lor fizice și psihologice. Utilizarea echipamentului individual de protecție specific (EIP) în funcție de riscurile date este de o mare importanță în prevenirea efectelor negative asupra sănătății în rândul lucrătorilor în situații de urgență. Scopul acestei cercetări a fost de a dezvolta, pentru lucrătorii de urgență, un sistem de EIP, într-o structură modulară compus din: i) strat modular 1: stratul interior, în contact cu pielea/EIP subvestimentar, cu funcția de confort senzorial și termo-fiziologic și care asigură protecție termică; ii) strat modular 2: stratul intermediar (de bază)/uniforma de serviciu – cu funcția de protecție limitată la factorii de risc specifici unei acțiuni de intervenție imprevizibile (riscuri termice: căldură prin convecție, flacără; riscuri din mediul extern: stropiri lichide; riscuri mecanice: tăiere, abraziune etc.); iii) stratul modular 3: stratul exterior/EIP specializat, cu funcție de barieră împotriva factorilor de risc specifici pentru misiunile de intervenție la foc, condiții meteorologice extreme etc. Această abordare modulară oferă câteva avantaje, inclusiv păstrarea confortului și flexibilității până când misiunea de intervenție necesită utilizarea următorului nivel de protecție. Acest lucru ajută la asigurarea faptului că lucrătorii de intervenție în caz de urgență nu sunt în situația de a alege între siguranța sau eficacitatea misiunii lor.

Cuvinte-cheie: *protecție, uniforme de serviciu, straturi specifice misiunii, straturi modulare, lucrători de urgență*

INTRODUCTION

Current environmental, economic, and political developments and trend data all suggest an increase in the severity and frequency of disasters in the future. Phenomena that support this assumption include increased energy use, progressive global warming, climate change and pollution, population growth, dispersal of industrialization around the globe, expansion of transportation facilities, and the growing spread of terrorism. Emergency workers' priorities are to protect human life, property and the environment, and their most common fields of action include everyday emergencies (road accidents, crime scenes, gas explosions, fires); natural disasters (floods, storms, fires, earthquakes, volcanic eruptions); industrial accidents (involving hazardous materials, such as in the nuclear and mining sectors); transport accidents (major car crashes, plane crashes, rail accidents); terrorist and criminal attacks (bomb attacks, gas attacks, shootings); massive public events (negative events during concerts, sports events, demonstrations) [1, 2]. The nature of the work of emergency responders puts them at the top of those professions who have to deal with a considerable number of occupational health and safety hazards which are often unavoidable. Frequently they do not face one single safety risk, but a complex combination of risk factors, including the unpredictability of the situations they are required to work in.

The purpose of protective clothing and equipment is to shield responders from injury while operating efficiently in hazardous environments and provide the highest level of protection against a range of possible threats. The specificity of intervention missions makes emergency workers face, during incidents, a multitude of known and unknown threats. That is why there are frequent situations in which they are not outfitted with the best and/or the most appropriate personal protective equipment (PPE) against the risks specific to the intervention action. Responders consistently expressed a desire for a modular system built upon a duty uniform that provides limited protection and physiological benefit in combination with a series of modular, mission-specific layers to provide specialized protection.

A systems or modular approach allows emergency responders to move beyond a "one size fits all" solution and allows for the customization of their PPE ensemble in varied response environments [3]. This helps ensure that responders are not in the position of choosing between their safety or mission effectiveness.

Today, advanced computer simulation techniques and virtual garments prototyping are indispensable for the development of garments and their fitting on the 3D body models within a virtual environment, as well as real-time virtual clothes try-on [4].

This paper discusses a personal protective clothing system for emergency responders built upon a duty uniform that provides limited protection and physiological benefits (for example, moisture wicking) in combination with a series of modular, mission-specific layers, to provide specialized protection.

DEVELOPMENT OF THE PROTECTIVE CLOTHING SYSTEM FOR INTERVENTIONS IN EMERGENCY SITUATIONS

The methodology used for designing and achieving the modular PPE system for interventions in emergencies is based on a multidisciplinary approach to developing and managing "complex systems". Starting from the needs analysis, the key needs of the PPE system were identified, which were the basis for establishing the key performance parameters and the high-performance parameters. The established performance parameters were translated into design requirements, based on which the raw materials, realization technologies, and PPE system's conception (design) were identified.

The analysis of the needs/capabilities identified for the health and safety of the emergency responders, to prioritize, highlights the following key needs to be met by the PPE system, in the modular structure, for emergency response actions: User Comfort; Certification of protection properties by the legislation in the field of PPE; Durability for Daily Wear; Usability/Functionality; Aesthetics; Multi-service Applicability; User acceptability; Reasonable cost [5].

Starting from the analysis of the types of aggressions against which protection must be ensured: thermal risks (flame, heat, contact with incandescent materials, etc.); mechanical risks (abrasion, tearing, etc.), risks specific to working in cold conditions (low temperatures, air currents, temperature fluctuations, contact with cold surfaces, etc) the solution for accomplishing of the PPE system for intervention in emergency situations, adopted is a multi-layered structure consisting of:

- *modular layer 1*: the inner layer, in contact with the skin/ Underwear PPE, with the function of sensorial and thermophysiological comfort [6, 7] and which ensures thermal protection;
- *modular layer 2*: the intermediate (basic) layer/Duty uniform – with the function of limited protection to the specific risk factors of an unpredictable intervention action (thermal risks: convection heat, flame; risks from the external environment: liquid splashes; mechanical risks: cutting, abrasion, etc.);
- *modular layer 3*: the outer layer/specialized PPE, with a function of barrier against specific risk factors for fire intervention missions, extreme weather conditions etc.

To ensure the protective function, the clothing used for this purpose must be designed and manufactured in accordance with the essential health and safety requirements established in Annex II of Regulation (EU) 2016/425 of the European Parliament and of the Council of 9th of March 2016 regarding on personal protective equipment and repealing Council Directive 89/686/EEC.

Considering the essential health and safety requirements, specific to the risk of protection against heat and/or fire, have been established the minimum performance requirements that must be met by the materials used in the production of:

– the base layer (Duty uniform) of the PPE system for intervention in emergency situations, namely: limited flame spread coding letter A1: the mean value of after flame time ≤ 2 s, the mean value of afterglow time: ≤ 2 s; convective heat transfer index, 2 performance levels; radiant heat transfer index, 2 performance levels; dimensional changes ± 3%; tensile strength min. 450 N in both directions; tear strength, min. 25 N in both directions; seam strength, min. 225 N;

– the modular protective layer – specialized PPE for fire intervention missions, namely: thermal resistance after exposure to a temperature of 180°C for 5 minutes; limited flame spread coding letter A1: the mean value of after flame time ≤ 2 s, the mean value of afterglow time: ≤ 2 s; convective heat transfer index, 2 performance levels; radiant heat transfer index, 2 performance levels; dimensional changes ± 3%; tensile strength min. 450 N in both directions; tear strength, min. 25 N in both directions; seam strength, min. 225 N; resistance to penetration of liquid chemical substances, rejection rate, min. 80%.; resistance to water vapour, 2 levels of performance, resistance to water penetration, 2 levels of performance.

Considering the essential health and safety requirements specific to the risk of protection against the cold associated with the presence of bad weather with or without mechanical risks the minimum performance requirements that must be met by the materials used to manufacture the modular protective layer – Specialized PPE for intervention missions in extreme weather conditions, namely: the resulting effective thermal insulation Iclor, min. 0.310 m^2°K/W; air permeability, 3 performance classes, min 100 mm/s; resistance to water penetration, 2 performance classes, min 8000 Pa; water vapour resistance of the combination of layers, max. 55 m^2Pa/W; tear resistance of the outer material, min. 25 N; tensile strength, min. 450 N; dimensional changes, max ± 3%; seam strength, min. 225 N.

The operational requirements were defined considering the following attributes of the PPE system: i) the garments included within the PPE system; ii) the key performance parameters of each PPE garment; iii) other performance requirements of PPE components or the system; iv) any physical requirements of PPE components or the system and v) any requirements for interoperability and/or maintenance [7].

Materials

Based on the performance requirements imposed for each modular layer of clothing in the component of the intervention PPE system, execution materials were selected (table 1).

Physical-mechanical and physical-chemical characteristics of the fabrics were determined in the accredited laboratories of INCDTP (table 2).

Design of the garment's modular layers of the PPE system for interventions in emergency situations

Based on the protection requirements and the specified minimum necessary performance parameters, the assortment range of the possible intervention PPE system was established, as follows:

a) **Underwear PPE** – the inner layer of the intervention PPE system consists of a long-sleeve blouse, made of two parts (front and back) assembled on the side line, straight sleeves provided at the end with a hem and long pants adjusted at the waist with elastic, provided with a slit made of two identical gussets in the shape of a hexagon and with a hem at the end. The joints are made by sewing with flame-retardant sewing thread.

b) **Duty uniform** – intermediate/base layer of the intervention PPE system in the two-piece structure

Table 1

BASIC PROPERTIES OF THE SELECTED TEXTILES SUPPORTS				
Component	**Material**	**Structure**	**Thickness (mm)**	**Weight (g/m^2)**
Underwear PPE (inner layer)				
Knit fabric	Meta-aramid 93% Para-aramid 5% Antistatic 2%	weft interlock	0.95	215
Duty Uniform (base layer)				
	Aramid 29% FR viscose 59% Polyamide 10% Antistatic 2%	1/1 plain ripstop	0.44	219
Specialized PPE for firefighters				
Outer fabric	Para-aramid 78% Meta-aramid 20% Antistatic 2%	1/1 plain ripstop	0.45	212
Thermal moisture barrier	Thermal barrier: 3-D spunlace non-woven: aramid Membrane: ePTFE/PU BI-component	-	1.41	170
Thermal liner	Non-woven: FR viscose/aramid Fabric: viscose FR/aramid/polyamide	-	0.972	229
Specialized PPE for interventions in extreme weather conditions				
Outer fabric	Laminated material in 3 layers Layer 1: Fabric, 100%PES Layer 2: 100% PTFE Layer 3: Knit, 100% PES	-	0.52	227
Removable lining	Fabric 100% PES Non-woven 100-% PES Fabric 100% PES	-	-	61 155 61

Table 2

PHYSIC-MECHANICAL AND PHYSIC-CHEMICAL CHARACTERISTICS OF FABRICS (SELECTION)								
Characteristic	**UM**	**Values obtained in the accredited laboratories of INCDTP**						**Reference document**
		S1	**S2**	**S3.1**			**S3.2**	
				S3.1.1	**S3.1.2**	**S3.1.3**		
Mass per unit area	g/m^2	215	219	212	170	229	227	SR EN 12127
Thickness	mm	0.95	0.446	0.45	1.417	0.972	0.52	SR EN ISO 5084
Tensile strength warp	N	-	905	2653	-	-	1326.6	SR EN ISO 13934-1
Tensile strength weft	N	-	796	2056	-	-	939	SR EN ISO 13934-1
Tear strength warp	N	-	36.2	245	-	-	51.8	SR EN ISO 13937-3
Tear strength weft	N	-	34.6	213	-	-	52.8	SR EN ISO 13937-3
Bursting strength	kPa	449.3	-	-	-	-	-	SR EN ISO 13938-2
Bursting distension	mm	45.1	-	-	-	-	-	SR EN ISO 13938-2
Resistance to abrasion	cycles	120000	80000	26245	-	-	87144	SR EN ISO 12947-2
Dimensional change when washing – long.	%	–0.33	–0.46	–0.79	–2.05	–0.06	–0.86	SR EN ISO 6330 SR EN ISO 5077 SR EN ISO 3759
Dimensional change when washing – trans.	%	–0.5	–1.52	–0.26	–1.19	–0.33	–0.59	
Air permeability	l/m^2s	1390	111.1	64.48	-	-	1.237	SR EN ISO 9237
Water-vapour resistance, Ret	m^2Pa/W	5.97	5.43	6.93	21.84	8.37	17.74	SR EN ISO 11092
Thermal resistance, Rct	$m^{2\circ}K/W$	0.0418	0.0214	0.0214	0.0629	0.0442	0.0219	SR EN ISO 11092
pH of aqueous extract		6.94	7.05	-	-	-	6.34	SR EN ISO 3071
Resistance to surface wetting (spray test)	note	-	-				5(100)	SR EN ISO 4920
Resistance to water penetration	mm col. water	-	-	Over 9950			Over 9950	SR EN ISO 811
Resistance to limited flame spread		– no test specimen burns up to the top and side edges – no test specimen produces melted or ignited remains – no test specimen forms the hole – the mean value of after flame time: 0 s – the mean value of afterglow time: 0 s					-	SR EN 15025

Note: S1 is knitted fabric made of yarn 93/5/2% meta-aramid fibres/para-aramid fibres/antistatic fibres; S2 – woven fabric 29/59/10/2% aramid fibres/FR viscose fibres/polyamide fibres/antistatic fibres; S3.1.1 – woven fabric 78/20/2% para-aramid fibres/meta-aramid fibres/antistatic fibres; S3.1.2 – 3D spunlace non-woven made of para-aramidic/meta-aramidic fibres + ePTFE/PU-bicomponent membrane; S3.1.3 – non-woven made of FR viscose fibres/aramid fibres + viscose FR/aramid/polyamide fibre fabric; S3.2 – laminated material in 3 layers: 100% PES fabric + PTFE film + 100% PES knit.

consists of: a blouse with classic sleeves with cuffs with buttons, frontal closure system with a zipper covered with slit fixed with velcro tape, 2 pockets with closed flaps with buttons applied to the chest and straight trousers, adjusted at the waist with a belt, slit with zipper and button, 2 pockets with an oblique opening at the upper part of the front, 2 pockets with an oblique opening at the upper part of the back, 2 straight pockets provided inside the oblique ones at the back, 2 pockets with bellows and flaps on the sides, collars, knee pads. The joints are made by sewing with flame-retardant sewing thread.

c) **Specialized PPE for intervention missions in case of fires** – the outer layer of the intervention PPE system, made in a modular structure: Outer suit + removable lining.

The outer suit consists of: a jacket with a tunic collar closed with a flap from the base material and velcro tape, with the back cut from a single piece, the chest cut from two symmetrical pieces, the right sleeves, from two longitudinal pieces provided with a gusset, adjusted at the wrist with a clamp from the base material fixed with velcro tape; front closure system with zipper and slit in the base material fixed with velcro tape, 3 pockets applied to the chest with flaps closed with velcro tape, one on the upper part of the left chest and two on the lower part of the chest. It has retro-reflective and fluorescent horizontal bands applied by sewing that wrap around the blouse at chest level and the end and around the sleeves; pants with right end, adjusted at the waist with two bands positioned laterally from the base material; provided with adjustable elastic straps with buckles; slit closed with a zipper; 2 pockets applied to the thighs with flaps closed with velcro tape. It has retro-reflective and fluorescent horizontal strips applied by sewing that wrap around every leg.

The removable lining consists of: a jacket with a back cut from a single piece, chests cut from two symmetrical pieces, a frontal closure system with velcro tape, straight sleeves, from 2 longitudinal pieces finished with a patent tricot cuff; trousers with right end, adjusted at the waist with Velcro tape, slit closed with Velcro tape. The consolidation of the 2 clothing layers (outer suit and lining) is done with Velcro tape.

d) **Specialized PPE for intervention missions in extreme weather conditions** – the outer layer of the intervention PPE system – Short coat with removable hood and lining – consists of the chest, back, sleeves, front plate, back plate, slits (upper and lower), hood, collar, epaulettes, slanted slits and pockets, pockets with flaps and flaps, cuffs. On the inside, a short coat is provided with a removable lining top using zippers.

The design of the basic and model patterns for the garment's modular layers included within the PPE system was based on the geometric method of pattern construction, using Gemini Pattern Editor's special CAD design software.

Verification of patterns matching designed according to individual body dimensions was accomplished by modelling 2D/3D patterns and simulating garments modular layers, included within the PPE system, on the parameterized mannequin, by using Optitex PDS software for visualization, modelling and fitting the virtual body of the prototype.

The development of new PPE systems is complex, costly, and time-consuming. The use of modelling and simulation can reduce the development time and production costs of new PPE systems [8, 9]. Therefore, in the first step, we made virtual prototypes of integrated systems of modular protection layers using the OptiTex software suite.

The stages completed were the following: i) 2D design of the basic patterns by the data from the size table of the model and in correlation with the real dimensions of the products using the Pattern Design Software (PDS); ii) Simulation of PPE systems on a virtual mannequin using the Optitex 3D Suite software. The 2D patterns made with the PDS software were placed on the parameterized model and the types of seams were defined for the virtual assembly by simulating their sewing. The landmarks were deformed according to the shape of the human body; iii) Evaluation of the fit of the product on the body: after the completion of the 3D simulation process of the product, the appearance of the product and the way it sits on the surface of the body (its fit or product-body correspondence) were analysed (figures 1–4) [10].

RESULTS ADN DISCUSSION

The evaluation of the performance of the modular protection layers from the component of the PPE system for emergency intervention was carried out through specific laboratory tests to verify the protection parameters imposed by the specifications of the applicable standards [11–15], namely SR EN ISO 11612:2015 (EN ISO 11612:2015) – Protective clothing. Clothing to protect against heat and flame.

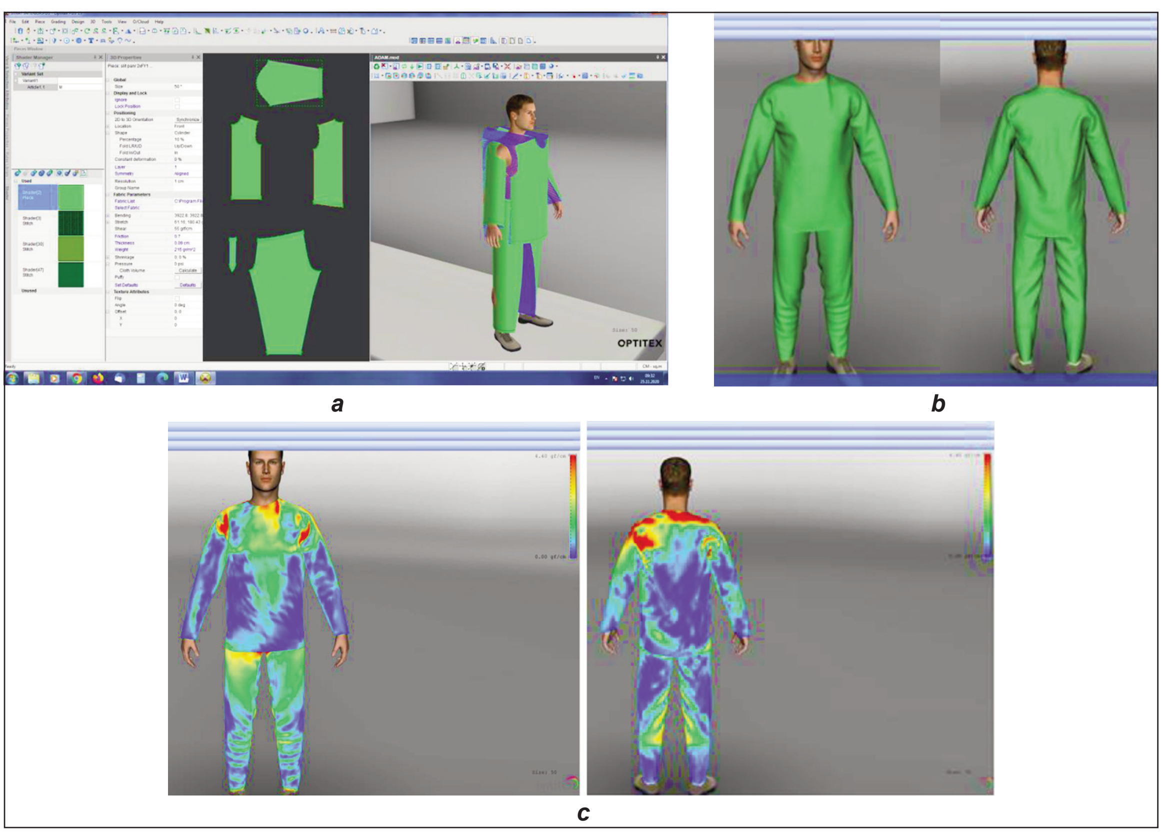

Fig. 1. Modular layer 1 – Underwear PPE: *a* – the 2D patterns with seam lines; *b* – virtual try-on verification; *c* – tension map

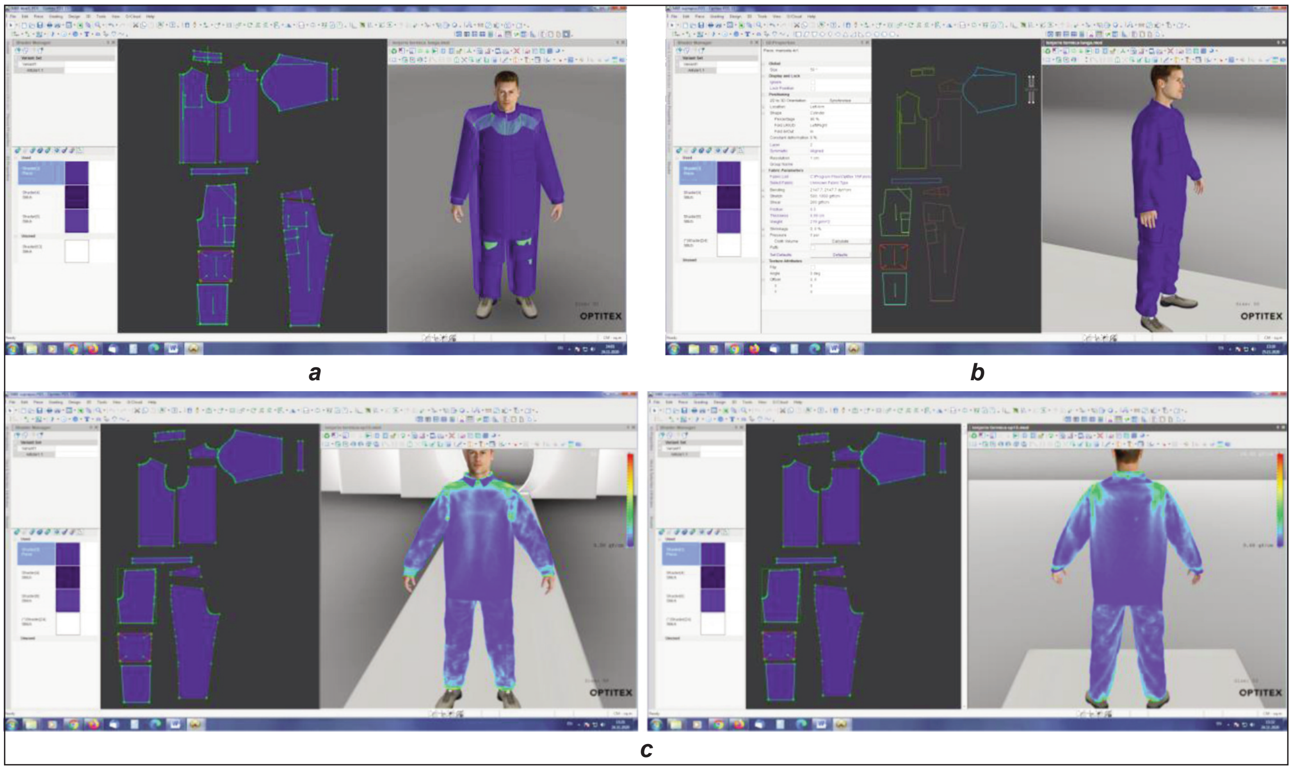

Fig. 2. Modular layer 1 (Underwear PPE) + Modular layer 2 (Duty Uniform): *a* – the 2D patterns with seam lines; *b* – virtual try-on verification; *c* – tension map

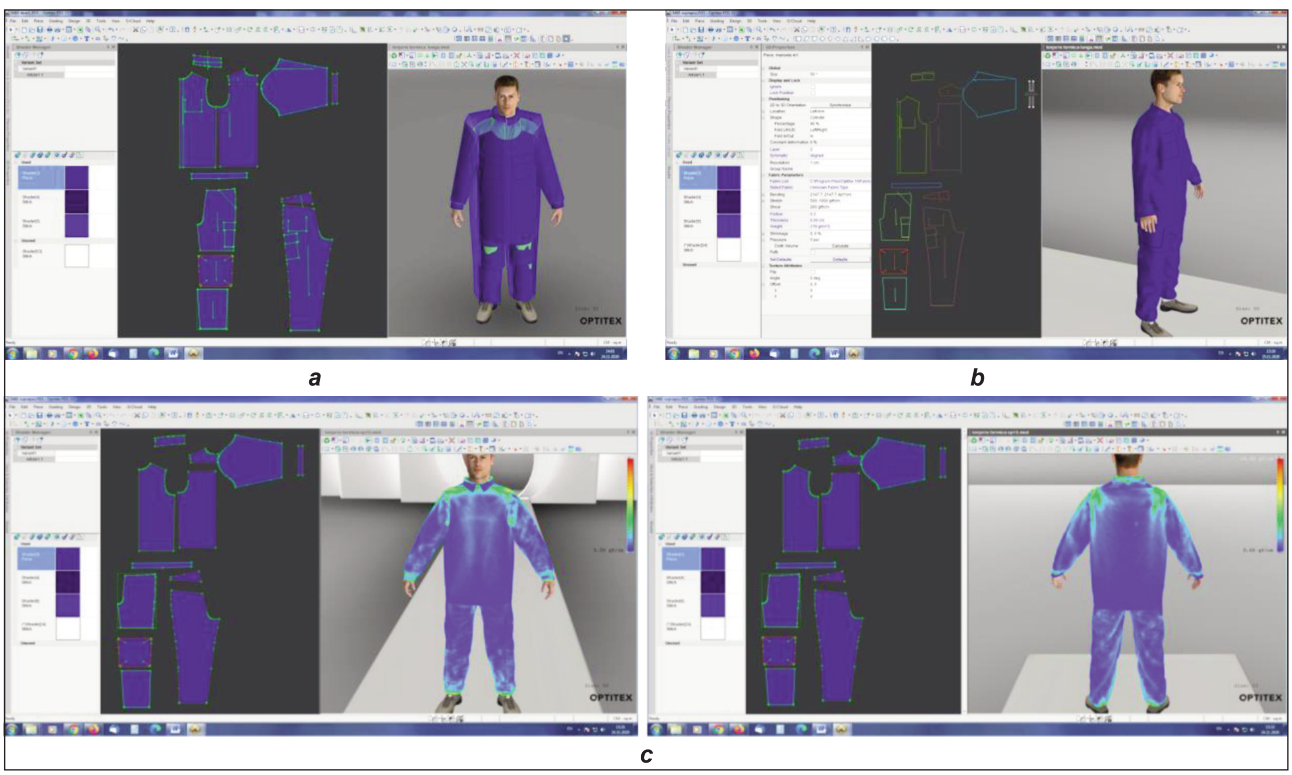

Fig. 3. Modular layer 1(Underwear PPE) + Modular layer 2 (Duty Uniform) + Modular layer 3.1 (Specialized PPE for firefighters): *a* – the 2D patterns with seam lines; *b* – virtual try-on verification; *c* – tension map

Minimum performance requirements; SR EN 469: 2020 (EN 469:2020) Protective clothing for firefighters. Performance requirements for protective clothing for firefighting activities; SR EN 342: 2018 (EN 342: 2018) – Protective clothing. Ensembles and garments for protection against cold; SR EN 343:2019 (EN 343:2019) – Protective clothing. Protection against rain; SR EN ISO 13688:2013 – Protective clothing – General requirements.

The performance evaluation carried out, based on the results obtained in the laboratory tests, highlighted that:

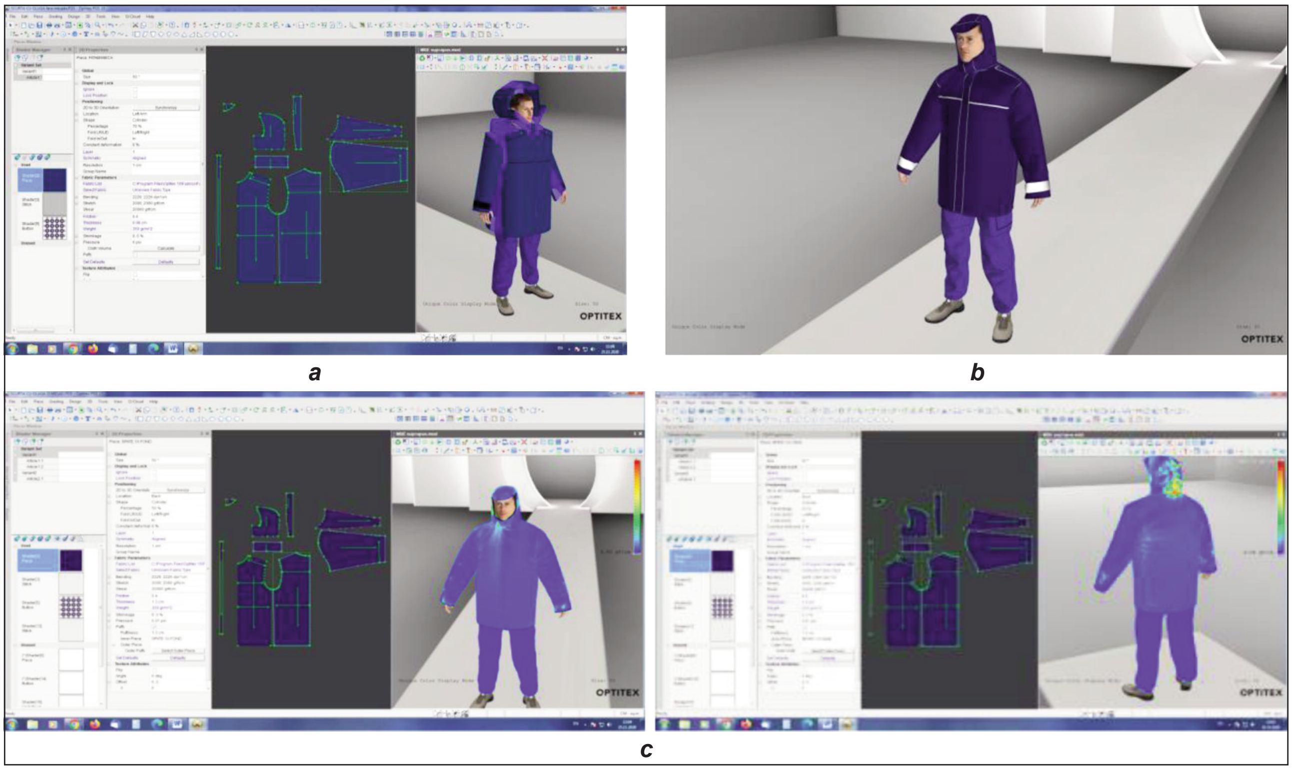

Fig. 4. Modular layer 1 (Underwear PPE) + Modular layer 2 (Duty Uniform) + Modular layer 3.2 (Specialized PPE for interventions in extreme weather conditions): *a* – the 2D patterns with seam lines; *b* – virtual try-on verification; *c* – tension map

• *Modular layer 1* – interior layer (in contact with skin) – Underwear PPE has characteristics according to the specifications of the following standards: a) SR EN ISO 11612:2015: point 6.3 (resistance to limited flame spread) – the mean value of after flame time and afterglow time: 0 s, code letter A1; point 6.4 (dimensional change) within the limits imposed, less than ± 3%, in both directions, longitudinally and transversely; point 6.5.3 (burst strength) above the minimum required value, 200 kPa; point 6.9.2 (pH value) within the required limits, greater than 3.5 and less than 9.5; b) SR EN ISO 13688:2013: point 4.2 (innocuousness – the content of carcinogenic amines) within the imposed limits, undetectable; point 4.3 (design); section 4.4 (comfort);

• *Modular layer 2* – base layer (intermediate) – Duty uniform has characteristics according to the specifications of the following standards: a) SR EN ISO 11612:2015: point 6.3 (resistance to limited flame spread) – the mean value of after flame time and afterglow time: 0 s, code letter A1; point 6.4 (dimensional change) within the limits imposed, less than ± 3%, in both directions, warp and weft; point 6.5.1 (tensile strength) above the minimum value imposed, 300 N in warp and weft; point 6.5.2 (tear strength) above the minimum value imposed, 15 N in warp and weft; point 6.9.2 (pH value) within the required limits, greater than 3.5 and less than 9.5; b) SR EN ISO 13688:2013: point 4.2 (innocuousness – the content of carcinogenic amines) within the imposed limits, undetectable; point 4.3 (design); section 4.4 (comfort);

• *Modular layer 3.1* – outer layer Specialized PPE for firefighters has characteristics according to the specifications of the following standard: SR EN 469:2020: point 6.1 (resistance to limited flame spread) – the mean value of afterflame time and afterglow time: 0 s, code letter A1; point 6.5 (thermal resistance) – dimensional changes after exposure 5 minutes at 180°C, below 5%; point 6.6 (tensile strength) above the minimum value imposed for the outer material of the PPE for firefighters, 450 N in warp and weft; point 6.7 (tear strength) above the minimum value imposed for the outer material of the PPE for fighters, 25 N in warp and weft; point 6.8 (surface wetting), degree of softening above the minimum value imposed for the outer material of the PPE for firefighters, 4 (ISO degree scale); point 6.9 (dimensional change when washing) below the required minimum values, ± 3% (for all materials in the component of the PPE for firefighters); point 6.10 (resistance to penetration of liquid chemicals), rejection rate over 80% for each of the liquid chemicals mentioned in the standard (for the set of materials in the component of the PPE specialized for firefighters); point 6.11 (resistance to water penetration) over 20 kPa, level 2 performance (for the multilayer assembly with a barrier of moisture of the PPE specialized for firefighters); point 6.12 (water vapor resistance), below 30 m^2Pa/W, performance level 2 (for the set of materials in the component of the PPE specialized for firefighters);

• *Modular layer 3.2* – outer layer: Specialized PPE for interventions in extreme weather conditions (Jacket with detachable hood and lining) has characteristics according to the specifications of the following standards: a) SR EN 343:2019: point 4.2 (resistance to water penetration) above the limit values imposed for performance class 4 (20000 Pa); point 4.3 (water vapor resistance) below the maximum value imposed, 40 m^2Pa/W; point 4.4 (tensile strength) above the required value, 450 N in warp and weft; point 4.5 (tear strength) above the imposed value, 20 N in warp and weft; point 4.6 (dimensional changes) below the required minimum values, ± 3% in both directions of the material; b) SR EN 342:2018: point 4.2 (thermal resistance) above the required minimum value, 0.31 m^2K/W; point 4.3 (air permeability, AP) within the limit values imposed for performance class 3 (AP < 5 mm/s); point 4.4 (resistance to water penetration) above the limit values imposed 8000 Pa; point 4.5 (water vapor resistance) below the maximum value imposed, 55 m^2Pa/W; point 4.6.1 (tear strength) above the minimum value imposed, 20 N in warp and weft; d) SR EN ISO 13688:2013: point 4.2 (innocuousness}: (pH value) within the required limits, greater than 3.5 and less than 9.5; point 4.3 (design); section 4.4 (comfort);

The results of the evaluation of the way of fitting the modular layers/integrated systems of modular layers of the EIP for intervention in emergency situations on the parametrized virtual mannequin are the following:

1. Simulation of the inner layer (in contact with the skin) – underwear PPE (figure 1): the appearance of the component products of the model is appropriate; checking and evaluating the body-product fit – highlights the closeness of the products to the body, without exerting a pressure that exceeds the allowed limit;
2. Simulation of the PPE system for emergency intervention that integrates the inner layer (in contact with the skin) – underwear PPE and the intermediate (base) layer – Duty Uniform (figure 2): the appearance of the products that are components of the Duty Uniform, dressed over the underwear PPE, it is appropriate; checking and evaluating the body-product fit – highlights a great lightness of the clothing layer (blue colour on the tension map), thus ensuring good wearing comfort;
3. Simulation of the emergency PPE system that integrates the inner layer (in contact with the skin) – underwear PPE, the intermediate (base) layer – Duty uniform and specialized PPE for firefighters (figure 3): the appearance of the product's components of the specialized PPE for firefighters, worn over the Duty uniform and underwear PPE; visualization of the tension map shows a good body-product correspondence, without pressure exerted on the body;
4. Simulation of the emergency PPE system that integrates the inner layer (in contact with the skin) – underwear PPE, the intermediate (base) layer – Duty uniform and specialized PPE for interventions in extreme weather conditions (figure 4): the appearance of the component product of the specialized PPE for interventions in extreme weather conditions – Short coat with removable hood and lining worn, over the Duty uniform and underwear PPE, is appropriate; viewing the tension map shows a good body-product correspondence, without pressure exerted on the body.

CONCLUSIONS

This research aimed to develop, for emergency workers, a PPE system, in a modular structure, built upon a duty uniform that provides limited protection and physiological benefits in combination with a series of modular, mission-specific layers to provide specialized protection.

Starting from the needs analysis, the key needs of the PPE system were identified, which were the basis for establishing the key performance parameters and the high-performance parameters. The established performance parameters were translated into design requirements, based on which the raw materials, the realization technologies, and the conception (design) of the PPE system were identified

The objective laboratory testing indicates that the fabrics selected for the garment's modular layers included within the PPE system meet or exceed the minimum performance requirements defined in the operational requirements specification.

The solutions and advantages offered by the Optitex software suite were used for the virtual prototyping of the PPE system for emergency intervention, before the physical realization and verification of its compliance through 3D simulation on an avatar.

For 3 variants of the integration of the modular layers in the interventions PPE system, after the completion of the 3D simulation process, the appearance of the product and the way it sits on the surface of the body (its fit or product-body correspondence) were analysed.

The PPE system, in the modular structure, integrates state-of-the-art protective technologies; provides basic protection from most likely threats (for example fire, extremes weather etc.); enhances daily-wear comfort; provides increased localized protection as needed (for example knees, forearms); includes next-to-skin layer and outer layer to provide varying levels of protection as needed; the modular layers easily donned and undonned.

This modular approach: provides some advantages, including preserving comfort and flexibility until the intervention mission requires the use of the next level of protection. This helps ensure that emergency responders are not in the position of choosing between their safety or mission effectiveness.

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Authors:

DOINA TOMA, GEORGETA POPESCU, ALINA POPESCU, SABINA OLARU,
ADRIAN SALISTEAN, IONELA BADEA

National Research and Development Institute for Textiles and Leather,
16 Lucretiu Patrascanu Street, 030508, Bucharest, Romania
e-mail: office@incdtp.ro

Corresponding author:

DOINA TOMA
e-mail: doina.toma@incdtp.ro