The complex design concept for functional protective clothing

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Review

Over the last two decades extensive work has been carried out by a number of institutes with the aim of developing efficient protective clothing for industrial workers, as well as for the armed forces. The primary requirement for both civil and defence applications is protection, respectively need for protection - for saving valuable humans faced with various hazards and climatic conditions. This contribution presents certain peculiarities of a complex design concept for protective clothing, as an important component of personal protective equipment. The requirements for protective clothing are given according to their purposes, functions, respectively type of protection, as well as the system's approach to the design, development and implementation of protective functional clothing. The research core focus in the grounded model development as the progression from initial product design goals, i.e. problem recognition, through the idea development in view of technical solution to the developed product - prototype, and finally, to evaluation of the final solution and implementation of the functional protective clothing, and certification procedures.
Key words: *functional textiles, protective clothing, design concepts, methodology*

1. Introduction

The present protective clothing has been many times evaluated mainly from the viewpoint of it's protective performance. However, according to the ever-increasing requirements for protective clothing, the end user expects more comfortable and functional protective clothes. Thus ever-increasing requirements for protecting valuable human life against potentially-harmful chemicals, military chemical agents and biological agents, or during situations of a natural catastrophe or disaster, radiation health risk, and/or urban terrorism, have resulted in changes in approach when designing and evaluating individual components of a clothing system. Protective clothes are used in order to protect valuable human life from those various hazards and climatic conditions encountered by the wearer. A clothing system, as a dynamic component, is supposed to be designed by having in mind the requirements and expectations of the end-users, based on two critical questions, namely: What is the chemical (or biological, radiation health risk, or fire-fighting) challenge? What is the work scenario or the application? In terms of the actual usage conditions and work environment, several questions must be answered in order to design the appropriate development methodology and technology for protective clothing and/or clothing systems, according to the requirements of the Personal Protective Equipment Directive (Directive 89/686/EEC), in accordance with harmonised European and International standards [2-16]. The Personal Protective Equipment (PPE) covered by this directive is divided into 3 categories:

Category I – 'Simple' design Personal Protective Equipment – covering

exclusively PPE intended to protect the wearer against: mechanical action whose effects are superficial, cleaning materials of weak action and easily reversible effects, risks encountered in the handling of hot components which do not expose the user to a temperature exceeding 50 degrees C, or to dangerous impacts, atmospheric agents of a neither exceptional nor extreme nature, minor impacts and vibrations etc. which do not affect vital areas of the body and whose effects cannot cause irreversible lesions, and sunlight.

Category II – 'Intermediate' design Personal Protective Equipment – PPE which is neither simple nor complex, e.g. cycle helmets, high visibility clothing.

Category III – 'Complex' design Personal Protective Equipment – intended to protect against mortal danger, or against dangers that may seriously and irreversibly harm the health of an individual, the immediate effects of which cannot be identified in sufficient time as covering exclusively:

- filtering respiratory devices for protection against solid and liquid aerosols or irritant, dangerous, toxic or radio-toxic gases;
- respiratory protection devices providing full insulation from the atmosphere, including those for use in diving;
- PPE providing only limited protection against chemical attack or against ionising radiation;
- emergency equipment for use in high-temperature environments, the effects of which are comparable to those of an air temperature of 100 degrees C or more and which may or may not be characterised by the presence of infra-red radiation, flames or the projection of large amounts of molten material
- emergency equipment for use in low-temperature environments, the effects of which are comparable to those of an air temperature of -50 °C or less;
- PPE to protect against falls from a height;
- PPE to protect against electrical risks and dangerous voltages or that used as insulation in high-tension work.

The flowchart for the particular categories of Personal Protective Equipment according to the Directive 89/686/EEC is shown in Fig.1.

Considering to the consequence of issues in this work will be presents peculiarities of a complex design concept for functional protective clothing, where design criteria for functional protective clothing must be unequivocal specified; for example protection from chemicals is achieved by blocking their penetration and permeation through the fabrics of the clothing [4-6, 10, 11, 17]. This is an effective method for providing sufficient protection; however, total blockage of the penetration and permeation also affects the transport of any heat and moisture generated by the wearer of the protective clothing, and results in possible heat-stress. It witnesses the complexity of designing protective clothing and asks for even higher requirements when designing this type of protective clothing, both from the point of view of protection and comfort, and from that of functionality.

2. Designing functional protective clothing

Designing protective clothing as an integral part of personal protective equipment (PPE) is an extremely complex task. Protective clothing must be so designed and manufactured by foreseeing those conditions of use for which it is intended so that the user can perform the risk-related activities normally whilst still enjoying, at

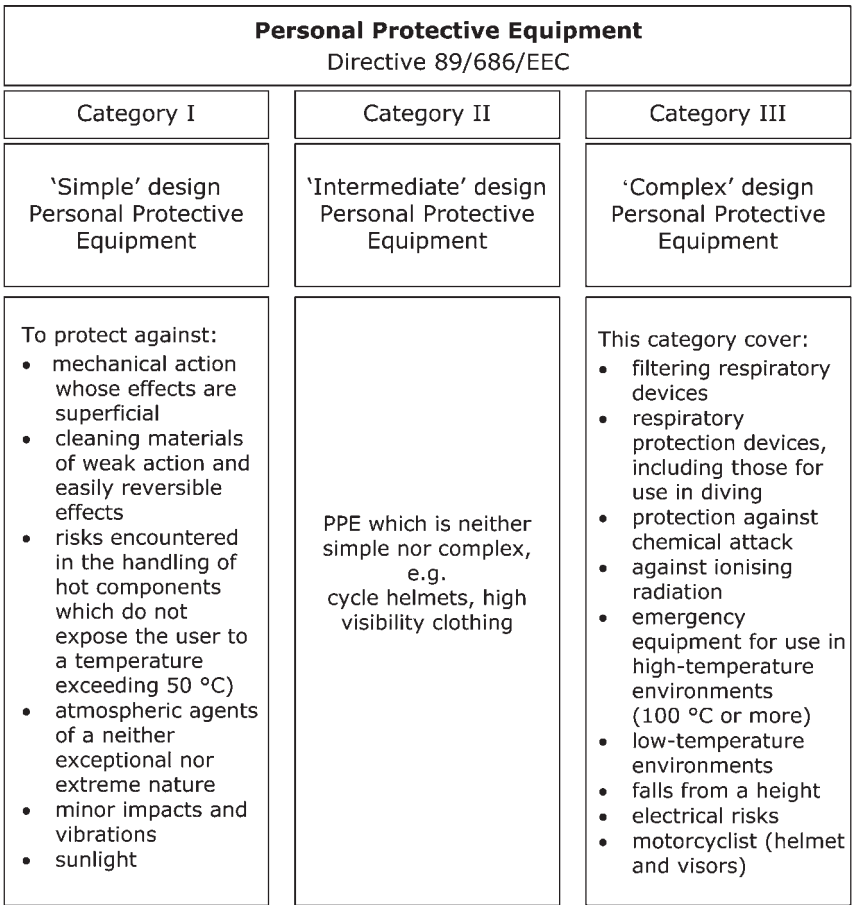

Fig.1 Categories of Personal Protective Equipment according to the Directive 89/686/EEC

the same time, appropriate protection at the highest possible level. Protective clothing should be designed and manufactured so as to facilitate correct positioning for the user whilst remaining in place for the foreseeable period of use, bearing in mind ambient factors, the movements to be made, and the postures to be adopted [1, 2]. For this purpose, it is necessary to enable optimisation of personal protective equipment and its adaptation to user morphology, by all appropriate means, such as an adequate adjustment and attachment system, or the provision of an adequate size-range.

Additionally, a contemporary engineering approach within the area of protective clothing development offers the opportunity of developing functional protective clothing, by incorporating so-called intelligent components. Modern technical developments are, in this way, used in enhancing the functionalities of protective clothing systems - by providing intelligent functions to this type of clothing. Functional protective clothing provides a special functionality for the wearer, such as assistance when monitoring and evaluating those potential hazards encountered by the user, such that conventional protective clothing could not. Functional protective clothing with intelligent characteristics is also considered to be an object of interdisciplinary research, covering different disciplines. The multi-disciplinary nature of functional protective clothing with intelligent characteristics necessitates the integration of protection research, material science, clothing engineering, comfort, functionality, whilst including the objectives of the environment and communication, as illustrated in Fig.2.

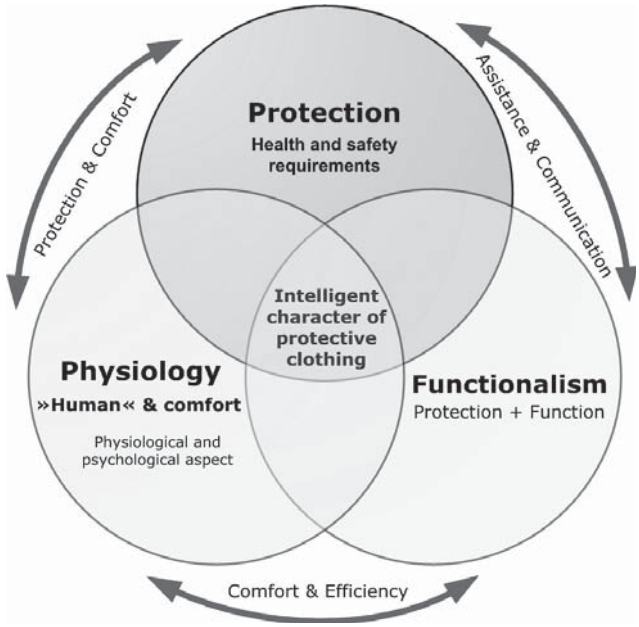

Fig.2 Multidisciplinary approach to functional protective clothing

2.1. Engineering requirements in designing

The above clearly indicates that the successful product-development of a personal protection system against hazardous, resp. functional protective clothing is only possible when researchers integrate into a multidisciplinary research team. The functional protective clothing development process follows the new product development process, in general, but only partly.

According to the Directive 89/686/EEC [1] and pertaining standards, protective clothing must provide, apart from those specific additional requirements which they must satisfy in order to provide adequate protection against all the risks encountered, adequate technical functionality with intelligent characteristics, as well as the necessary level of comfort. Comfort includes the physiological and psychological aspects on one hand, and the mechanical and ergonomic aspects on the other. More attention needs to be focused on understanding ergonomic issues, heat stress implications, and the relationship between the task and the clothing used. The degree of thermophysiological comfort when wearing, is defined by the thermophysiological properties of the built-in fabrics, resp. fabric layers, as well as the particular degree of mechanical and ergonomic comfort. The last two are a result of the mechanical parameters of the fabric used, adequate design, and optimal garment construction [18-21]. Improved fit and comfort are necessary to help ensure proper and consistent use at all times.

This means, from the engineering point of view, that the clothing is supposed to be ergonomically-designed, in accordance with the dynamic anthropometric conditions of use, whilst wearing-comfort and a high-degree of free movement are necessary when performing the required activities and tasks. The clothing should be designed so as to bear in mind all the possible conditions of usage, for example, carrying tools, breathing devices, sensor and actuator systems etc.

The requirements to be fulfilled during the development of those personal-protection systems to be used against hazards, should result in optimal protective clothing, whilst the selected process needs to be unambiguously defined.

3. Grounded model development

The research model defines the progression from initial product design goals, i.e. problem recognition through the idea development in view of technical solution to the developed

product – prototype and wear test, and finally, to evaluation of the final solution and implementation of the functional protective clothing, and certification procedures. A successful design should include the following steps in order to identify basic requirements resp. user-needs and the development a product that meets the identified needs:

a) problem recognition,
b) problem definition,
c) objective set-up
   - defining the level of protection, and
   - defining the additional functions - intelligent character of protective clothing,
d) idea development / technical solution
   - the choice of materials and acceptability of materials when developing protective clothing
   - defining a method for assessing protective performance (for example: chemical and/or biological resistance, flame-retardant, thermal resistance, water vapour resistance, etc.),
   - defining the physical and mechanical properties, and the special requirements of the protective materials,
   - defining thermo-physiological requirements for the protective materials, and
   - defining adequate components, such as sensors and actuators, completed using a processing unit (data processing), storage, transmission and communication functions, that will be integrated in to the protective clothing,
e) clothing-selection guidelines, including:
   - design specifications,
   - prototype construction,
   - design refinement and
   - prototype development,
f) evaluation / modification / selection of the prototype,
g) checking the ergonomic features of protective functional clothing,
- wear test / industrial evaluation,

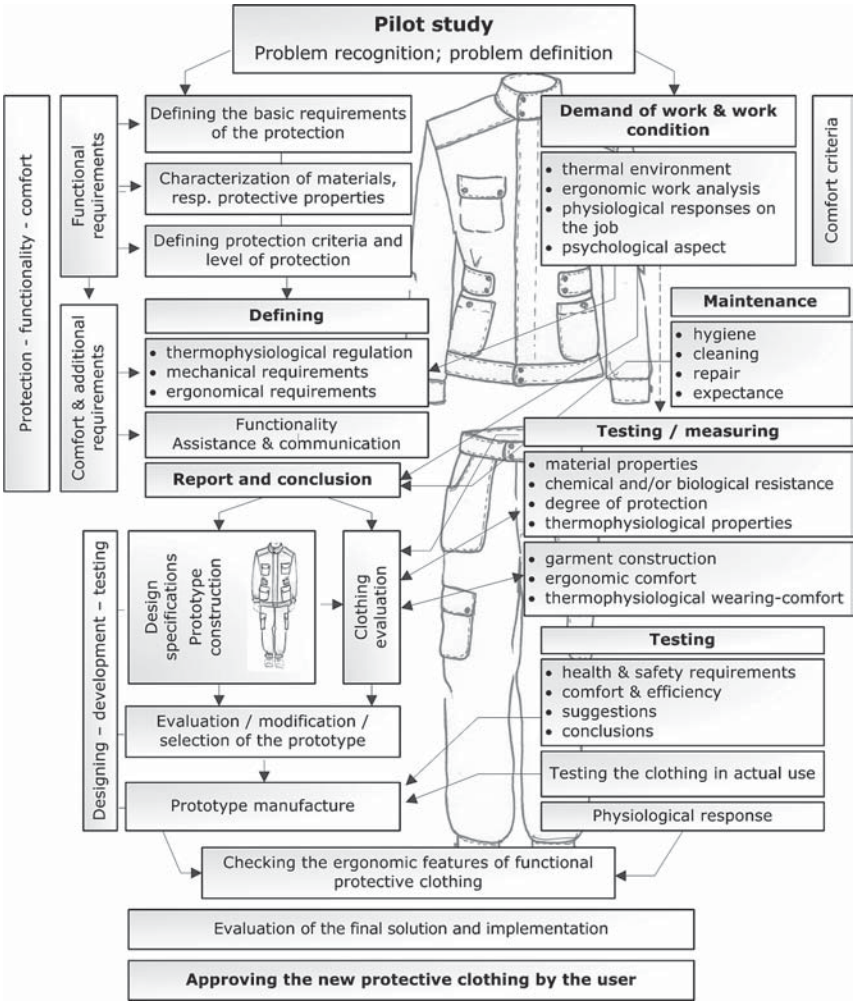

Fig.3 Systems approach to the design, development, and implementation of a functional protective clothing system

h) evaluation of the final solution and implementation of the functional protective clothing, and
i) certification procedures according to the Directive 89/686/EEC.

From the point of view of virtual-usage conditions or work environment, various questions concerning the nature (chemical / biological / radiation health risk / firefighting, etc.) of the challenge and the work scenario must be answered in order to select adequate kinds of materials, as well as appropriate types and styles of garments. Having the exact answers to these questions, protective clothing resp. clothing system that can be combined with appropriate material - fabric selection and a seam-type based the protective characteristics of the hazard itself. Protective materials should have primary protective properties such as being puncture-resistant, flame-retardant, chemically-resistant, biologically-resistant, or nuclear-resistant materials, and any required combination of these properties [4, 6, 9-12, 14-17, 21-24]. In addition to the development of new materials, focus has shifted to those factors that affect the end-user. A new generation of lightweight chemical and biological protective materials is based on selectively permeable membrane technology, which means that the cell membrane has some control over what can cross it, so that only certain molecules can either enter or leave the cell. These novel materials provide protection against highly-toxic compounds, including offensive chemical and biological agents [25-

27]. It is important to note that no single material protects against all chemicals, and that no material is totally impermeable. The selection of clothing material that offers the best protection against a particular chemical must be based on the chemical's resistance performance upon contact with the chemical [17, 26].

Apart from the above-mentioned demands, it is also necessary to mention that underwear should play a major part in a system of layered protection and if this is to be used in the protective system, it must be appropriate to the aim that is intended.

The technological resp. electronic components, whilst ever-decreasing in dimension and weight, are generally relatively stiff and solid. L. E. Dunne [28] proposes careful distribution of these solid elements over the body's surface, as this can reduce their perceptibility and discomfort. F. Gemperle et al. [29] address this issue by determining optimal shapes and body localisation for wearable technology.

Moreover, special attention needs to focus on ergonomic issues and human subject. Human subject tests for comfort, physiological load, cold or heat protection, ergonomical design, fit, loos of performance, rain/moisture protection and conspicuity/visibility of the clothing must be also defined and described. Human subject tests for comfort, ergonomic design, loss of performance and rain/moisture protection are described and proposed for evaluation of protective clothing in general by G. Havenith and R. Heus [30].

It is obvious that these complex requirements should be met when designing protective clothing, from the point of material characterisation, design, seam performance, quality and standards. All of them are supposed to ensure the highest-efficiency of protective clothing during its end-use. The protective clothing as part of personal protective equipment should be designed so that, for example, boots, helmets, groves and breathing

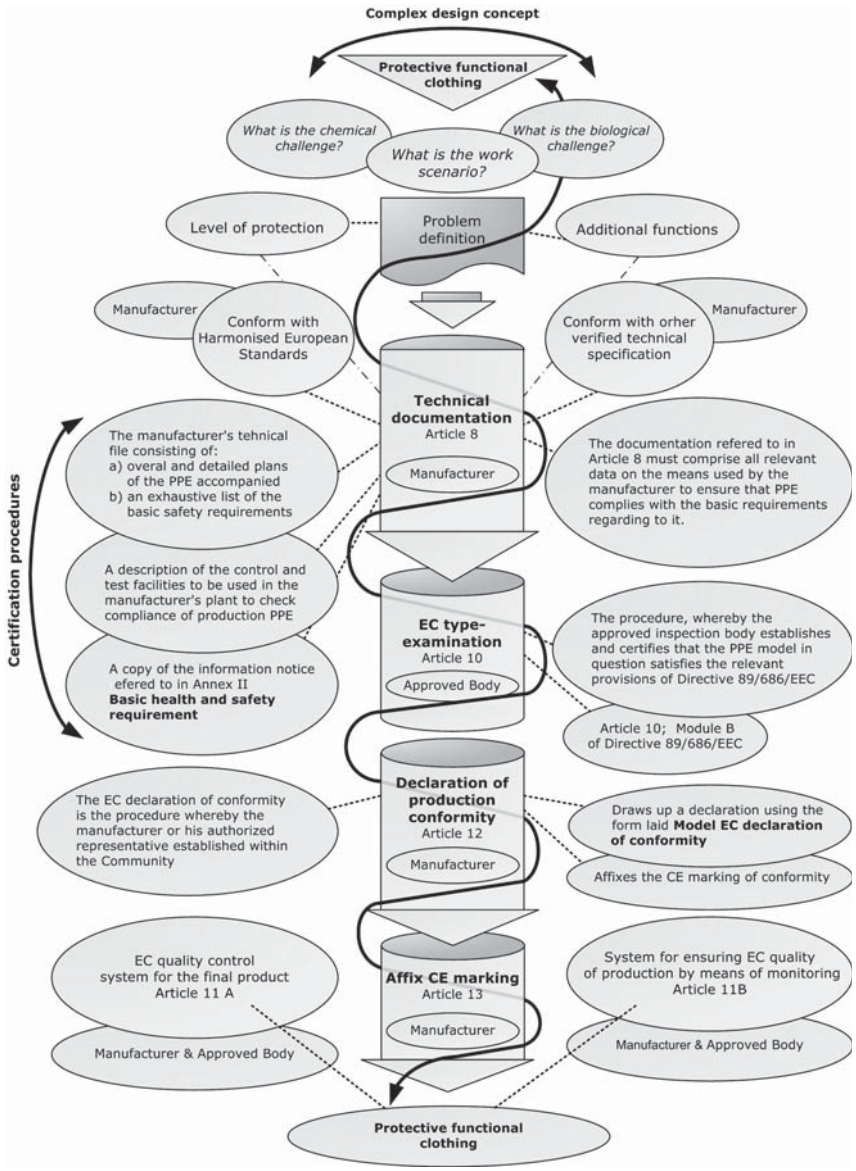

Fig.4 Flowchart for the complex design concept of functional protective clothing according to the Directive 89/686/EEC

apparatus have the potential to be compatible with the clothing by ensuring that cuffs, collars, trouser bottoms are designed to allow these other items to be donned and to interface realistically. Following accepted standards is a key factor when designing a protective clothing that satisfies the needs of the end-user. The standards deal with:

- those requirements concerning necessary material properties and finished protective clothing characteristics, as regarding the intended usage, and all the possible conditions encountered in the case of an accident,
- those methods of testing and evaluating clothing protective properties, and
- the manner of marking the individual fields of a protective clothing, the manner of marking garment sizing-systems, CE conformity marking, etc.

Design criteria for protective clothing must be specified so that it can be unambiguously as either a 'suitable' or 'fail', and can be expressed as guidance for manufacturers. In the case that these criteria cannot be expressed

as guidance for manufacturers, these are outside of the certification body's responsibility, for example, closure systems shall be constructed so as to fulfil the performance requirements of the garment.

The research model as overall system of approaching the design, development, and implementation of functional protective clothing, is shown in Fig.3. A fundamental expectation that resulted in this work is the treatment of a manifest protective clothing as a bunch of various dimensions of complex design value of functional protective clothing, a concept that is central to the model.

This design concept focuses on product-development issues by considering the objective characterisations of the materials, taking into account verified technical specifications, the development of new methods and techniques for the manufacture of multifunctional protective clothing, and includes the integration of health and safety requirements, physiology, resp. human comfort, as well as functionality. The intelligent character of functional protective clothing is based on intersectional health and safety requirements, human comfort and functionality (protection and function), and focuses on the monitoring and evaluating of those potential hazards to be encountered by the user.

The degree of technological integration within a functional protective clothing system depends on its type of intelligent character - its functions. All contemporary protective clothing needs additional equipment for measuring and processing.

The complex design concept for the multi-disciplinary development nature of the functional protective clothing according to the Directive 89/686/EEC [1] relates to the integration of health and safety requirements during research, physiology, ergonomy, as well as appropriate developments in the methodology and technology of protective clothing, together with the appropriate standards and other verified technical specification, as illustrated by the flowchart in Fig.4. This research has used an extensive grounded model-building process to development a model of the elements of complex design concept for functional protective clothing.

4. Conclusion

This contribution presents the peculiarities of a complex design concept for functional protective clothing, as an important component of personal protective equipment, together with a systematic approach to the design, development, and implementation of a functional protective clothing system, with a flowchart of a complex design concept, according to the Directive 89/686/EEC. The research core focus in the grounded model development as the progression from initial product design goals, i.e. problem recognition through the idea development in view of technical solution to the developed product - prototype and wear test, and finally, to evaluation of the final solution and implementation of the functional protective clothing, and certification procedures.

This idea can be transformed into reality through functional protective clothing as a product development process. Previously suggested models go through several steps from problem recognition, problem definition, idea generation, design, prototype development, evaluation of the final solution, and implementation of functional protective clothing, to certification procedures according to the Directive 89/686/EEC.

The aim is to find solution to avoid overprotection by developing protective clothing systems that adjust the protection level according to the current level of the hazard in question. In this way it is possible to decrease physiological stress of user in the work environment. Namely, work safety is an important part of safety culture, and it is part of the effective quality system in the work environment.

Future work will focus on multifunctional protective clothing development by considering the objective characterisation of materials, taking into account verified technical specifications, the development of new methods and techniques for the manufacture of multifunctional protective clothing, including adequate technical functions and their intelligent character, as well as the necessary level of comfort.

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