

# Process Qualification of the Individualization of Protective Clothing Design Based on 3D Scanning Technique

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## Abstract

*The process of individualizing personal protective equipment (PPE) is aimed at achieving optimal fit to the user's body, thus maximizing comfort, especially when PPE is applied in critical conditions. The aim of the research was to confirm the possibility of implementing PPE in real industrial conditions and to estimate the comfort of use in real conditions of use. In order to perform the last stage of the personalization procedure for firefighter suits, process qualification was carried out in an industrial environment, and the firefighter's PPE fabricated was validated under real conditions of firefighters' activities. The effect of implementation of the individualization procedure confirmed optimal fitting of the PPE to the individual user's body and allowed for improvement of the comfort of use.*

**Key words:** protective clothing, design, customization, personalization, 3D scanner, validation, process qualification.

## ■ Introduction

There is a constant search for high-quality products and services for clothing manufacturers at reduced production costs, and interest in improving 3D scanning methods used by clothing manufacturers and users, both in terms of a wide range of anthropometric measurements as well as individualization of the design of clothing products, is constantly growing. Optimal fitting of personal protection equipment (PPE) to the user's body is the most important aspect allowing for improvement of the effectiveness of user protection in typical activities in the working environment. Several methods have been applied to increase the comfort of PPE, including personalization performed using a wide range of techniques. A promising technique that has enhanced the range of application is 3D scanning, which improves the personalization process and helps to obtain reproducible results of the aforementioned process.

The need to implement a procedure to improve the process of making protective clothing by reducing the time significantly is the most important problem in the area of PPE personalization. Moreover, the application of 3D scanners brings a number of benefits, including quick and precise contactless measurement. Precise measurement reduces the risk of errors occurring in traditional measurements.

Validation of the technology is most often focused on two areas: fabrication of a product in a real industrial environment and comprehensive verification (valida-

tion) of the product under real conditions of use. The results of validation confirm whether all processes and procedures, equipment, materials, operations and the organizational system ensure the production and repeatability of a product of the required quality.

During earlier research, installation (IQ) and operational qualifications (OQ) were performed [1, 2, 5].

The research carried out during IQ developed preliminary assumptions for the individualization of an advanced protective clothing design for a group of people working in a high-risk environment: firefighters. The preliminary assumptions developed were verified by analyzing the risks and conditions of use of the selected special clothing in the area of typical activity [1, 2]. During OQ, one batch of 12 pieces of the individualized two-piece special clothes was made based on the individualization procedure using a 3D scanner [2]. Additionally, a reference batch was made using the standard product range of the selected manufacturer. The clothes were made of aramid fabric with GORE membrane (PTFE), taking into account the reflective and fluorescent tape system in accordance with the domestic regulation [3]. Surveys from the test, providing user feedback from real conditions of use, resulted in a significant reduction in "inaccurate fit" responses in the group of the individualized PPE [5].

The general aim of the study was to achieve improvement of the comfort of

the firefighter through implementation of the personalization procedure for PPE (special suits). The hypothesis defined focused on the possibility of implementing and performing the personalization procedure elaborated in industrial conditions, resulting in significant improvement of firefighters' comfort.

The hypothesis defined focused on the possibility of implementing and carrying out the personalization procedure developed in an industrial environment, which would allow for significant improvement of the comfort and safety of firefighters. This objective was achieved by the last stage of validation (process qualification) in industrial conditions of the prototype protective clothing batch for a group of people working in an environment posing a high risk to health and life, individualized on the basis of the 3D scanning technique.

## ■ Materials

Three-piece clothing for firefighters (consisting of a heavy jacket and trousers as well as a light jacket), including two-piece clothing meeting the requirements of PN-EN 469:2008 (heavy jacket and trousers) and, additionally, a lightweight jacket that meets the requirements of PN-EN 15614:2009 for individualization of the design of clothes, was selected for the performance of validation (process qualification; PQ) in industrial conditions. The individualization procedure (IP) developed was validated in real industrial conditions in another industrial plant, as described in [5].

The most important asset of heavy clothes is the outer fabric, manufactured with the involvement of high-strength PBI fibrefibres (PBI Performance/USA). The individualized clothing is marked with perforated tapes 50 and 75 mm wide. The personalized PPE fulfilled the requirement of Order No. 9 of the Polish Chief Commandant of the State Fire Service [3]. Additionally, the individualized clothing complies with the CE certificate. Clothes fabricated in PQ were tested for dimensional functional assessment at the work stations of fire brigade officers in Lodz/Poland.

Figures 1-3 show the individualized clothing.

## Methods

### Individualization procedure (IP)

The individualization procedure (IP) of the design of advanced protective clothing for people working in a highly health- and life-threatening environment was described in [2, 5]. 6 firefighters participated in 3D scan processing in an industrial environment.

### Questionnaire

Analysis of the individualization procedure's effectiveness was carried out via a MORATEX questionnaire portal (<http://www.ankietamundurowi.pl/>) according to the questionnaire described in [2] after 5 months of use in real conditions of firefighters' work.

### Process qualification (PQ)

The aim of PQ was to demonstrate IP repeatability and compliance with the requirements of installation and operational qualifications (IQ and OQ) [2] and with quality criteria for individualized PPE made by another manufacturer but differing in design from those tested in OQ [2].

The data collected during the implementation of PQ should verify that the IP is reproducible and in accordance with the accompanying, verified documentation.

Individualized, three-piece, multi-layered clothes for 6 firefighters were designed based on the IP and standard manufacturing procedures of the industrial plant where validation took place.

In order to protect the personal data of persons involved in measurements using



Figure 1. Front view of individualized clothing resulting from PQ (heavy jacket and trousers).



Figure 2. Rear view of individualized clothing resulting from PQ (heavy jacket and trousers).



Figure 3. Front view of individualized light jacket resulting from PQ.



Figure 4. Rear view of individualized light jacket resulting from PQ.

the Body Scanner 3D (Human Silhouette Scanner Vitus XXL/Human-Solutions/USA) and to protect information stored on computers, the procedure for securing personal data was implemented, as described in [2]. The procedure contains the requirements for user data protection with respect to records of participants in measurements, for securing measurement data stored on computers, as well as for defining system administrators.

The individualized prototype clothing batch made over the course of PQ was classified for use in real-world conditions.

The assessment of size functionality in performance studies was carried out in 3 steps by:

1. the transfer of individualized clothes for commercial tests with an assessment of the fitting of the clothes to the user's silhouette, carried out in the presence of the clothing manufacturer – the positive result of which is confirmed by the handover certificate;
2. carrying out, in the course of ongoing commercial tests, an assessment of size functionality, documented by photographs (preliminary functional tests);

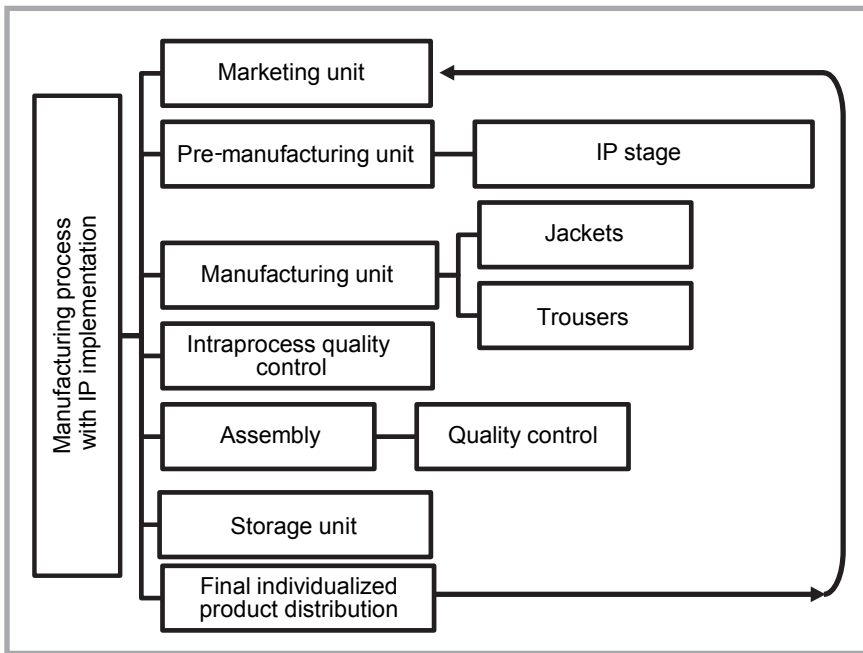


Figure 5. PQ of clothing individualization with implementation of IP.

3. development of an assessment of size functionality (during the performance test) based on surveys completed by users through an existing survey portal of the Institute.

## Results and discussion

### 3D scanning results

Individualized PPE were made in accordance with the IP. Data of the persons involved in the studies were adequately secured in accordance with the personal data protection policy. On the basis of the measurements carried out and design templates prepared, a batch of the selected type of three-piece protective clothing was made for the selected, individualized group of users.

The subject of the research, the location of the research area, and the controller of personal data authorized to perform pseudonymization of the test group's per-

sonal data were selected. The test group was distinguished with respect to the GDPR [8] personal data protection procedure and ethical considerations. Measurement by 3D laser scanning of the human figure was performed for each of the 6 firefighters individually. The results of 3D measurements were implemented to develop clothing templates for the sizes of individual scanned silhouettes.

For the design of individualized jackets, the following measurements were performed: height, chest circumference, hip circumference, back width on the shoulder line, length of back to waist, sleeve length, and arm circumference at the biceps, whereas for the design of individualized trousers: the height, belt circumference, hip circumference, thigh circumference, the height from the waist to the ground (leg length on the side), and the length from the step to the ground (leg length after step) were taken.

All people scanned were given the same outfits, consisting of a balaclava designed to obscure facial features, t-shirt and leggings, and informed how they could put on a balaclava so that not even the eyes can be seen. Firefighters from the test group moved in small, several-person groups to the changing room located in close proximity to the scan point. While moving to the scan point, officers were assured of discretion – any movement of those not involved in the process was excluded from the space. Just before the scan process itself, there was a reminder of the device's training material, and how to measure and set the position using the 3D scanner.

Then a prototype batch of clothes was made as part of PQ, each set of which was adapted to the individual sizes of the 6 scanned people in the test group. The number of individualized clothes fabricated was determined by analysis of documents containing the capacity of the fire truck, given as 3-6 people [7], and the number of fire trucks leaving at one time for an event: 1-3 [6].

Table 1 contains the results of the 6 firefighters' scans for the IP of the clothing design containing three pieces: a heavy jacket and trousers as well as a light jacket. The completed, individual 6 scans were transferred to the selected manufacturer (other than the one that participated in the operational qualification) [2] where PQ took place. Six IP clothes adapted to the individual dimensions of the 3D-scanned officers were fabricated.

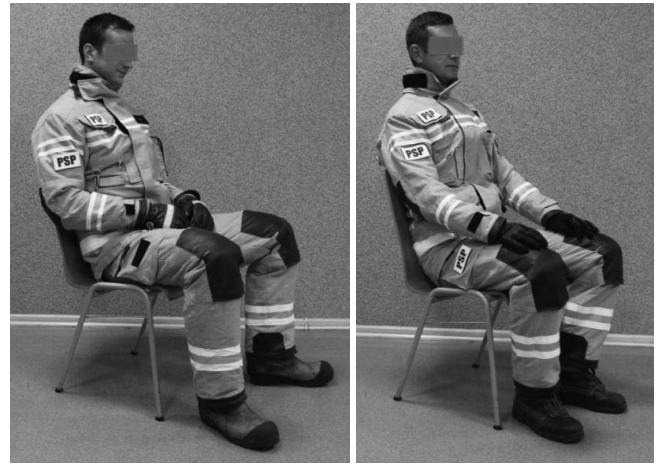
In order to improve the real conditions of manufacturing of the three-piece, multi-layer clothes individualized to the user's silhouette, the process of making clothes was divided into two stages: the production of jackets (light and heavy) and the production of trousers (heavy) (Figure 5).

Table 1. Scan results [cm] of silhouettes of the 3D-scanned persons.

User code	Height	Chest circumference	Waist circumference	Hip circumference	Back width on shoulder lines	Length to waist	Length from crotch to ground (leg length to crotch)	Length from waist to ground (leg length to hip)	Sleeve length	Thigh circumference	Arm circumference at bicep
KM501	193.7	111.5	93.6	109.9	42.7	70.3	76.6	111.0	64.5	L63.4 R61.6	L36.8 R35.6
KM502	187.5	93.5	87.7	105.3	34.8	67.3	75.5	109.9	62.2	58.8	L30.3 R29.7
KM503	182.4	105.7	99.6	110.5	39.1	60.5	74.0	109.9	64.5	L64.6 R63.9	35.4
KM504	175.2	127.9	105.5	113.0	46.8	63.3	67.5	109.9	68.7	L63.8 R65.2	L35.4 R36.5
KM505	186.6	113.1	92.0	103.4	44.3	64.1	74.5	109.9	L66.5 R67.9	L59.4 R59.9	L33.6 R35.1
KM507	175.7	98.5	85.6	98.3	38.4	62.0	69.0	109.9	62.8	L53.9 R54.9	L26.1 R35.1



*Figure 6. Fitting of clothes during standing activities.*



*Figure 7. Fitting of clothes during seating activities.*



*Figure 8. Fitting of clothes during walking activities.*



*Figure 9. Fitting of clothes during kneeling activities.*



*Figure 10. Fitting of clothes during crawling activities.*



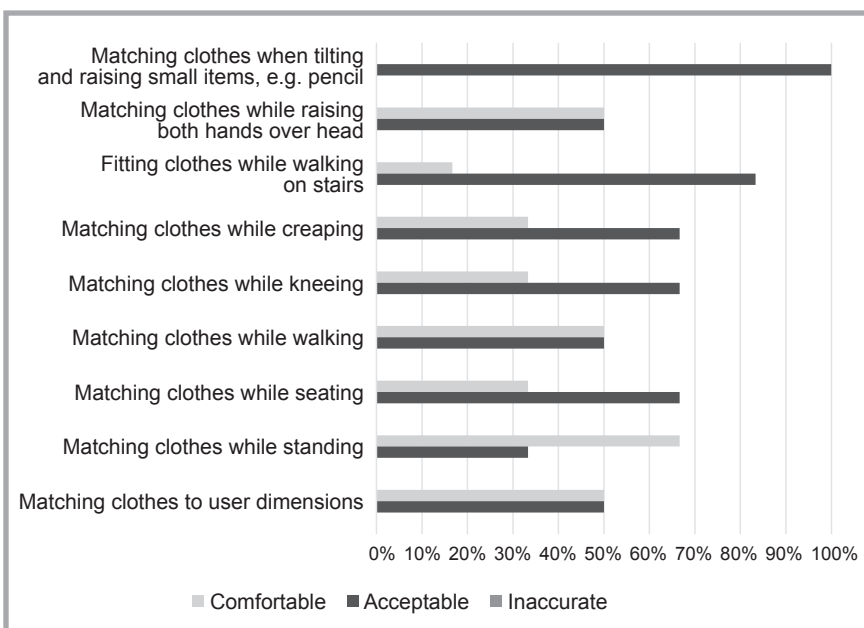
*Figure 11. Fitting of clothes while climbing stairs.*



**Figure 12.** Fitting of clothes while raising both hands above the head.



**Figure 13.** Fitting of clothes when performing the activities of leaning and lifting small objects.



**Figure 14.** Results of the performance test of clothing (heavy jacket and trousers) under real conditions of use.

### Preliminary functional tests

For the batch of individualized, special clothes designed consisting of three pieces, a preliminary assessment of size functionality was carried out by checking the following : 1) fitting of clothes to the user's dimensions; 2) adjustment of clothes at the time of performing actions (**Figures 6-13**).

The preliminary tests performed showed positive fitting of the individualized firefighter's three-piece clothing to individual firefighters. The acceptance of the preliminary test allowed for starting the performance test in real conditions of the firefighters' activities.

### Performance test

The performance of the individualized, three-piece set for firefighters was assessed by users in a survey after 5 months of the clothes' use under real working conditions.

**Figures 14-17** present the test results of the performance of IP fabricated three-piece clothing for firefighters during PQ.

The implementation of IP in the production of firefighter's clothing resulted in a significant increase in comfort assessment by the user when the individualized PPE was applied in standard activities. The absence of inaccurate ratings for the whole system, consisting of a heavy jacket and trousers supported by a light jacket, was indicated after 5 months of the performance test (**Figure 14**). An acceptable rating of comfort assessment was found for the criterion of fitting clothes when leaning over and raising small items (100% positive answers), whereas the criterion of fitting clothes while standing was positively rated by approx. 70% users giving a comfortable rating. A comfortable rating was more prevalent when the individualized PPE was assessed in a static position.

The assessment of the heavy jacket yielded approx. 17% negative ratings for the fit to the circumference on the hip line (**Figure 15**). However, a comfortable rating was predominant in the assessment of the jacket (67-85% positive answers), whereas an acceptable rating ranged from 17% to 33%.

The same phenomenon was found in the assessment of the heavy trousers' fit to the hip circumference line, where 17% negative assessments were observed (**Fi-**

gure 16). There were 17-67% acceptable ratings, and 33-83% comfortable ratings.

A single negative rating (17%) of the fit to the hip circumference line was found in the verification of the light jacket's comfort (Figure 17). The predominance of a comfortable rating in the fitting of the sleeve width criterion in comparison with the acceptable rating was also observed. The other criteria showed an equilibrium between the comfortable and acceptable assessment.

The comfort assessment of the individualized PPE consisting of three-piece individualized clothing for firefighters resulted in the predominance of the comfortable and acceptable ratings, showing the advantage of the individualization procedure's implementation over the standard design of PPE. The type of PPE selected for individualization was the most critical, taking into the account aspects of the design as well as the safety required, being the worst case of the PPE used by firefighters from the perspective of ergonomic features. Thus, the predominance of the comfortable assessment over the acceptable assessment resulting from the static evaluation is understandable due to the complexity of the design as well as the necessity to fulfill safety requirements.

The results of the operational qualification of the models of individualized PPE published in [5] were confirmed after the implementation of the IP in another industrial plant.

## Conclusions

The results of the last stage of IP validation (process qualification) under real conditions of manufacturing and of firefighters' activities confirms the possibility of obtaining comfortable PPE even when IP implementation was performed in various industrial plants and with a change of the PPE's design.

The repetition of the IP in another plant and using other firefighters as compared with the operational qualification performed (OQ) [2,5] showed repeatability of the comfort assessment and validated the fitting of the firefighters' multi-piece clothing batches.

The individualized clothing fabricated was validated in terms of performance and fitting under real conditions of typical firefighter activities during five

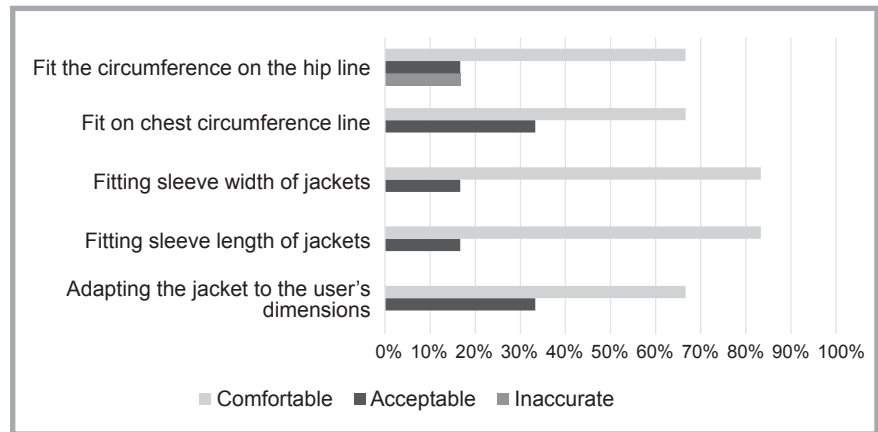


Figure 15. Results of the performance tests of heavy jackets under real conditions of use.

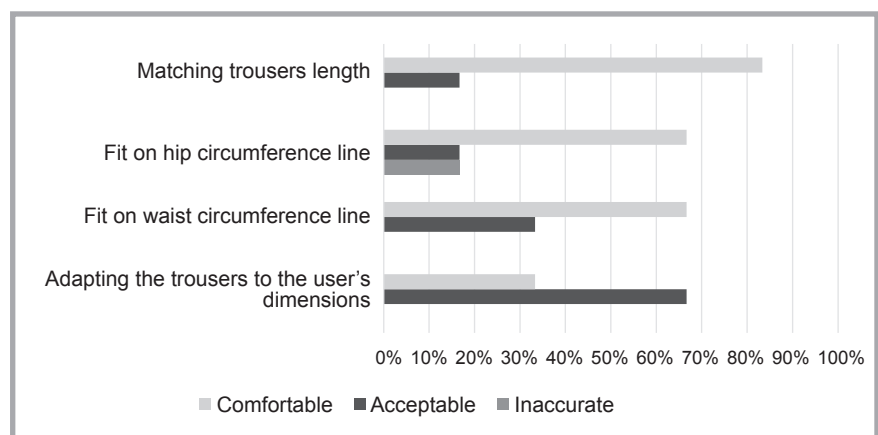


Figure 16. Results of the performance test of heavy trousers under real conditions of use.

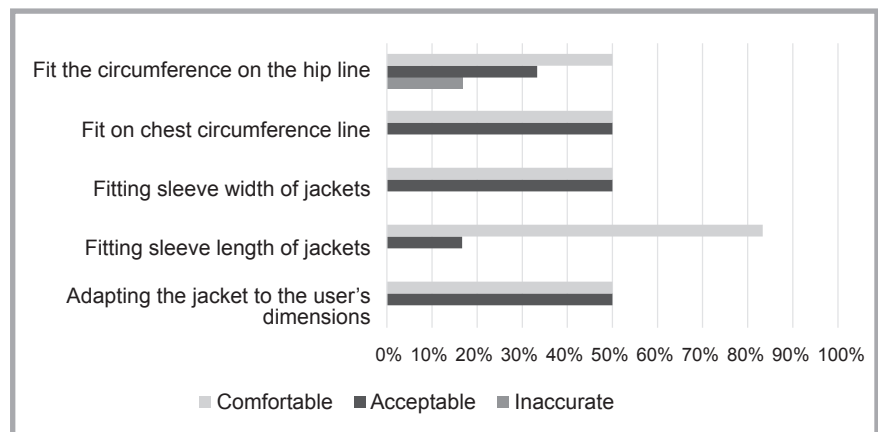


Figure 17. Results of the performance test of the light jacket under real conditions of use.

months of use and assessed according to strictly defined fitting criteria.

The IP of the advanced PPE for users working in environments posing a high risk to life and health was validated during the performance test and showed that significant comfort is the most important feature in the effective performance of a firefighter's tasks.

## Acknowledgements

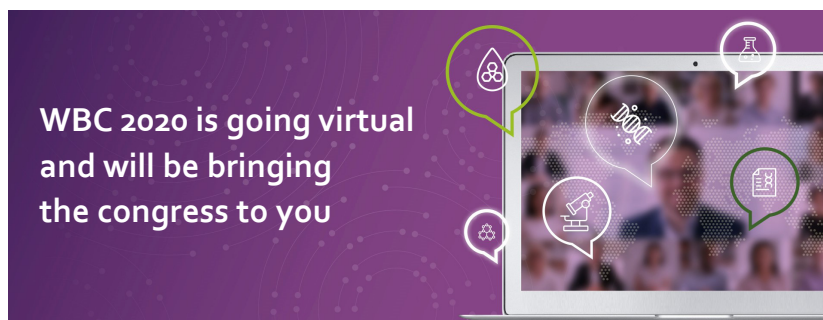
The research were carried out within the framework of project No. III.N.1 "Individualization of advanced protective clothing for people working in environments with a high risk of life and health", acronym AWATAR, carried out within the framework of the fourth stage of the Multi-annual Program "Improvement of safety and working conditions", supported in 2017-2019 in the field of scientific research and development works

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