MINISTRY OF EDUCATION
National University for Science and Technology POLITEHNICA Bucharest
Doctoral School of Industrial Engineering and Robotics

Ing. Daniel Onuț N. BADEA

DOCTORAL THESIS

Optimizing the design and testing of personal protective equipment

Doctoral advisor,
Professor Oana-Roxana CHIVU PhD Engineer

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Ing. Daniel Onuț N. BADEA

SUMMARY
DOCTORAL THESIS

Optimizing the design and testing of personal protective equipment

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Doctoral advisor	Professor Oana-Roxana CHIVU PhD Engineer	National University for Science and Technology POLITECHNIC Bucharest
Reviewer	Professor Dan Florin NIȚOI PhD Engineer	National University for Science and Technology POLITECHNIC Bucharest
Reviewer	Professor Lucian–Ionel CIOCA PhD Engineer	“Lucian Blaga” University of Sibiu
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- 2023 –

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Foreword

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Daniel Onut Badea

Introduction

Context

Currently, the digitalization and automation of the economic landscape in Romania and beyond has determined an increased level of security in the work environment, although there are still many occupations that require continuous protection of workers, especially in countries where traditional methods of thing are still prevalent. Changes in the economic situation have brought about changes in the nature of hazards in the work environment and new risks have appeared that were not known before (emerging risks) due to new methods, substances and materials used, work practices (work customs) and climate change.

When work environments change, workers can be negatively affected psychologically, physically or socially. With increased exposure to a variety of safety and health risks, as well as increased vulnerability and inability to adapt to them, the risk of injury to a worker is amplified and can influence their behavior at work and beyond.

Theoretical framework of the research

The theoretical framework outlined in Figure I.5 supports this research approach.

Figure I.5 Conceptual research framework

Research topic

The intention of this research, which is the subject of the doctoral thesis, is to incorporate the concept of occupational safety and health management into the general management system, with the two components: ensuring the safety of workers through the use of protective equipment in the work process and ensuring safety at the workplace of work, by providing workers with protective equipment appropriate to the risks they are exposed to in the work environment. The goal is to form a unitary ensemble. Thus, research is necessary to reduce uncertainty and discrepancies regarding current and future working conditions in Romania. The research will give policymakers a better understanding of how to make evidence-based decisions that support worker safety and health.

Significance and rationale of the research

Evaluation of the protective properties of textile materials is imperative for the continued advancement of protective clothing. Workers and manufacturers rely on research to generate reliable data sets, guaranteeing that textiles meet their intended purpose without compromising their protective properties, even after repeated washes. This ensures that users can work safely. To achieve this goal, this study will investigate how different protective fabrics used in the clothing of workers in high-risk sectors (such as firefighting and welding) behave under various thermal exposures, perspiration, and washing. Testing of samples will be conducted in both wet and dry conditions, both before and after washing. Laboratory tests will assess various factors such as tensile strength, tear strength, seam strength, permeability, and the behavior of materials under radiant heat, including their response to radiant heat exposure.

Basic logic of the research process and thesis structure

The content of the doctoral thesis is structured in 9 chapters and includes a number of 140 pages dedicated to the scientific study and bibliographic references. This research begins with an Introduction that outlines the research context, scope, purpose, research flow and the structure of the PhD thesis, providing the foundation of the study.

Chapter 1, entitled Literature Review, analyzes current research in the field and reviews existing studies. This summary of research conducted on the protective properties of fabrics used in the manufacture of PPE demonstrates that, at this time, knowledge and information is neither comprehensive nor up-to-date. The identification of data and knowledge gaps is the basis of this research study.

Chapter 2, The role and importance of personal protective equipment in the prevention of accidents and occupational diseases, explores the importance of personal protective equipment in preventing accidents and occupational diseases. It aims to examine the various types and categories of PPE and how they can help prevent work-related accidents and diseases when other measures are not enough.

Chapter 3, titled National and European legislative framework regarding personal protective equipment, aims to provide an overview of the existing legislative framework, along with national and European regulations and standards regarding safety and health at work, with specific emphasis on Personal Protective Equipment. This initial analysis was used to support the overall scope of the research, enabling a deeper understanding of the needs associated with personal protective equipment to reduce the risk of exposure to heat and flame in the work environment.

Chapter 4, Documentary summary of the types, forms of manifestation and means of prevention and protection of risks of exposure to heat and flame in the work environment, provides a summary of the different types and forms of exposure to heat and flame, as well as the various means to prevent and protect against these risks. It includes statistical data on work-related accidents at both national and European levels. This chapter will explore the risks and illnesses that come with being exposed to heat and flames, as well as give an introduction to the protective clothing necessary for these dangerous work environments. Addressing these topics will provide information on the characteristics of heat and flame exposure risks, along with effective methods of protection. This will give us a clear understanding of the current knowledge covered in this study.

Chapter 5, titled Conclusions on the current state of research on personal protective equipment used in work environments with heat and flame exposure, summarizes the main findings and progress made in the field of PPE research.

The sixth chapter, titled Directions, main objective, and research and development methodology for designing and testing personal protective equipment, focuses on the main objective and research-development methodology for designing and testing individual protective equipment. It provides an overview of the research-development directions and objectives. A well-defined approach to the research process was established. A systematic structure for the research stages and techniques was established. Considering the innovative nature and potential of the research, the next chapter addressed the development of an experimental study focused on the analysis of textile materials used in the manufacture of personal protective equipment.

The development of Chapter 7, titled Experimental research on the analysis of textile materials used in the manufacturing of individual protective equipment, involved conducting experiments to study the protective properties of textile materials used in making protective clothing for work environments with heat and flame exposure. Analysis was conducted on a series of textile samples to generate documented results.

In Chapter 8, Risk assessment methodology to determine appropriate personal protective equipment, a methodology for assessing risk levels and determining the appropriate personal protective equipment in work environments with heat and flame exposure was developed, using data from the experiments conducted in Chapter 7. A methodology has been established to procure suitable personal protective equipment and ensure the safety and health of workers in the workplace.

Chapter 9, titled Final conclusions and personal contributions on the design and testing of personal protective equipment. Limitations of research. Recommendations for future directions of research, include the author's main findings and contributions. Limitations of the research study are highlighted, along with suggestions for further research.

Complexity and novelty of the research

The research complexity depends on the importance and relevance of the topic, national and international regulations, the nature and extent of potential risks, and the ever-changing work environments that introduce new safety and security risks for workers. An interdisciplinary and multidisciplinary research approach was used to gather evidence on the protective properties of textiles used in manufacturing personal protective equipment for workers in heat and flame exposure work environments. As shown in Figure I.7, the general research approach combines information and data gathered from the literature, focus group discussions, laboratory experiments, evaluation of results, and the author's expertise in the researched field.

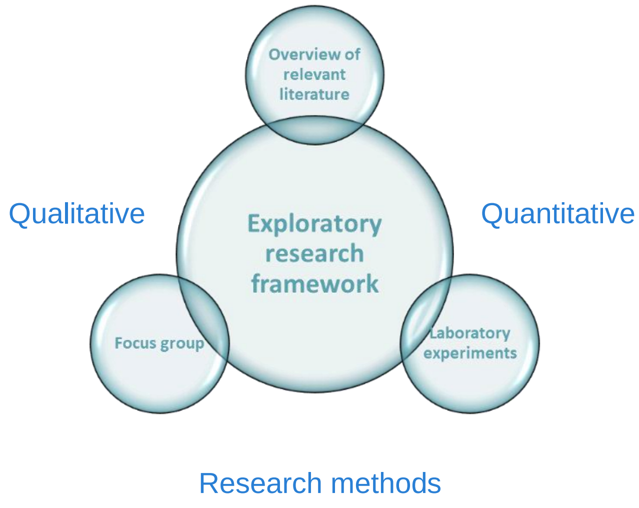

Figure I.7 The general research framework addressed

Chapter 1. Literature review

1.1 Overview of relevant literature

The analysis of the effects of external factors on the protective properties of textile materials used in the production of PPE is the main goal of the doctoral thesis. The research results can serve as a guide for employers and PPE manufacturers in Romania to protect the safety and health of workers. This will help prevent potential risks from exposure to heat and flame in the work environment.

Graphically, Figure 1.1 illustrates the literature review process in a generic manner.

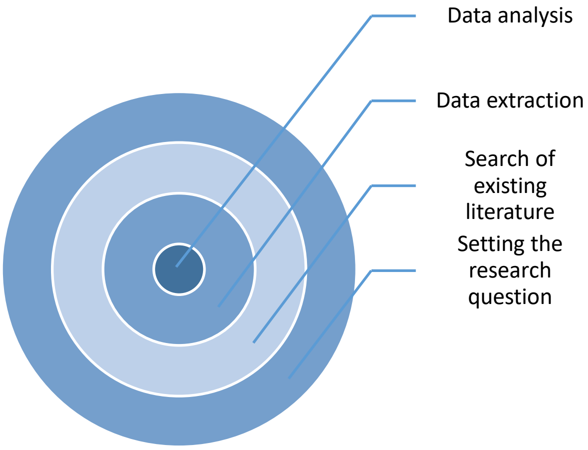

Figure 1.1 The review process of specialized literature

1.2 Concepts and theories in the field of personal protective equipment

Risk is defined as the estimation of the likelihood and severity of negative consequences [100]. Risk perception and risk tolerance are two important and impactful elements in the decision-making process regarding occupational safety and health.

The ability to recognize the severity (magnitude) and components of a risk is known as risk perception. Risk is assessed based on the person's perception of its likelihood and its negative effects.

Risk tolerance is a person's ability to accept and be comfortable with some risk. Lack of knowledge of the seriousness of the risk or inability to understand the seriousness of the risk can lead to a higher risk tolerance (acceptance). The variables that have an impact on risk perception and tolerance are:

- Developing a safe environment by fostering a culture of safety.
- Implementation of occupational health and safety legislation
- Stress at work can hinder a worker's ability to make sound decisions.
- The worker's capacity in relation to the work process.

1.3 Summarizing existing knowledge and identify areas of uncertainty and gaps in the literature

The analysis of current research on textiles used in the production of personal protective equipment for working in heat and flame-exposed environments has resulted in the following conclusions:

(a) Research has identified two main approaches: enhancing the protective performance and comfort of protective clothing. No review of these features is documented in recent studies, leaving many challenges and possibilities for further research. This is because the protective properties and comfort often contradict each other.

(b) Research has not provided comprehensive data and detailed information on the external factors that impact the protective performance of textiles used in manufacturing protective clothing for work environments where heat and flame exposure is a concern.

(c) Research has had limited opportunities to study and combine different factors that contribute to the effectiveness of textiles used in producing protective clothing for work environments exposed to heat and flame.

(d) The protective properties of PPE may change. Different scenarios have been identified where the work environment can be deemed safe for workers based on the protective clothing they use. However, it's important to note that the protective properties of the clothing may be compromised if they have been exposed to conditions that could alter the characteristics of the personal protective equipment being utilized.

(e) The limited evidence and information currently available suggests that existing protective clothing allows workers to operate under normal, "routine" conditions for their safety and health. However, in order to fully understand the protective properties of textiles used in producing work equipment for environments with heat and flame exposure, we need to conduct new experimental tests. These tests will provide additional and up-to-date data and knowledge, considering the following factors:

- the real conditions in the work environment and
- the impact of sweat and repeated washing on the protective properties of textile materials used in the production of PPE for activities involving contact with heat and flame.

Chapter 2. The role and importance of personal protective equipment in the prevention of accidents and occupational diseases

2.1 General concepts

Protective equipment is universally recognized as the term used to describe the equipment worn by workers to reduce the risk of injury and occupational disease. This risk may arise from exposure to thermal, chemical, physical, electrical, mechanical, or other types of hazards present in the work environment. Personal protective equipment is intended to serve as a safety barrier and which:

- it has been designed with the aim of protecting the user from risk factors;
- they have an indirect function because by using them, they can prevent the occurrence of phenomena that can cause accidents. For example, wearing

protective anti-static clothing while handling explosive substances helps protect against electrostatic charging caused by friction, but not against the effects of an explosion.

2.2 Personal protective equipment classification

In accordance with Regulation (EU) 2016/425, PPE is to be classified in the following risk categories [1]:

Category I - lowest risk category;

Category II - includes risks that are not part of categories I and III;

Categoria III - consists solely of risks with the most severe consequences.

The allocation of personal protective equipment can be determined by the specific areas of the body they protect. The criterion currently used in the classification system is the zone protected by PPE.

2.3 Role of personal protective equipment

It is a legal requirement of every state that employers ensure the safety, physical integrity and health of workers and others in the work environment. This obligation is achieved in a structured way, through the implementation of occupational health and safety management. The aim is to prevent work accidents and occupational diseases. To achieve this objective, appropriate technical and organizational measures must be implemented, based on the risk factors identified in the work environment.

Figure 2.5 shows three distinct prevention/protection measures for workers:

i. Intrinsic prevention;
ii. collective protection;
iii. personal protection.

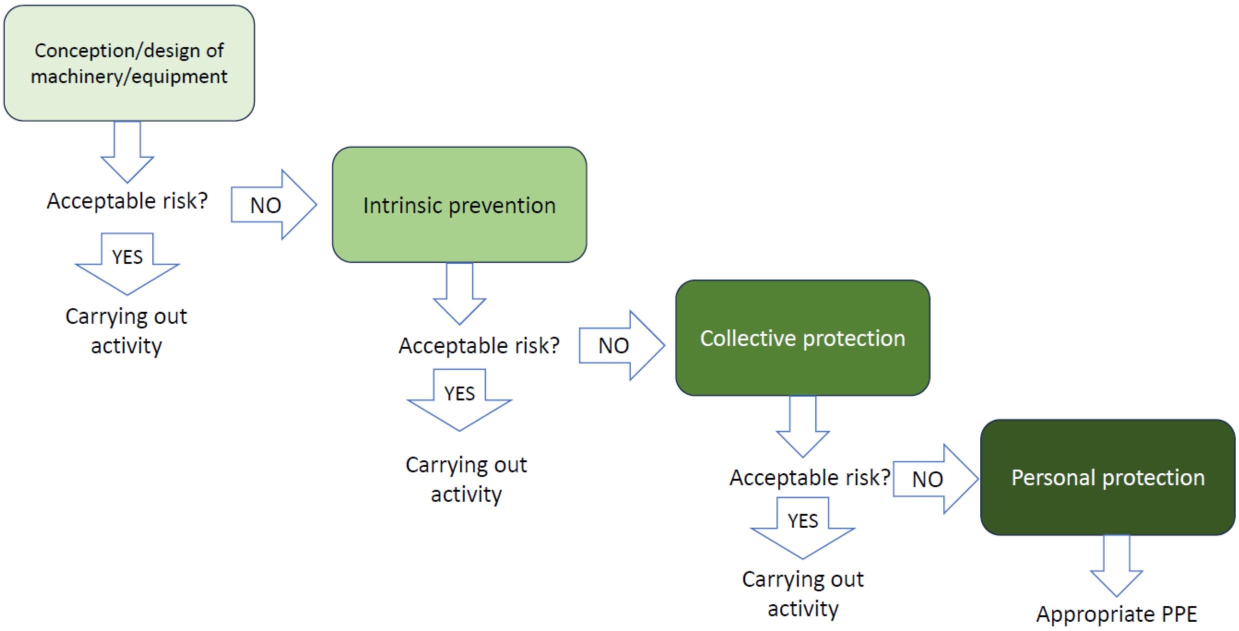

Figure 2.5 Types of prevention measures

Chapter 3. National and European legislative framework regarding personal protective equipment

3.1 Legislative framework on occupational safety and health

In a communication about working conditions and updating legislation and policy regarding safety and health at work in the European Union, the European Commission informed the European Parliament that they have evaluated the existing EU laws through the Regulation on Adequate Regulation (REFIT) program. This evaluation found that these laws generally function well and are suitable for their intended purpose. However, the Commission emphasized the need for continuous progress, as there are certain areas where the regulations should be updated to enhance and expand protection. Additionally, the Commission highlighted the importance of strengthening the implementation, adherence, and enforcement of these regulations. The analysis has shown that certain provisions of specific directives no longer match the current situation. This highlights the need to find effective methods to address emerging risks.

Table 3.1 shows the occupational health and safety measures implemented at the EU level [38].

Table 3.1 Occupational safety and health measures implemented at EU level [38]

No. crt.	Implemented measures
1.	Improving the working environment is crucial, with a specific emphasis on safeguarding the safety and health of workers
2.	Working conditions
3.	Social security and the social protection of workers
4.	Protection of workers in the event of employment termination.
5.	Information and consultation of workers
6.	Collective representation and defense refer to the act of advocating for the interests of both workers and employers. It involves the collaboration between management and employees to address common concerns and ensure a harmonious work environment.
7.	Working conditions for third-country nationals legally resident in the territory of the Union
8.	Integration of people excluded from the labour market
9.	Equality between men and women in terms of opportunities in the labor market and fair treatment at work.

3.2 National legislative framework on personal protective equipment

The national legislation for safety and health at work is governed by the National Strategy for Safety and Health at Work for the period 2018-2020. This framework includes the key elements of the European framework for safety and health at work [71]. National occupational safety and health regulations are essential to protect the safety and health of workers.

3.3 European legislative framework on personal protective equipment

In Europe, worker safety and health are among the most important issues for societies. Recently, the European Union (EU) has had to adapt its management and regulation of work due to the ongoing COVID-19 pandemic and other external factors.

The labor market and work environment have experienced significant transformations as a result of new technologies, globalization, demographic shifts, and economic changes. These changes have introduced new challenges concerning the safety and health of workers. It is important to take steps to recognize, evaluate, and manage risks in the workplace in order to establish a safe and healthy work environment. To prevent, combat, and reduce workplace risks, new procedures have been introduced and implemented. These procedures require the use of personal protective equipment to ensure protection against occupational accidents and diseases. The use of personal protective equipment is crucial in this context to prevent occupational accidents and diseases.

To enhance product safety and improve product quality, regulations are established at the European level. These regulations result from the collaborative efforts of various stakeholders, including producers, consumers, and regulatory authorities. They apply to specific materials, products, processes, or services.

A standard, which is a technical document, serves as a rule, guide, or definition.

The use of standards ensures that different systems can work together smoothly, as well as ensuring security. It also makes it easier for companies to be a part of the value chain and engage in trade. In addition, standards are used to implement EU regulations and policies.

Chapter 4. Documentary summary of the types, forms of manifestation and means of prevention and protection of risks of exposure to heat and flame in the work environment

4.1 Statistical data on occupational accidents at the national and European level

Eurostat's European Statistics on Accidents at Work (ESAW) classification system defines accidents at work as events that happen during work and result in physical or psychological harm. Eurostat is the source for statistical data on occupational accidents across the European Union [86].

The European Union recorded 3347 fatal work accidents in 2021, a decrease of 11 deaths compared to the previous year. The data is presented in Figure 4.1. Figures from 2021 indicate that the Netherlands, Greece, Finland, Sweden, and Germany had a rate of less than 1.00 fatal accidents per 100,000 employed individuals. On the other hand, Romania, France, Malta, Lithuania, and Latvia had a rate of above 3.00 fatal accidents per 100,000 employed individuals.

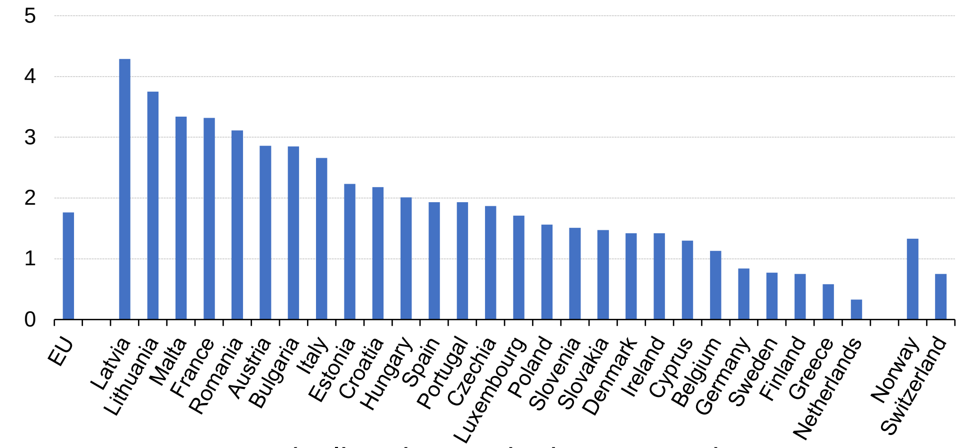

Figure 4.1 Fatal accidents at work, UE, 2021
(incidence rates per 100 000 persons employed), Source: Eurostat (online data code: hsw_n2_02) [86]

During 2021, the rate of non-fatal work accidents was 1,516 per 100,000 employed individuals. Romania and Bulgaria have the lowest rate of non-fatal accidents, with less than 100 accidents per 100,000 employed individuals. On the other hand, Denmark and France have the highest rate, with more than 2,500 accidents per 100,000 employed individuals. The low number of non-fatal accidents could be a result of under-reporting, which may be influenced by various factors. This could be due to challenges in reporting, such as the absence of efficient reporting systems. The statistical data is presented in Figure 4.2.

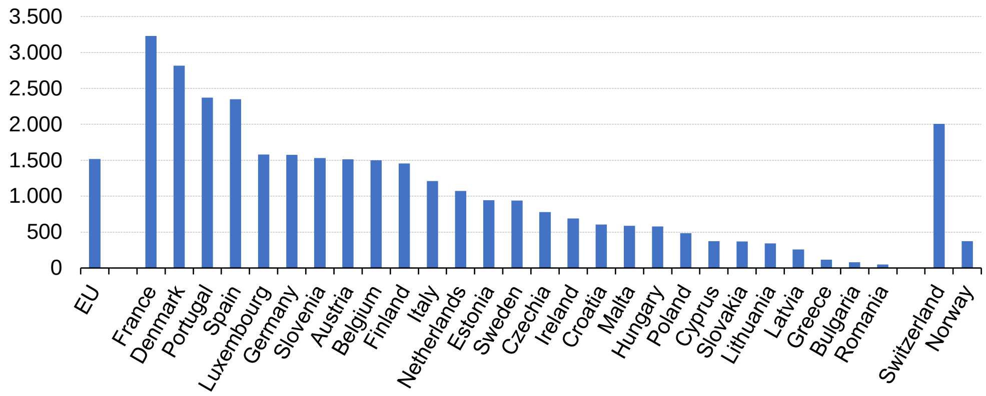

Figure 4.2 non-fatal accidents at work, UE, 2021
(incidence rates per 100 000 persons employed), Source: Eurostat (online data code: hsw_n2_01) [86]

A closer examination of the data presented in Figure 4.3 provides insights into the specific types of injuries that occur when workers have accidents. During 2021 in the EU, the two most common types of injuries were wounds and superficial injuries (28.0%) and dislocations, sprains, and strains (26.0%). Concussion and internal injuries accounted for 19.5% of injuries, while bone fractures accounted for 11.0%.

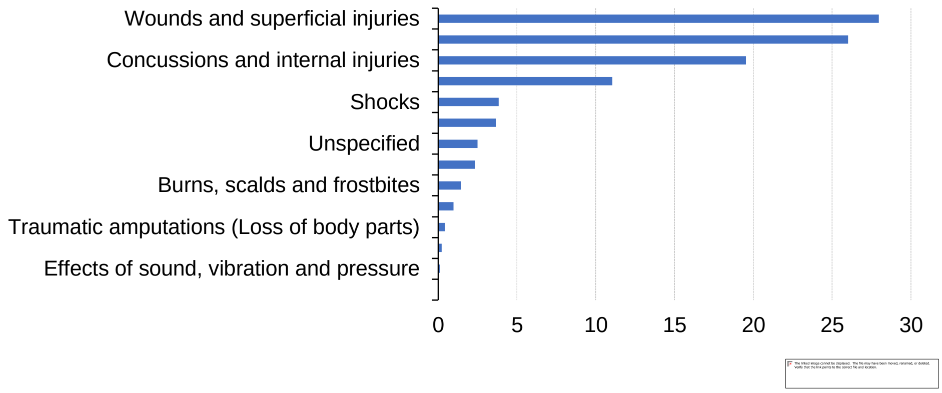

Figure 4.3 Fatal and non-fatal accidents at work by type of injury, EU, 2021 (% of accidents), Source: Eurostat (cod de date online: hsw_n2_07) [86]

Occupational accident data is a valuable tool to understand the demands of the workplace and to establish the safety and well-being of staff. This data allows for the development of strategies to mitigate emerging risks that arise in dynamic work environments.

4.2 Risk of heat and flame exposure

In a variety of occupational environments, such as welding or firefighting, heat and flame can pose a significant risk to workers. The use of personal protective equipment is essential for worker safety. Workers in hot and cold environments must be protected from the risk of exposure to heat and flame. Nomex®-based clothing is typically the most popular type of protective clothing used in these work environments.

4.3 Occupational risks and diseases caused by exposure to heat and flame

The main risks faced by workers in a work environment exposed to heat and flame include:

- sparks generated during welding can start fires or cause burns if they come into contact with flammable or other dangerous substances.
- the heat conducted through pipes can be transferred and may come into contact with combustible materials or other hazardous substances.
- explosive materials can generate high levels of pressure, gas and heat when exposed to extreme temperatures;
- various reagents, when mixed with water, can produce a gas that is flammable.
- oxidizers have the potential to start fires either on their own or by releasing oxygen or other flammable gases that can ignite a fire.
- skin burns can occur when there is contact with hot surfaces, open flames, or sparks.
- heat stress can lead to occupational illnesses such as heatstroke, heat exhaustion, heat cramps, or heat rash.

The most common occupational diseases caused by exposure to heat and flame are:

- *Heatstroke* occurs when the body temperature rises rapidly and sweating does not happen, preventing the body from cooling down. Confusion, changes in mental status, difficulty speaking, blurred vision, and loss of consciousness are among the symptoms.
- *Exhaustion* Excessive sweating can cause heat exhaustion, which occurs when the body loses an excessive amount of water and salt. Headache, nausea, dizziness, thirst, high temperature is among the symptoms.
- *Heat cramps* Workers who sweat excessively during their activities may develop heat cramps if the salt level in their body decreases. Muscle cramps, pain, or spasms in the abdomen, arms, or legs are some of the symptoms.
- *Rash* is caused by profuse sweating. Persistent rashes or inflammatory skin symptoms are among the symptoms.

4.4 Appropriate protective clothing against the risk of heat and flame exposure

Determining the appropriate protective clothing for these work conditions involves assessing the protective properties of the fabrics used in making personal protective equipment in relation to the different external factors encountered in the work environment. In order to ensure the protective nature of the textile materials used in the production of protective clothing, laboratory tests must be carried out that involve exposure of the clothing to heat, abrasion, compression, etc.

Chapter 5. Conclusions on the current state of research on personal protective equipment used in work environments with heat and flame exposure

Based on the analysis of current research on personal protective equipment used in workplaces exposed to heat and flame, the following conclusions are highlighted:

- Globally, many workers are exposed to thermal risks in their workplaces. These occupations are classified as having a high risk of occupational injury and disease. The interest of researchers in this field has been gradually increasing, as evidenced by the growing number of scientific publications published worldwide. (v. § 1.1).

- Data and literature show that the use of personal protective equipment (PPE) still raises several concerns and issues regarding worker safety.
  - data and literature show that the use of personal protective equipment still raises several concerns and issues regarding worker safety.
  - wearing personal protective equipment can restrict movement.
  - the lifespan of personal protective equipment depends on the duration and conditions of their use.
  - improper handling, use, and storage of PPE can result in additional contamination and a shorter lifespan.

- Risk perception and risk tolerance are crucial concepts in making decisions regarding occupational health and safety. They have a significant impact on the choices made in this field. It thus becomes imperative to implement safety programs to increase risk awareness and reduce risk tolerance so that organizations and workplaces remain safe and healthy (v. § 1.2).

- Analysis of the current research on textile materials reveals that, despite numerous studies, there remains a lack of information and data regarding textiles used in the production of PPE for activities involving heat and flame exposure. Furthermore, the gap between theoretical knowledge and practical application has not been diminished yet. To date, only data relevant to specific, pointed research questions have been obtained, rarely being sets or databases that include both textile material properties and information related to moisture or other thermally relevant properties (v. § 1.3).

- Protective equipment, also known as PPE (Personal Protective Equipment), refers to the gear worn by workers to minimize the risk of injury and occupational disease resulting from exposure to thermal, chemical, and physical hazards. It is recognized globally as the term that encompasses such equipment. Personal protective equipment (PPE) is designed to act as a safety barrier, protecting the user from the potential risks they may encounter in their work environment (v. § 2.1).

- The risks are ranked based on the level of protection offered by the equipment: minor, serious, and those of medium severity that do not fit into either category. The most common way of classifying personal protective equipment (PPE) is based on the part of the body it safeguards. In other words, PPE is categorized according to the area it protects, such as head protection, noise protection, eye and face protection, respiratory protection, hand and arm protection, foot and calf protection, skin protection, trunk and abdomen protection, and full body protection (v. § 2.2).

- Seen as the final option for worker safety and health, individual protection has been devalued, diminishing its significance. Despite this, personal protective equipment (PPE) serves as the last line of defense between the risk factor and the human body. This highlights the importance of researching the protective properties of personal protective equipment (PPE) (v. § 2.3).

- The analysis of the national and European legislative context revealed that some provisions in certain directives no longer align with the present situation. It also highlighted the need to find effective ways to address new and emerging risks (v. § 3.1 – 3.3).

- Occupational accident data is a valuable tool to understand job requirements. This data allows for the development of strategies to mitigate emerging risks that arise in dynamic work environments. Statistical data indicate that although there has been a slight decrease in the number of work accidents, they remain at a rather worrying level (v. § 4.1).

- The risk of exposure to heat and flame is present in various occupational settings, such as welding or firefighting. This risk poses a significant danger to the safety and well-being of workers. Flame retardant and heat-resistant textiles have been developed to prevent fire spread and combustion (v. § 4.2).

- The primary risks that workers face in a work environment with heat and flame exposure, as well as the most common occupational diseases caused by this exposure, have been identified. This information will be used to design an effective occupational safety and health (OSH) management system that promotes positive safety and health practices (v. § 4.3).

- Choosing the appropriate protective clothing for these working conditions involves assessing the protective properties of the fabrics used in PPE manufacturing, considering the various external factors present in the work environment. To ensure the protective properties of textile materials used in the production of protective clothing, laboratory tests must be conducted. These tests involve subjecting the clothing to various conditions such as heat, abrasion, compression, and more (v. § 4.4).

Chapter 6. Directions, main objective, and research and development methodology for designing and testing personal protective equipment

6.1 Research and development directions

The research and development directions are aligned with the latest developments in personal protective equipment research:

- Developing a new approach in OSH management by incorporating the two main elements of a safe work environment: the use of PPE and the provision of PPE appropriate to the risks to which workers are exposed in the work environment, as an alternative and an essential means to ensure safety and workers' health;
- Development of an experimental research study that evaluates and analyzes the mechanical (tear, tensile), thermal (radiant heat), and physical (air permeability) properties of textile materials used in the production of PPE for protection against heat and flame. The study will also examine how these materials perform after they have been exposed to the evaporation of sweat.
- The development of two research methodologies is underway. The first methodology focuses on risk assessment for selecting personal protective equipment appropriate for work environments with heat and flame exposure. The second methodology aims to obtain PPE appropriate for the identified workplace risks, considering the actual working conditions.
- Implementation of new methodologies in practice involves the identification and evaluation of risks at workplaces where there is exposure to heat and flame.

6.2 The main objective of research and development

The research aims to offer PPE manufacturers and users updated information and data on the protective properties of textiles in hazardous environments where there is a risk of heat and flame exposure. This will help decrease the occurrence of occupational accidents and illnesses.

The primary objective (PO) of this research is to evaluate the textile materials used in the manufacture of protective clothing worn by workers exposed to heat and flames at their workplace.

The key objectives (OCs) of this study include:

OC1. Investigating the effects of humidity on radiant heat flux through a thermal protective clothing system.

OC2. Evaluation of the protective performance of textile materials under conditions of degradation caused by washing, humidity, perspiration, heat, and cold.

To achieve key objectives, *specific objectives (OS) have been set:*

OS1. Analysis of existing knowledge on personal protective equipment used in work environments with exposure to heat and flame.

OS2. Review of the national and European legislative framework governing personal protective equipment used in workplaces with potential exposure to heat and flame.

OS3. Structuring a typology of individual protective equipment and their purpose in preventing work accidents and occupational diseases.

OS4. Development of two research methodologies: risk assessment for choosing appropriate PPE and procurement of necessary PPE at the workplace.

OS5. Theoretical and experimental basis for studying the protective properties of textile materials used in manufacturing protective equipment for work environments exposed to heat and flames. Additionally, this research explores the effectiveness of protective equipment in preventing work accidents and occupational diseases.

6.3 Research and development methodology

The overall research approach, as shown in Figure 6.2, is derived from a combination of various research methods.

Data collection phase			
↓	*Literature review*		Relevant publications
	Group discussions (focus group)	Qualitative research	Face-to-face discussions
	Laboratory experiments	Quantitative research	Analysis and interpretation of results
Personal contributions to PPE design and testing			

Figure 6.2 Scheme of research methodology

The research started by gathering information from relevant literature on the current state of research in the field of personal protective equipment, specifically focusing on those used in work environments where there is a risk of heat and flame exposure. The accumulated information provided a foundation for understanding the research progress and the current context.

Qualitative information was collected through focus group research. The research consisted of three 60-minute sessions with a small group of four participants who were OH&S researchers. The purpose of the sessions was to discuss the use of personal protective equipment in workplaces with exposure to heat and flame. A face-to-face approach was adopted, with free, flexible discussions.

The research objectives and methodology were subsequently developed through experiments. Laboratory studies have been conducted on textile materials used to produce protective clothing designed for protection against heat and flame exposure risks.

Chapter 7. Experimental research on the analysis of textile materials used in the manufacturing of individual protective equipment

7.1 Selection of textile materials

To achieve the research objectives, we conducted experiments in the laboratory to examine the mechanical properties (tear and traction), thermal properties (radiant heat), and physical properties (air permeability) of the textile materials used in the production of PPE. Additionally, we evaluated their protective performance after drying perspiration. Different types of textiles with unique structures were tested to assess the impact of repeated washing and perspiration on their durability. Eight different types of thermal protection textiles were chosen for this research, specifically for use in the production of protective clothing. The characteristics of the textiles are presented in Table 7.1.

Table 7.1 Detailing selected textiles

Fabric sample	Composition	Mass per unit area (g/m^2)
A	80% Bbc + 19% PES + 1% AS	185
B	75% cotton + 24% PES + 1% AS	275
C	98% Aramid fibers (93% Nomex/ 5% Kevlar) şi 2% AS	265
D	54% Viscose FR+20% Lână+20% PA + 5% Aramid fibers +1% AS	375
E	26% Bbc + 41% PES + 32% modacrilice+1% AS	330
F	99% Bbc +1% AS	220
G	75% meta-aramid fibers /23% para-aramidice /2%AS	195
H	98% Aramid fibers /2%AS	210

1.2 Test methods

Experiments conducted in the laboratory followed the test conditions outlined below:

- Testing samples in their initial state;
- Testing samples of the textile material in both dry and wet states after subjecting it to a cleaning process involving 5 to 50 washing cycles;
- Testing the samples of the textile material in both dry and wet states after conditioning for 7 hours in a salt water solution (25 g salt per 1 liter of water) is done to simulate the sweaty working conditions of the worker and the article of clothing;
- Testing the samples after conditioning for 7 hours at a temperature of 50 °C

- Testing the samples after conditioning them for 7 hours at a temperature of -10°C.

A 7-hour conditioning was applied to samples A - F using a salt water solution (25 g of salt per 1 liter of water). This was done to simulate the sweat conditions of the user and the garment.

7.2.1 Methods for testing the mechanical protection performance of selected textiles (tear, tensile and seam strength)

7.2.1.1 Tearing behavior

The tear resistance of the selected samples was evaluated according to the standard SR EN ISO 13937-2:2001 Textiles — Tear properties of fabrics — Part 2: Determination of tear force of trouser-shaped test specimens (Single tear method) [94].

7.2.1.2 Traction behavior

The tensile strength of the selected samples was tested according to SR EN ISO 13934-1:2013 Textiles — Tensile properties of fabrics — Part 1: Determination of maximum force and elongation at maximum force using the strip method [95].

7.2.1.3 Seam tensile strength

The tensile strength of the seams of the selected samples was evaluated according to SR EN ISO 13935-1:2014 Textiles — Seam tensile properties of fabrics and made-up textile articles — Part 1: Determination of maximum force to seam rupture using the strip method [96].

7.2.2 Methods for testing the thermal protection performance of selected textile materials (radiant-heat)

7.2.2.1 Determination of heat transfer index on exposure to radiant heat

To determine the heat transfer index when exposed to radiant heat, it was tested according to SR EN ISO 6942:2022 Protective clothing Protection against heat and fire Method of test: Evaluation of materials and material assemblies when exposed to a source of radiant heat [80].

7.2.2.2 Residual tensile strength of material exposed to radiant heat

In accordance with SR EN ISO 13934-1:2013 Textiles Tensile properties of fabrics. Part 1: Determination of maximum force and elongation at maximum force using the strip method, the residual tensile strength of the material exposed to radiant heat was evaluated [95].

7.2.3 Test methods for physical protection performance of selected textile materials (air permeability)

7.2.3.1 Air permeability test

The air permeability test was performed in accordance with SR EN ISO 9237:1999 Textiles. Determination of the permeability of fabrics to air [98].

7.3 Experimental results on the protective characteristics of selected samples

7.3.1 Tear resistance

The results of the tests performed on the selected samples are presented in Figures 7.7 – 7.18.

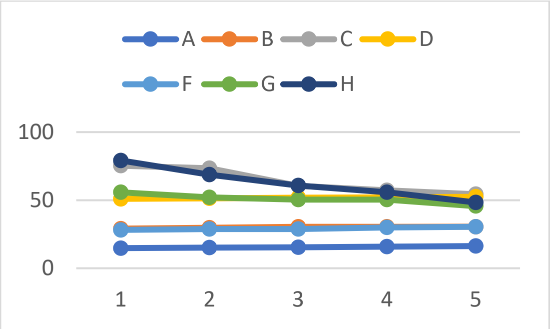

Figure 7.7 Distribution of tearing force values after application of washing pretreatment, longitudinal direction

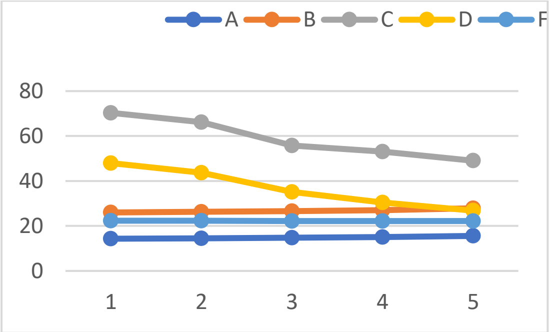

Figure 7.8 Distribution of tear force values after washing pretreatment application, transverse direction

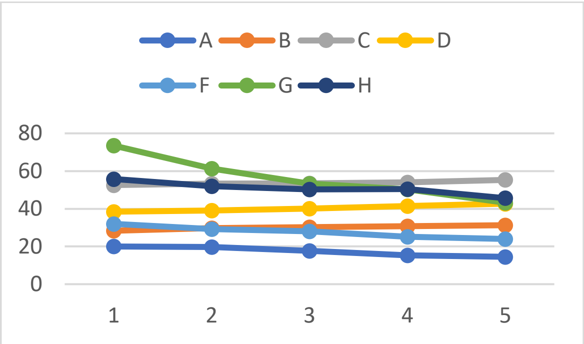

Figure 7.9 Distribution of tear force values after conditioning to humidity, longitudinal direction (conditioning 23°C and 85%)

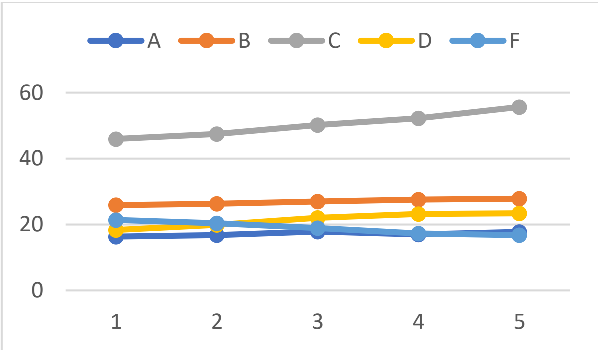

Figure 7.10 Distribution of tear force values after conditioning to moisture, transverse direction (conditioning 23°C and 85%)

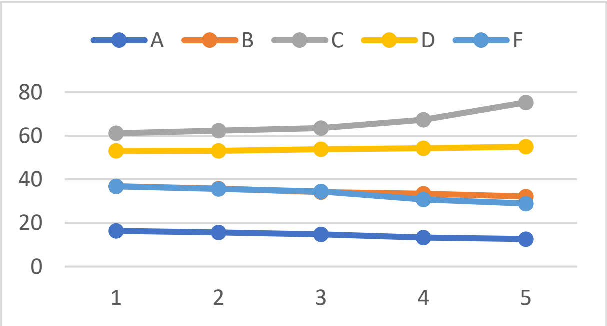

Figure 7.11 Distribution of tear force values after washing pretreatment application, longitudinal direction (conditioning 7 hours in saline solution, dry state)

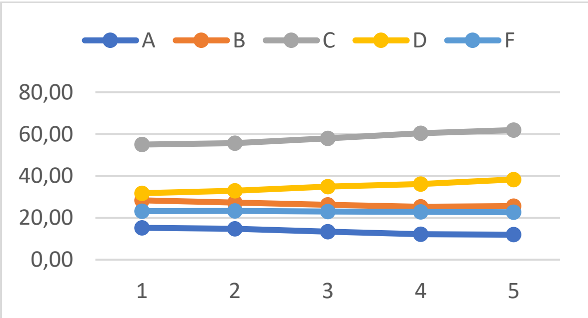

Figure 7.12 Distribution of tear force values after washing pretreatment application, transverse direction (conditioning 7 hours in salt solution, dry state)

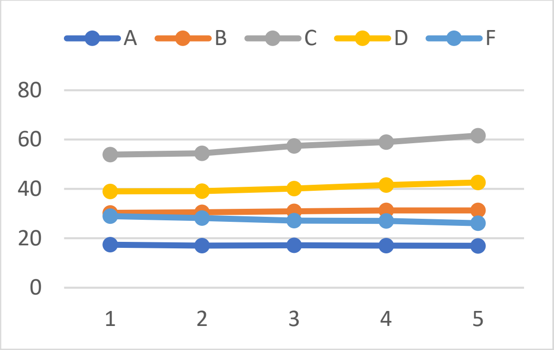

Figure 7.13 Distribution of tearing force values after washing pretreatment application, longitudinal direction (conditioning 7 hours in salt solution, wet state)

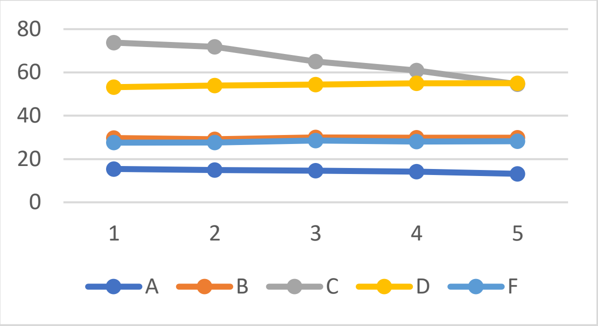

Figure 7.15 Distribution of tearing force values after the application of washing pretreatment, longitudinal direction (conditioning 7 hours at 50°C)

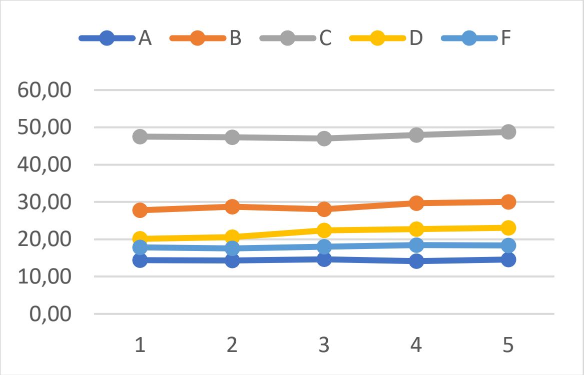

Figure 7.14 Distribution of tear force values after washing pretreatment application, transverse direction (conditioning 7 hours in salt solution, wet condition)

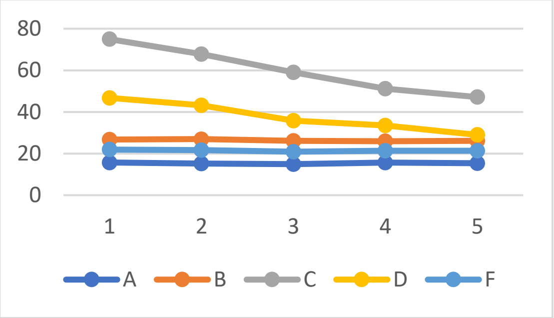

Figure 7.16 Distribution of tearing force values after the application of washing pretreatment, transverse direction (conditioning 7 hours at 50°C)

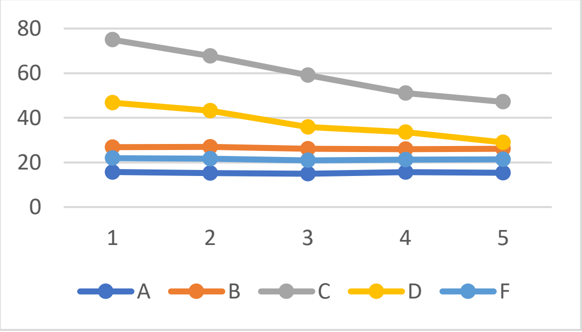

Figure 7.17 Distribution of tearing force values after the application of the washing pretreatment, longitudinal direction (conditioning 7 hours at -10°C)

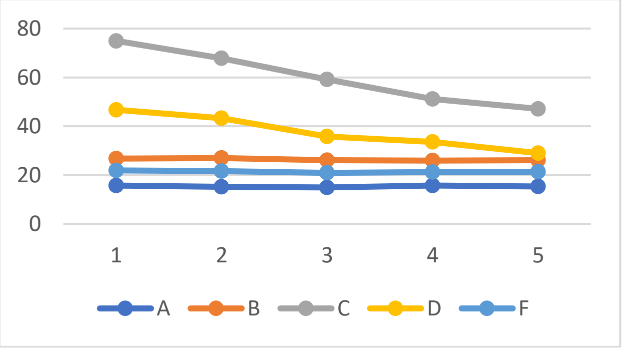

Figure 7.18 Distribution of tear force values after the application of the washing pretreatment, transverse direction (conditioning 7 hours at -10°C)

7.3.2 Tensile strength

Test results are shown graphically in Figure 7.20 for improved understanding.

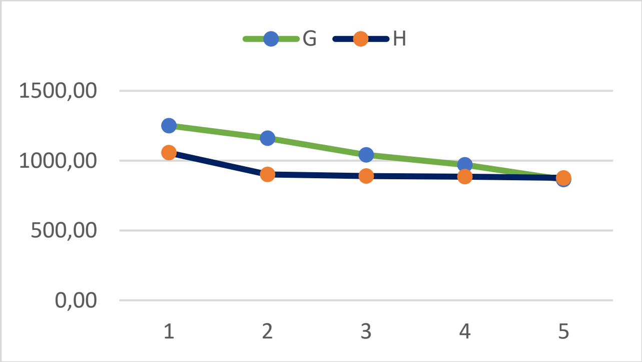

Figure 7.20 Distribution of breaking strength values (N) after moisture conditioning, longitudinal direction (conditioning 23°C and 85%)

7.3.3 Tensile strength of seams

The results of the tests performed on the material samples are presented graphically (Figures 7.22 – 7.23).

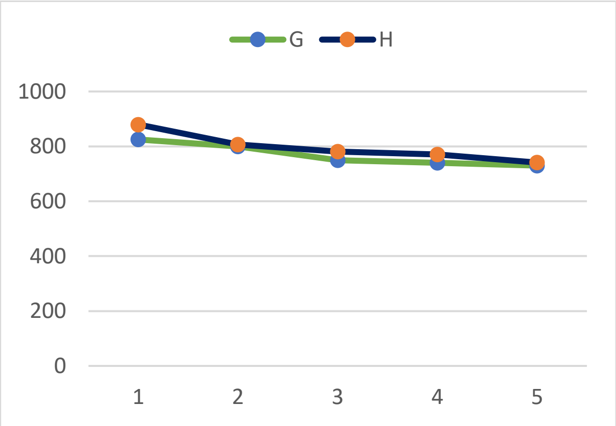

Figure 7.22 The distribution of the values of the maximum breaking force of the seams by the tape method (N)

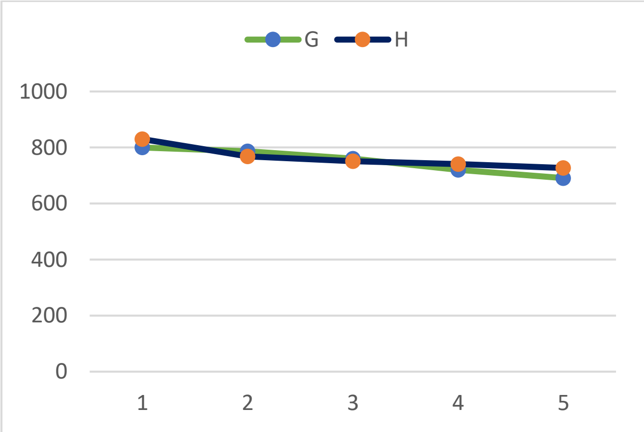

Figure 7.23 Distribution of the values of the maximum breaking force of the seams by the tape method (N) after moisture conditioning, longitudinal direction, (conditioning 23°C and 85%)

7.3.4 Resistance to radiant heat

Table 7.17 shows the results of the tests performed.

Table 7.17 Influence of humidity on radiant heat transfer index

Sample	Conditioning 23°C and 85%	Incident calorific flow density, (kW/m²)	Time to increase temperature with 12°C, (s)	Time to increase temperature with 24°C, (s)	Radiation heat transfer index HTI_{24}- HTI_{12}, (s)
Multilayer Layer 1 - 98% flame retardant aramid fibers	50 Washes	40	16,4	24,3	7,9

Sample	Conditioning 23°C and 85%	Incident calorific flow density, (kW/m^2)	Time to increase temperature with 12°C, (s)	Time to increase temperature with 24°C, (s)	Radiation heat transfer index HTI_{24}- HTI_{12}, (s)
and 2% AS, mass of about 210 g/m2; Layer 2 - impermeable polyurethane membrane laid on a layer of 100% non-woven aramid fibers Layer 3 - aramid and viscose fabric	50 Washes Conditioning 23°C and 85%		16,1	23,	7,6
Multilayer Layer 1- 76% meta-aramidic/23% para-aramidic 1% AS, with a mass of about 210 g/m2 Layer 2 - impermeable polyurethane membrane laid on a layer of 100% non-woven aramid fibers Layer 3 - flame retardant aramid and viscose fabric	50 Washes	40	16,6	24,4	7,8
	Washes Conditioning 23°C and 85%		16,2	24,1	7,9
Multilayer Layer 1 – 98% aramidic + 2% AS, weight 195g/m2 Layer 2 – 50% aramid/50% viscose, coated on PU membrane Layer 3 - 98% aramid + 2% antistatic	50 Washes	40	16,4	20,6	4,2
	Washes Conditioning 23°C and 85%		16,3	20,4	4,1

7.3.5 Residual tensile strength of material exposed to radiant heat

The table below (Table 7.18) shows the results of the tests performed on the selected fabric samples.

Table 7.18 Influence of moisture on residual tensile strength of material exposed to radiant heat

Sample	Conditioning 23°C and 85%	Incident heat flow density, (kW/m^2)	Traction force, (N) longitudinal steering	Traction force, (N) Transverse steering
Multilayer Layer 1 - 98% flame retardant aramid fibers and 2% AS, mass of about 210 g/m2; Layer 2 - impermeable polyurethane membrane laid on a layer of 100% non-woven aramid fibers Layer 3 - aramid and viscose fabric	50 Washes	10	1310	1060
	50 Washes Conditioning 23°C and 85%		1300	1010

Sample	Conditioning 23°C and 85%	Incident heat flow density, (kW/m²)	Traction force, (N) longitudinal steering	Traction force, (N) Transverse steering
Multilayer Layer 1 - 76% meta-aramid/23% para-aramid 1% AS, with a mass of about 210 g/m2 Layer 2 - impermeable polyurethane membrane laid on a layer of 100% non-woven aramid fibers Layer 3 - flame retardant aramid and viscose fabric	50 Washes	10	1300	1100
	50 Washes Conditioning 23°C and 85%		1310	1050
Multilayer Layer 1 – 98% aramidic + 2% AS, weight 195g/m2 Layer 2 – 50% aramid/50% viscose, coated on PU membrane Layer 3 - 98% aramid + 2% antistatic	50 Washes	10	1010	960
	50 Washes Conditioning 23°C and 85%		1000	950

7.3.6 Air permeability determination mm/min (equivalent in l/m2. s)

Test data on selected material samples are shown graphically in Figures 7.27 to 7.32.

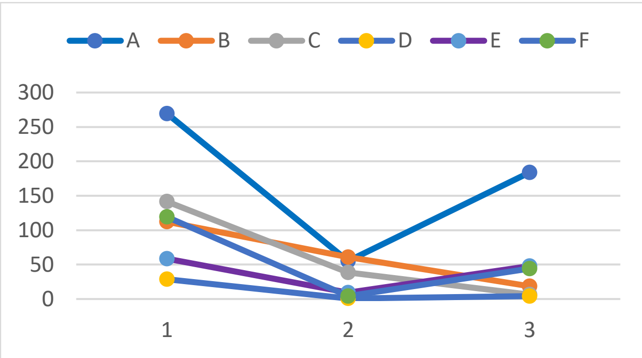

Figure 7.27 Distribution of air permeability resistance values after conditioning (23°C and 85%, dry state)

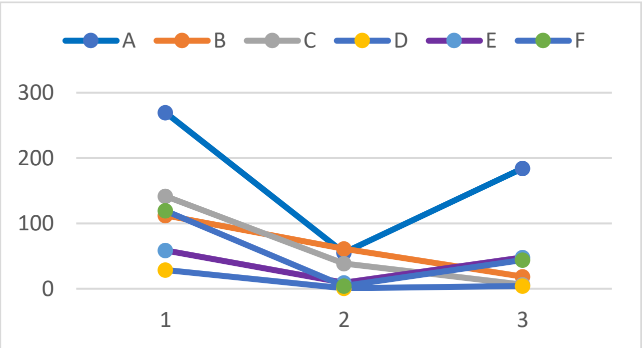

Figure 7.28 Distribution of air permeability resistance values after conditioning (23°C and 85%, wet state)

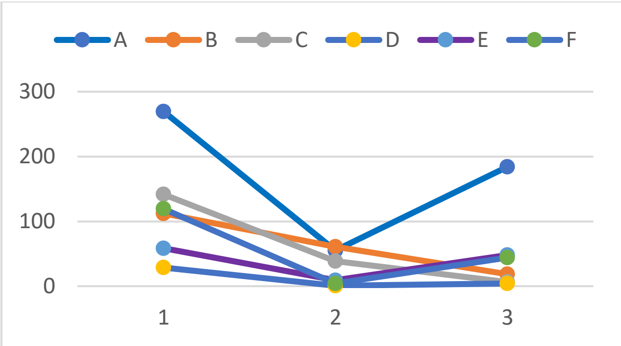

Figure 7.29 Distribution of air permeability resistance valuesafter applying the washing pretreatment (conditioning 7 hours in salted solution, dry state)

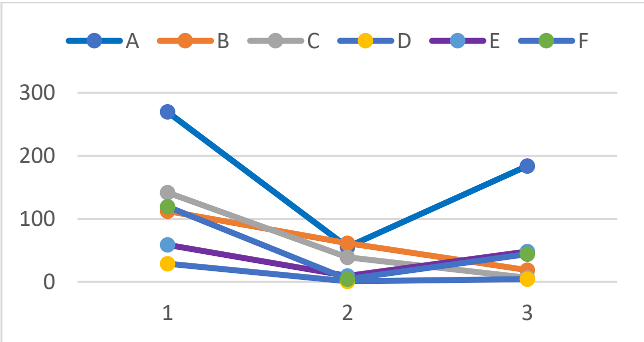

Figure 7.30 Distribution of air permeability resistance values after applying washing

pretreatment (conditioning 7 hours in salted solution, wet state)

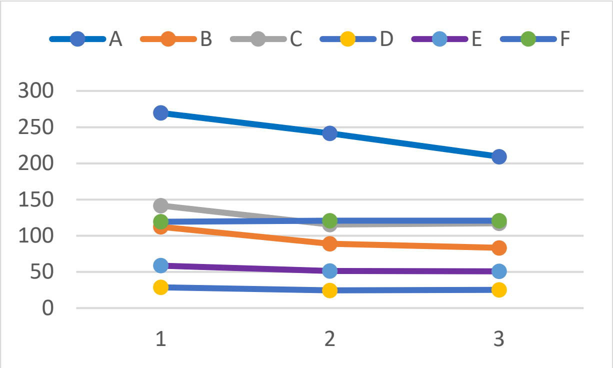

Figure 7.31 Distribution of air permeability resistance values after application of washing and conditioning pretreatment 7 hours in salted solution (conditioning 3 hours at 50°C)

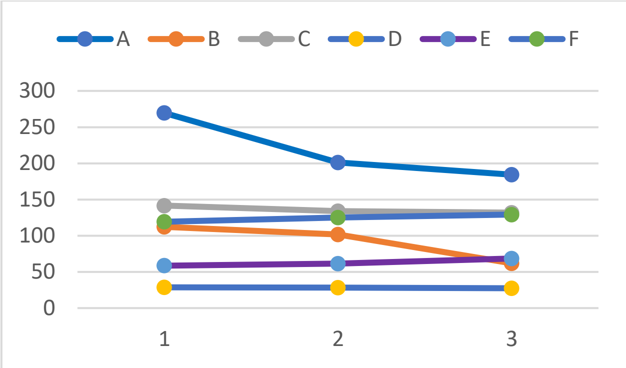

Figure 7.32 Distribution of air permeability resistance values after application of washing pretreatment (conditioning 3 hours at -10ºC)

7.4 Interpret of the results

By comparing the results of the experimental tests with the values obtained for samples of the material in its initial state, unconditioned, the following results were obtained:

Tear resistance

- These modifications only apply to the shape of the blades in the longitudinal direction, after pre-treating the blades for A, B, D, and F;
- The tear force in the longitudinal direction decreases for samples C, G, and H after applying the washing pretreatment;
- The tearing force in the transverse direction for samples A, B, and F does not show significant changes after the washing pretreatment has been applied;
- The tearing force in the transverse direction decreases for samples C, D, and H after applying the washing pretreatment;
- The longitudinal tearing force for samples A, B, C, and D did not show significant changes after moisture conditioning was applied;
- The tear force in the longitudinal direction decreases for samples C, D, and H after moisture conditioning;
- The transverse tearing force for samples A and B did not show significant changes after the moisture conditioning;
- The tearing force in the transverse direction decreases for samples C, D, and F after moisture conditioning;
- There are no significant changes in the tearing force in the longitudinal direction after conditioning for 7 hours in a salt solution in the dry state for samples A, B, D, and F;
- The tearing force in the longitudinal direction decreases for samples C after they have been conditioned for 7 hours in a salt solution, while in a dry state;
- There are no significant changes in the tear force in the transverse direction after 7 hours of conditioning in a salt solution. This applies to samples A, B, and F in both the dry state and after conditioning;
- Tear force in the transverse direction decreases for samples C and D after being conditioned in a salt solution for 7 hours in a dry state;

- There were no significant changes in the tearing force in the longitudinal direction after 7 hours of conditioning in a wet state with saline solution for samples A, B, and F.
- The tearing force in the longitudinal direction decreases for samples C and D after being conditioned in a salt solution for 7 hours in the wet state;
- There were no significant changes in the tearing force in the transverse direction after the samples A and B were conditioned for 7 hours in a salt solution in a wet state;
- The tear force in the transverse direction decreases for samples C, D, and F after being conditioned in a salt solution for 7 hours under wet conditions;
- There are no significant changes in the tearing force in the longitudinal direction after conditioning for 7 hours at 50oC for samples A, B, C, and F;
- The tearing force in the longitudinal direction decreases for the samples after being conditioned for 7 hours at 50°C;
- There are no significant changes in the tearing force in the transverse direction after conditioning samples A and B for 7 hours at 50°C;
- The tear force in the transverse direction decreases for samples C, D, and F after conditioning for 7 hours at 50°C;
- There are no significant changes in the tearing force in the longitudinal direction after conditioning for 7 hours at -10°C for samples A, B, C, and F;
- The tearing force in the longitudinal direction decreases for the samples after being conditioned for 7 hours at -10°C;
- There are no significant changes in the tearing force in the transverse direction after conditioning for 7 hours at -10°C for samples A and B;
- The tear force in the transverse direction decreases for samples C, D, and F after being conditioned for 7 hours at -10°C.;

Tensile strength

- For samples G and H, the washing pretreatment resulted in a decrease in the tensile strength of both materials;

Tensile strength of seams

- For samples G and H, the application of the washing pretreatment resulted in a decrease in the tensile strength of the seams;

Radiant heat resistance

- The radiant heat resistance of the samples exposed to radiant heat remains almost unaffected by the moisture conditioning treatment;

Residual tensile strength of material exposed to radiant heat

- The residual tensile strength of the samples exposed to radiant heat remains almost unchanged after applying the moisture conditioning treatment;

Determination of air permeability mm/min (equivalent in l/m2.s)

- Samples A, B, and F have high permeability when they are initially dry. However, this permeability decreases after the washing pretreatment and subsequent conditioning in a saline solution;
- Sample C demonstrated no change in air permeability after undergoing a washing pretreatment. However, a significant decrease in air permeability was observed after saline conditioning;

- Samples D and E did not show any significant changes in air permeability after undergoing washing and conditioning pretreatments using a saline solution.

7.5 Discussion and conclusions

The results of laboratory tests lead to the following conclusions:

- Samples A, B, and F did not demonstrate any significant changes in tear strength after undergoing a pre-treatment of washing and conditioning in saline solution for 7 hours. These samples contain a high percentage of cotton, more than 75%;
- Samples C, D, E, G, and H are composed of aramid or modacrylic fibers. These fibers have a higher resistance to tearing. However, the washing pretreatment applied to these samples results in a decrease in this resistance;
- After being conditioned in saline for 7 hours, samples C, D, and E did not experience a significant decrease in tear strength;
- For samples G and H, the pretreatment used for washing resulted in a decrease in both the tensile strength of the fabric and the seams;
- The strength of samples exposed to radiant heat, both in terms of radiant heat strength and residual tensile strength, is almost unchanged when a moisture conditioning treatment is applied;
- Samples A, B, and F, which contain more than 75% cotton, show high permeability when dry. However, this permeability decreases after the washing pretreatment and subsequent conditioning in a saline solution;
- Sample C, which contains aramid fibers, did not show any change in air permeability after washing pretreatment. However, a significant decrease was observed after conditioning the sample in saline solution;
- Samples D and E, which contain a high proportion of viscose or modacrylic fibers, do not exhibit significant changes in air permeability after undergoing washing and conditioning pretreatments using a saline solution.

Summarizing the results of the laboratory tests, the following are evident:

- Summarizing the laboratory test results, textile materials made mostly of cotton maintain their tear resistance regardless of the 7-hour solution washing and conditioning pretreatments. These materials also have a high permeability when dry, even after undergoing these treatments, although the permeability decreases after the pretreatments are applied;
- Aramid or modacrylic fibers have superior tear strength. This strength is reduced when a wash pretreatment is applied, but it is not significantly affected by 7 hours of saline conditioning;
- The air permeability of the samples containing aramid fibers remains unchanged after the pre-washing treatment, but decreases significantly after being conditioned in saline solution;
- Washing and conditioning pretreatments in saline solution do not significantly impact the air permeability of materials containing a high percentage of modacrylic or viscose fibers;
- The application of the moisture conditioning treatment does not significantly alter the radiant heat resistance and residual tensile strength of the material exposed to radiant heat.

Chapter 8. Risk assessment methodology to determine appropriate personal protective equipment

8.1 Exploring the basics of PPE safety management

PPE management principles and techniques need to be documented in order to show how to supply, acquire, and confirm the appropriate PPE for the employer's activities. This necessitates a methodical assessment and review of procedures. The diagram in Figure 8.1 illustrates the management system used in the PPE field.

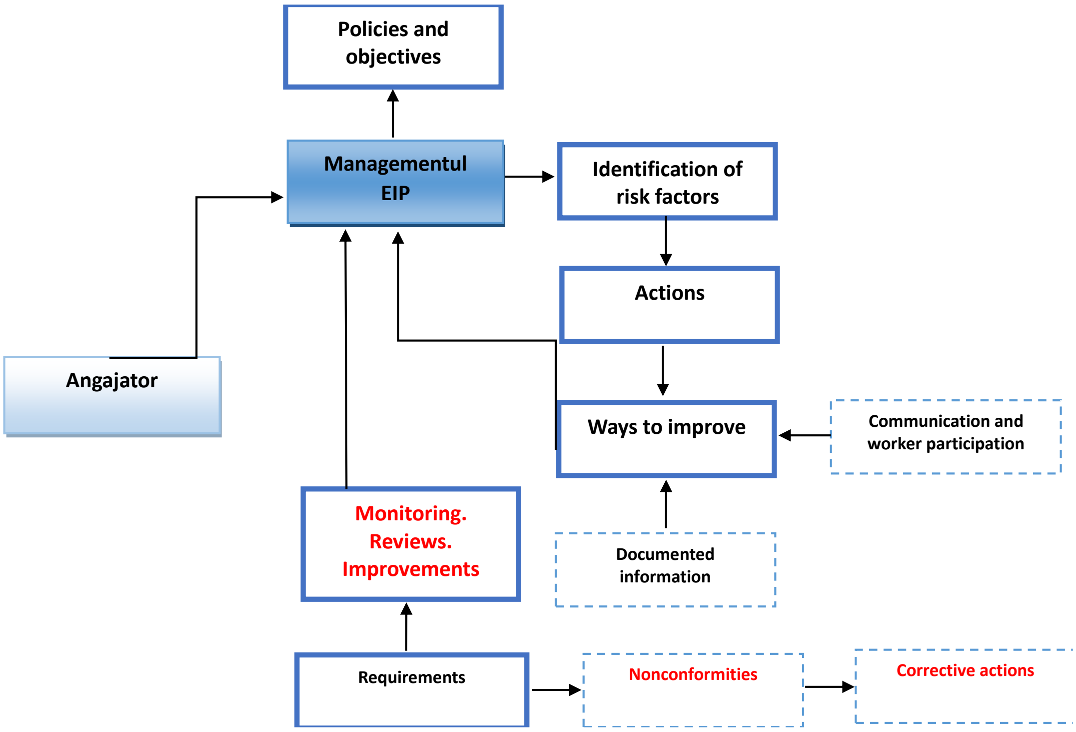

***Figure 8.4** Diagram of the management system in the field of PPE*

8.2 Development of the risk level assessment methodology for the selection of appropriate PPE for the work environment with exposure to heat and flame

The equipment requirements for each job are determined in consultation with the workers, and lists of allocated personal protective equipment (PPE) are created. The following three steps should be considered when developing the PPE needs and requirements:

- *Identifying the specific elements of activities that are carried out regularly or occasionally, such as repairs, maintenance, and interventions.*

Specific elements could include:
- types of tasks to be performed: duration and frequency.

- the location of the activity (inside, outside);
- type of activity (regular, occasional);
- who generally performs this task
- the materials that are being handled;
- the substances used or exposed to in the work environment include smoke, gases, vapors, liquids, powders, and solid substances.

- *Identifying the risk factors in the work environment*

Creating a checklist covering the risks in the workplace is useful to assist the identification process and should include information on:

- the workplaces;
- tasks or activities performed;
- the risks identified.

- *The methodology regarding the assessment of the level of risk for the selection of appropriate PPE for the work environment with exposure to heat and flame*

Knowing the risks to which the worker may be exposed is essential to making a well-informed and correct decision about the appropriate type of PPE. This risk assessment is not meant to analyze workplace risks. Its purpose is to determine the appropriate personal protective equipment (PPE) for individuals who are exposed to specific risk factors in the work environment. This type of evaluation should be integrated into the management system. The assessment methodology developed in this research is used for work environments that involve exposure to heat and flame.

When evaluating the potential impact on the user if exposed to the risk, it is important to consider the severity (S) of the potential consequences:

- uncovered body areas;
- effects on the body can be categorized into three different levels of intensity: low, medium, and high. Alternatively, they can be classified into five levels: negligible, low, moderate, high, and extreme.

When determining the probability (P) of user exposure to risks, the following factors must be considered:

- in the event of expanding or developing the activity, the likelihood of an accident or occupational disease resulting from a risk increases as the number of workers exposed to the task increases, regardless of whether similar incidents have occurred before or not;
- the frequency and duration of risk exposure;
- lack of facilities (for example, water);
- malfunction of equipment components, installations and security devices related to them;
- the wear level of the PPE;
- human errors.

To select the appropriate personal protective equipment (PPE) for workers exposed to heat and flame in the work environment, we use the risk level rating scale provided in Table 8.1.

Table 8.2 Risk level rating scale

Value	Probability (P)	Severity (S)
5	Almost certainly *(it will definitely appear)*	Extreme *(deaths, amputations, major fractures, chronic poisoning)*
4	Very likely *(chances are high that it will occur)*	High *(chemical and thermal burns, deep cuts, partial hearing impairment, permanent disability)*
3	Occasionally *(there may be more in the future)*	Moderate *(severe burns, fractures)*
2	Rare *(has not appeared for many years)*	Low *(light scratches, superficial burns, cuts)*
1	Very unlikely *(it is impossible to occur or never appeared)*	Negligible

The calculation formula is: $\mathcal{R} = \mathcal{P} \; x \; \mathcal{S}$

Where R stands for risk

P represents the probability

S represents severity.

The risk matrix is presented in Table 8.2.

Table 8.3 Risk matrix

Probability (P)	Severity (S)				
	1	**2**	**3**	**4**	**5**
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5

Legend: **Low risk**; **Medium risk**; **High risk**

Example of a typical scenario using the method risk assessment in order to choose the appropriate type of PPE

Firefighters on the job are exposed to hazardous situations that may involve flames, chemicals or serious injury. Potential risks to firefighters include:

Thermal hazards: In the event of a fire, firefighters are frequently exposed to flame (probability: very likely). Fire is the main risk factor and can produce radiant, convective or contact heat, which can even lead to the death of the worker (severity: extreme).
Calculation formula: 4 (Very likely) x 5 (Extreme) = 20 **High risk**

Chemical hazards: Firefighters may occasionally encounter oils and greases when they maintain or repair firefighting equipment. This happens occasionally. The degree of exposure is moderate (severity: low).
Calculation formula: 3 (Occasional) x 2 (Low) = 6 Medium **Risk**

Mechanical hazards: Firefighters frequently face the risk of serious injuries such as deep cuts, even permanent disability (severity: high) during the performance of their duties (probability: very likely).
Calculation formula: 4 (Very likely) x 4 (High) = **16 High risk**

8.3 Methodology for purchasing appropriate PPE

8.3.1 Determination of requirements

Determination of requirements involves:

- choosing the right types and assortments of personal protective equipment
- developing technical specifications to address the risks identified at the workplace.
- estimating the necessary quantities for each type of equipment;
- establishing the requirements for personal protective equipment includes ensuring that they have the CE mark, provide instructions in Romanian, and obtain certification from a notified body.

8.3.2 Purchase of PPE

The person responsible for providing Personal Protective Equipment (PPE) determines the level of protection required for the user based on the specific risks that the PPE is designed to protect against. For an informed decision, the person responsible for purchasing PPE must be trained in advance.

Table 8.5 includes a list of questions that you can consider when purchasing PPE.

Table 8.5 List of questions regarding the purchase of PPE

Question
Have you identified the activities and workspaces where workers need to use personal protective equipment (PPE)?
Have the associated risks been documented and assessed?
What is the required level of protection for PPE?
Are the body parts that need protection and the corresponding levels of protection identified?
Has the appropriate type of personal protective equipment (PPE), which combines the necessary features and performance to effectively address the identified risks, been chosen?
Is the personal protective equipment (PPE) suitable for the user and appropriate for the purpose and level of risk?
Has it been verified whether the PPE needs to be certified according to specific standards?
Has it been determined whether the PPE requires distinctive features for high visibility and/or identification, such as reflective material?
Is there information available on how to clean, decontaminate, and disinfect certain types of personal protective equipment (PPE)?
Is there information available on how to inspect, maintain, and dispose of limited-use personal protective equipment (PPE)?

Chapter 9. Final conclusions and personal contributions on the design and testing of personal protective equipment. Limitations of research. Recommendations for future directions of research

9.1 Conclusions on the conducted research

- To date, scientific research on work accidents and occupational diseases caused by heat and flame exposure has identified gaps in our knowledge:
- the protection performance criteria highlight the importance of considering the actual conditions in which the personal protective equipment (PPE) will be used. This is particularly important in work environments where there is exposure to heat and flame, as there are various environmental factors that may come into play. Therefore, it is necessary to analyze the conditions experienced by workers and compare them to the requirements outlined in the standard;
- insufficient information and knowledge exist regarding the protective properties of personal protective equipment (PPE) following washing and aging processes;
- for the most part, studies and analyzes on the protective properties of PPE have been carried out after workplace events (accidents, incidents) (s. § 1.3).
- Considering the importance of personal protection in ensuring the safety and health of workers, it is clear that while it should be the final option used after implementing collective and organizational protection measures, it may be the only measure to consider as the last line of defense against occupational accidents and diseases (s. § 2.1).
- The availability of different types of personal protective equipment (PPE), each designed to protect specific parts of the body, serve different functions, and are made of different materials, has led to the development of a classification system (s. § 2.2).
- In order for an organization to successfully implement an effective and appropriate Occupational Safety and Health (OSH) management system, it is important to integrate its two components into the overall management system. The Occupational Safety and Health (OSH) management system is built upon two key components. First, it prioritizes the safety and well-being of workers by advocating for the use of Personal Protective Equipment (PPE) to protect them. Second, it prioritizes workplace safety by providing workers with the necessary individual protective equipment that is suitable for the specific risks they may encounter. This requires two main things: allocating human and financial resources, and promoting an OSH culture at the organizational level. To achieve this, it is important to focus on communication and worker involvement, identifying and assessing risks, providing appropriate personal protective equipment (PPE), and implementing an evaluation and improvement management system (s. § 3.1).
- The National Strategy for Research, Innovation, and Intelligence Specialization 2022 – 2027 aims to link research activities with important societal challenges, such as welfare and social inclusion, health, technological advancements, and climate change [7]. The EU Strategic Framework on occupational safety and health for the period 2021-2027 has set the following objectives at the European level: [8]:

- preventing risks and promoting a safer and healthier workplace environment;
- maintaining the health of workers throughout their entire professional life;
- protection against work accidents and occupational diseases (s. § 3.2).

- Despite being considered a "last resort" for worker safety and health, personal protective equipment (PPE) still helps mitigate risks. Statistical evidence from national and European sources shows that the frequency of accidents at work is decreasing. Despite the small decrease of only 11 fatal accidents in 2021 compared to 2020, the number of accidents and the resulting human and economic losses still remain alarmingly high. (s. § 4.1).
- Exposure to heat and flame can pose a major hazard to workers, affecting their safety and health. The primary hazards in a work environment where there is exposure to heat and flame include sparks that can lead to fires or burns, heat being conducted through pipes, explosive materials, various chemicals, injuries to the skin from contact with hot materials or equipment, and thermal stress (s. § 4.3).
- Heat and flames pose significant health risks to workers in various industries such as metallurgy, glassmaking, the steel industry (including forges and foundries), welding, and firefighting. To protect them, there is a wide range of protective clothing (s. § 4.3).
- In occupations like welding and firefighting, workers often face exposure to high temperatures and flames, which can be hazardous to their safety and health. Flame retardant and flame-retardant fabrics are two classes of heat and flame-resistant textiles (s. § 4.3).
- Protective clothing worn by the mentioned workers may be exposed to heat, abrasion, compression, and moisture during their tasks. Consequently, laboratory tests are necessary to evaluate the protective properties of the textile materials used in making protective clothing (s. § 4.4).
- The choice of suitable protective clothing for these work environments involves determining the protective qualities of the textile materials used in the PPE. This evaluation considers the influence of various external factors that exist in the work environment (s. § 6.4).
- Laboratory experiments were conducted to analyze the protective properties of textile materials used in the production of protective clothing for heat and flame exposure, considering external factors encountered in real work environments (s. § 6.4.2)
- Laboratory experiments were conducted to study the effects of different factors on eight selected textile materials. The factors examined included aging from washing, humidity, excessive perspiration, extreme cold, and high heat. The laboratory tests were designed to support a more comprehensive understanding of the degradation (aging) phenomenon on a selected set of textile materials. These materials are currently being used in the production of protective clothing for work environments that involve exposure to heat and flame (s. § 7.1).
- The comparison of experimental research results showed that external factors, such as aging caused by washing, humidity, excessive sweating, extreme cold, and high heat, have varying effects on the protective properties of textile materials. Fabric composition plays a crucial role in determining the fabric's performance. For fabrics that have a higher percentage of cotton, tear resistance remains unchanged even after multiple wash cycles and 7-hour saline conditioning. Additionally, these fabrics have high permeability in their initial state, but this decreases after undergoing the

two pretreatment procedures. After being soaked in a saline solution, the material containing aramid fibers experiences a noticeable reduction in air permeability (s. § 7.2-7.3).

- The Occupational Safety and Health (OSH) management system should be tailored to the specific tasks and work environment of the workers (s. § 8.1).
- The research has developed and implemented a risk assessment methodology to determine the suitable type of personal protective equipment (PPE) for workers exposed to heat and flames in the workplace. This methodology became possible by identifying specific parameters that are considered when evaluating the risks that PPE protects against. The appropriate range of Personal Protective Equipment (PPE) will be determined by reviewing the risk assessment sheet. Taking into account the amount, duration and level of risk factors to which workers are exposed in the work environment, the selection of PPE will be made (s. § 8.2).
- The process of assessing the risk level for choosing the right personal protective equipment (PPE) in a workplace where there is exposure to heat and flame involves considering both the likelihood of an incident occurring and the potential impact on the worker's safety and health. If the risk cannot be eliminated or reduced to an acceptable level, it is necessary to implement both technical and organizational measures to ensure the safety and health of the workers. If these measures are not enough, then workers must be provided with personal protective equipment (s. § 8.2).
- The distribution of personal protective equipment (PPE) to workers highlighted the necessity to create a methodology for selecting and procuring PPE. The methodology involves two stages: identifying the PPE requirements and purchasing the appropriate PPE based on the identified risk factors in the work environment (s. § 8.3).
- Through scientific research conducted in this PhD thesis, the experimental data presented demonstrate how laboratory conditions can replicate real working conditions. This allows for an examination of how external factors influence the protective performance of PPE against heat and flame. The mechanical parameters (such as tear, traction, and seam strength), thermal parameter (radiant heat), and physical parameter (air permeability) of the textile materials used in PPE production were tested. The goal was to better understand how these materials degrade when subjected to cleaning and sweating, with the aim of developing improved fabrics for enhanced worker safety.
- The developed approaches and methodologies can be considered as a reference that can be tailored and utilized to evaluate various risk factors encountered in the workplace.

9.2 Personal contributions

Personal contribution from the perspective of research objectives

- Establish the research objective by addressing the identified issues and gaps in occupational safety and health concerning the use of personal protective equipment (PPE) in work environments with heat and flame exposure. The research will help manufacturers develop better and appropriate protective clothing for workers who regularly perform tasks with heat and flame exposure.

- Establishing specific objectives is crucial in order to illustrate the desired research outcomes that are necessary to achieve the main objectives.
- To achieve the research objectives, we used both quantitative and qualitative methods to collect data. These methods included reviewing literature, conducting focus group discussions, and performing laboratory experiments. This approach enhanced the research process by validating and reinforcing the research findings.

Personal contribution from the perspective of the documentary study developed within the research

- The purpose of this literature review is to provide an overview of the current state of research in the field and analyze established research. The study gives an overview of the protective qualities of the fabrics used in manufacturing PPE. However, it's apparent that the existing data and knowledge is not extensive enough. This step helped identify data and knowledge gaps and outline the main theories and concepts in the EIP field. This allowed the formulation of our own research with novelty and originality.
- Conducting research on the role of personal protective equipment (PPE) in preventing occupational accidents and diseases. The research aimed at presenting the main categories of PPE, their classification and purpose in the protection of workers, when technical and organizational measures are not sufficient. This stage has provided knowledge and facilitated the understanding of personal protection in preventing workplace accidents and occupational diseases.
- An investigation was conducted to examine the national and European legislative context regarding personal protective equipment (PPE) for occupational safety and health. The goal was to establish a foundation and enhance the overall framework for conducting research on the requirements of PPE used to protect against the risk of heat and flame exposure in the workplace.
- An in-depth study on the different types of heat and flame exposure, as well as the ways to prevent and protect against these risks, allowed for the presentation of statistical data on work accidents both at a national and European level. Also, we will discuss the potential risks and occupational diseases that can occur from activities where there is exposure to heat and flame. We will also cover the types of protective clothing that are suitable for these work environments. The purpose of this stage was to gather information about the risks associated with heat and flame exposure, in order to understand the current state of knowledge in the research area. This knowledge then informed the following stages of the research.

Personal contribution from the perspective of theoretical substantiation of research

- This text provides an overview of the existing knowledge regarding personal protective equipment (PPE) used in environments with heat and flame. It also aims to identify any gaps in research that currently exist within the literature.
- Examination of national and European laws regarding safety and health in the workplace, along with European standards concerning personal protective equipment (PPE), with the aim of identifying the key theories and concepts related to PPE.
- The presentation will discuss the significance of personal protective equipment in preventing accidents and occupational diseases. We will also cover the classification and description of the main categories of protection offered by such equipment.

- Presentation of the main risk factors that workers may encounter in work environments where they are exposed to heat and flame.
- Presentation of the evolution of statistical data on work accidents at national and European level, from which it can be seen that the number of accidents remains at a high level, to which are added the human and economic consequences of work accidents.
- Development of two methodologies. The first methodology focuses on conducting a risk assessment to determine the suitable personal protective equipment (PPE) for a work environment with heat and flame exposure. The second method involves obtaining the necessary PPE based on the assessment.
- The methodology and tools developed in this research can serve as a template for future use. They can be adapted to address different risk factors found in work environments.

Personal contribution from the perspective of experimental substantiation of research

- Evaluation of the mechanical properties (tear and tensile strength), thermal properties (radiant heat resistance), and physical properties (air permeability) of textiles used in the production of Personal Protective Equipment (PPE) for protection against heat and flames, as well as assessing their protective performance after sweat evaporation.
- Laboratory tests were performed on eight different types of thermal protection textiles that are currently utilized in the manufacturing of protective clothing.
- To test the impact of washing and perspiration on the performance of protective clothing, we conducted experiments on various textile materials. We examined mechanical properties such as tear strength, tensile strength, and seam strength, as well as thermal properties like radiant heat resistance. Additionally, we measured the air permeability of the materials. These tests were performed on the textiles after they were exposed to perspiration and underwent the aging process caused by washing. Laboratory tests were conducted to enhance our understanding of how the degradation process affects a specific set of textiles. These textiles are utilized in the production of protective clothing for work environments that involve heat and flame exposure.

9.3 Research limitations and future research perspectives

9.3.1 Limits of research

- If we had more textile samples, with a wider variety and larger sizes, we could have conducted more experiments and obtained more conclusive results.
- The research was limited in scope due to constraints in the number, variety, and size of the samples, as well as the range of laboratory equipment available. As a result, it was not possible to study the entire topic covered by the research.
- Time constraints - the research was not conducted over a sufficient period of time to collect sufficient data and draw more extensive conclusions.
- The research conclusions are limited in scope compared to researchers with access to a wider range of laboratory equipment.

9.3.2 Future research perspectives

- There are multiple legal requirements that PPE manufacturers must meet before they can sell their products. Much effort is dedicated to ensuring that firefighters and welders are adequately protected from various hazards they encounter, such as fire, high temperatures, smoke, molten metal, shock, and more. However, a limited number of studies on bacterial colonization of firefighter and welder equipment have been identified. Despite this, it is important not to overlook this factor for firefighter and welder occupations. In addition to causing unpleasant odors and physical discomfort, microbial growth can also result in a decrease in the tensile strength and durability of fabrics. Special emphasis should be placed on the biological deterioration of machinery's textile fibers, particularly those made of natural materials. The most common causes of textile fiber decomposition are fungi such as Aspergillus and bacteria like Bacillus.

- A significant number of firefighters and welders have been diagnosed with cancer. After re-evaluating in June 2022, the International Agency for Research on Cancer (IARC) classified occupational exposure to firefighting as carcinogenic to humans (Group 1) [101]. Metal oxides stick to skin or clothing, so regular soaps and detergents are ineffective at removing heavy metals. The research question that needs to be answered is: Even after washing, is it possible that the personal protective equipment used by firefighters and welders can cause illness in the workers who wear it?

* * *

The present doctoral thesis, through the research topic addressed, the applied methodology and results, is unique on a national level, forming logical connections between the studied topics to achieve the proposed objectives.

This PhD thesis is significant in the scientific community because it explores the mechanical (tear, tensile, and seam strength), thermal (radiant heat), and physical (air permeability) properties of textile materials used in manufacturing PPE. It aims to gain a deeper understanding of degradation, which is caused by the cleaning process of washing and the effects of perspiration. These tested properties will allow PPE manufacturers to provide sufficient protection for workers in various work environments, thereby aiding the development of new textile materials.

The significance of this PhD thesis lies in the fact that the integration of theoretical and experimental research has resulted in the creation of new knowledge and tools. These resources can assist workers, employers, and other stakeholders in promoting and preserving workplace safety and health.

It can also be appreciated that the theoretical, methodological and experimental parts that I developed during the research represent innovative contributions in the field of research dedicated to preventing and combating the risks of exposure to heat and flame.

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