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INTEGRATING THE AGE FACTOR IN DESIGNING INDUSTRIAL ENVIRONMENTS AND WORKSTATIONS IN THE WORKFORCE AGEING ERA

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ABSTRACT

As people spend a third of their lives at work and, in most cases, indoors, the work environment assumes crucial importance. The continuous and dynamic interaction between people and the working environment surrounding them produces physiological and psychological effects on operators.

The literature emphasizes that comfort and well-being in the workplace bring positive results regarding employee satisfaction and high job performance. On the other hand, environmental stressors affect work performance, and long-term exposure to those conditions leads to the development of diseases. Since productivity is critical to long-term profitability and success, industries must implement strategies to control the indoor environment to safeguard their employees.

Managing physical risks (i.e., ergonomic and microclimate) in industrial environments is often constrained by production and energy requirements.

In the food processing industry, for example, the safety of perishable products dictates storage temperatures that do not allow for operator comfort. Conversely, warehouses dedicated to non-perishable products often lack cooling systems to limit energy expenditure, reaching high temperatures in the summer period.

In addition, some exceptional events may determine new constraints maintained in working environments. For example, the recommendation to keep windows open during the winter period to limit the spread of coronavirus has remained an effective strategy in containing the influenza virus. However, the introduction of external cold and dry air causes thermal stress and local irritation of mucous membranes, eyes, and skin, making exposed subjects more susceptible to respiratory diseases.

In industry, the personal variables of operators can also act as constraints in achieving comfort. For example, ageing, a complex process that leads to physical and cognitive decline, significantly reduces human tolerance to environmental stresses. In the workplace, the inability of older workers to respond to prolonged stress conditions results in cardiovascular disease and musculoskeletal disorders. As workforce ageing is a worldwide trend, industries must adopt strategies to allow older workers to stay as long as possible at their workplace while keeping them safe, healthy, and productive.

However, the literature lacks studies quantifying the impact of environmental discomfort conditions based on the age of operators to suggest new technical, technological, and organizational solutions.

This thesis aims to deepen the physical hazards in industrial environments, exploring the relationships between environmental and personal factors. This thesis proposes methods and models to integrate the age factor into comfort assessment, highlighting technical and technological solutions to prevent or at least reduce microclimate risk in industrial environments.

The goal is to find new ways to support the ageing workforce by improving their comfort and performance, as well as their experience and skills.

The research activity is developed following a logical-conceptual scheme that highlights three main research areas: the analysis of factors influencing the work environment, the recognition of constraints that prevent the attainment of workers' comfort, and the design of solutions to safeguard the comfort of older operators. A chapter of this thesis is devoted to each of these three macro-areas, in which, after reviewing the state of the art and the main research directions, the specific research activities as well as the main results obtained, and the elements of innovativeness are illustrated. The results significantly contribute to science by laying the foundation for new research in worker health and safety in an ageing working population's extremely current industrial context.

SOMMARIO

Le persone trascorrono un terzo della loro vita al lavoro e, nella maggior parte dei casi, al chiuso; pertanto, l'ambiente di lavoro assume un'importanza cruciale. L'interazione continua e dinamica tra le persone e l'ambiente di lavoro che le circonda produce effetti fisiologici e psicologici sugli operatori.

La letteratura sottolinea che il comfort e il benessere sul posto di lavoro portano risultati positivi per quanto riguarda la soddisfazione dei dipendenti e le elevate prestazioni lavorative. Al contrario, condizioni di stress ambientale influiscono sulle prestazioni lavorative e l'esposizione a lungo termine a tali condizioni porta allo sviluppo di malattie occupazionali. Poiché la produttività è fondamentale per la redditività e il successo a lungo termine, le industrie devono attuare strategie di controllo dell'ambiente interno per salvaguardare i propri dipendenti.

La gestione dei rischi fisici (ergonomici e microclimatici) negli ambienti industriali è spesso limitata dai requisiti produttivi ed energetici.

Nell'industria alimentare, ad esempio, la sicurezza dei prodotti deperibili impone temperature di stoccaggio che non consentono il comfort dell'operatore. Al contrario, i magazzini dedicati ai prodotti non deperibili spesso non dispongono di sistemi di raffrescamento per limitare il dispendio energetico, raggiungendo temperature elevate nel periodo estivo.

Inoltre, alcuni eventi eccezionali possono determinare nuovi vincoli che vengono poi mantenuti negli ambienti di lavoro. Ad esempio, la raccomandazione di tenere le finestre aperte durante il periodo invernale per limitare la diffusione del coronavirus è rimasta una strategia efficace per il contenimento del virus dell'influenza. Tuttavia, l'introduzione di aria fredda e secca dall'esterno provoca stress termico e irritazione locale delle mucose, degli occhi e della pelle, rendendo i soggetti esposti più suscettibili alle malattie respiratorie.

Nell'industria, anche le variabili personali degli operatori possono agire come vincoli per il raggiungimento del comfort. Ad esempio, l'invecchiamento, inteso come processo che porta al declino fisico e cognitivo, riduce significativamente la tolleranza umana alle sollecitazioni ambientali. Sul posto di lavoro, l'incapacità dei lavoratori più anziani di rispondere a condizioni di stress prolungato si traduce in malattie cardiovascolari e disturbi muscolo-scheletrici.

Poiché l'invecchiamento della forza lavoro rappresenta una tendenza mondiale, le industrie devono adottare strategie per consentire ai lavoratori anziani di rimanere il più a lungo possibile sul posto di lavoro, mantenendoli sicuri, in salute e produttivi.

Tuttavia, in letteratura mancano studi che quantifichino l'impatto delle condizioni di disagio ambientale in base all'età degli operatori per suggerire nuove soluzioni tecniche, tecnologiche e organizzative.

Questa tesi si propone di approfondire i rischi fisici negli ambienti industriali, esplorando le relazioni tra fattori ambientali e personali. Questa tesi propone metodi e modelli per integrare il fattore età nella valutazione del comfort, evidenziando soluzioni tecniche e tecnologiche per prevenire o almeno ridurre il rischio microclimatico negli ambienti industriali.

L'obiettivo è trovare nuovi modi per supportare la forza lavoro che invecchia, migliorando il suo comfort e le sue prestazioni, nonché la sua esperienza e le sue competenze.

L'attività di ricerca si sviluppa secondo uno schema logico-concettuale che evidenzia tre principali aree di ricerca: l'analisi dei fattori che influenzano l'ambiente di lavoro, il riconoscimento dei vincoli che impediscono il raggiungimento del comfort dei lavoratori e la progettazione di soluzioni per salvaguardare il comfort degli operatori anziani. A ciascuna di queste tre macroaree è dedicato un capitolo della tesi, in cui, dopo aver passato in rassegna lo stato dell'arte e le principali direzioni di ricerca, vengono illustrate le specifiche attività di ricerca e i principali risultati ottenuti, nonché gli elementi di innovatività. I risultati ottenuti forniscono un contributo significativo alla scienza, ponendo le basi per nuove ricerche nel campo della salute e della sicurezza dei lavoratori in un contesto industriale estremamente attuale, caratterizzato dall'invecchiamento della popolazione lavorativa.

Integrating the age factor in designing industrial environments and workstations in the workforce ageing era

Integrazione del fattore età nella progettazione di ambienti industriali e postazioni di lavoro nell'era dell'invecchiamento della forza lavoro

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“The real voyage of discovery consists not in seeking new landscapes but in having new eyes.”

Marcel Proust

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1. INTRODUCTION

People worldwide are living longer (Eaves et al., 2015). The decline in fertility and the increase in life expectancy at birth are behind the sharp rise in the elderly population worldwide (Calzavara et al., 2020). In 2020, the projections of the Statistical Office of the European Union (EUROSTAT) showed a significant increase in the proportion of older adults in the EU-27, expected to reach 40.6 percent by 2050.

People living longer than before also work longer (Dimovski et al., 2019). Forecasts on the ageing of the workforce estimate that nearly one-fifth of workers will be aged 50 and over by 2050 (Eaves et al., 2016). The economic pressures of these demographic trends are pouring into pension systems, forcing workers to postpone their retirement (Case et al., 2015).

On the one hand, a long-lasting working life offers opportunities for industries thanks to the expertise and knowledge gained by aged workers over the years (Parkes, 2016), together with their better safety attitude (Han et al., 2019). On the other hand, postponing the retirement age increases the risk of exposure, hence the probability of developing occupational diseases (Varianou-Mikellidou et al., 2019). In fact, as workers age, many tasks they used to complete efficiently may become increasingly difficult due to a decline in mental and functional abilities (Choi, 2015).

The extension of working life, in most cases indoors, requires assessing the factors that determine the quality of the indoor environment as production systems supporting aged workers ensure the maintenance of a high operator's performance (Battini et al., 2018; Bogataj et al., 2019).

The continuous and dynamic interaction between people and the working environment surrounding them produces physiological and psychological effects on operators, affecting their well-being, safety, and performance (Ismail et al., 2009). Numerous studies underline how comfort and well-being in the workplace bring positive results in satisfied employees and high working performances (Isa and Atim, 2019; Kralikova and Koblasa, 2018; Szabo and Kajtar, 2018).

Employees' comfort and satisfaction strongly depend on indoor environmental quality (IEQ) factors such as ergonomics, temperature, air speed, humidity levels, lighting conditions, and noise (Tagliabue et al., 2021). These IEQ factors are the leading indicators of well-being within an environment. On the other hand, unsatisfactory working conditions (i.e., poor indoor air quality, insufficient ventilation, thermal discomfort conditions, poor lighting, and noise) can profoundly degrade learning and workers' performance (Mofidi and Akbari, 2016; Wang et al., 2021).

The decline in worker performance, defined as accomplishing a given task measured against known preset standards of accuracy, completeness, cost, and speed (Al Horr et al., 2016), affects economic growth and manufacturing efficiency (Digiesi et al., 2020).

On the other hand, production and energy requirements often affect the proper work environment management in support of operator health. For example, several control measures for temperature, humidity, and atmospheric composition extend the life of perishable products to meet consumer expectations. However, these environmental conditions may conflict with the health and safety of the workers involved (Laguerre et al., 2013).

In addition, warehouses dedicated to non-perishable goods often lack heating and air conditioning systems to limit energy expenditure, as they do not require storage temperatures (Akkerman et al., 2010; Rohdin and Moshfegh, 2011). On the other hand, those warehouses are characterized by the achievement of low temperatures during winter and high temperatures during the summer, presenting significant vertical temperature differences (Rahma et al., 2020). Exposure to severe heat or cold does not allow the achievement of comfort conditions and can result in adverse health effects, such as illnesses, injuries, and death (Wu et al., 2021)

Moreover, manufacturing processes in the ceramics and metallurgical industries also pose a microclimate risk to workers exposed to the high temperatures of kilns or welding processes.

Finally, some constraints that do not allow comfort are instituted to cope with exceptional events and then maintained. For example, the recommendation to keep windows open during the winter period to limit the spread of coronavirus has remained an effective strategy in containing the influenza virus (Abuhegazy et al., 2020). However, introducing cold, dry air from outside can cause thermal stress, discomfort, and other adverse effects on the health and safety of workers (Castaldo et al., 2018; Li et al., 2018; Salata et al., 2018; Wolkoff, 2021).

In considering factors limiting workers' comfort in the industrial environment, we also cannot fail to consider age (Eaves et al., 2016). Ageing reduces human tolerance to environmental stresses, and older workers comprise a significant proportion of the workforce (European Commission 2021). Therefore, industries must adopt strategies to enable older workers to remain at the workplace as long as possible, keeping them safe, healthy, and productive (Caporale et al., 2022).

To summarize the research context illustrated, Figure 1 depicts the benefits and challenges of the industry in the context of an ageing working population:

- Age-related advantages (1) refer to the benefits of a prolonged working life. These include the experience and knowledge gained by older workers over the years, along with improved attitudes toward safety and more conscious use of personal protective equipment, which enable older workers to more easily identify and cope with potentially critical situations.
- Age-related issues (2) concern the negative aspects associated with ageing. These include the potential development of occupational diseases, reduced productivity due to a decline in physical and cognitive abilities, and reduced tolerance to environmental stress.

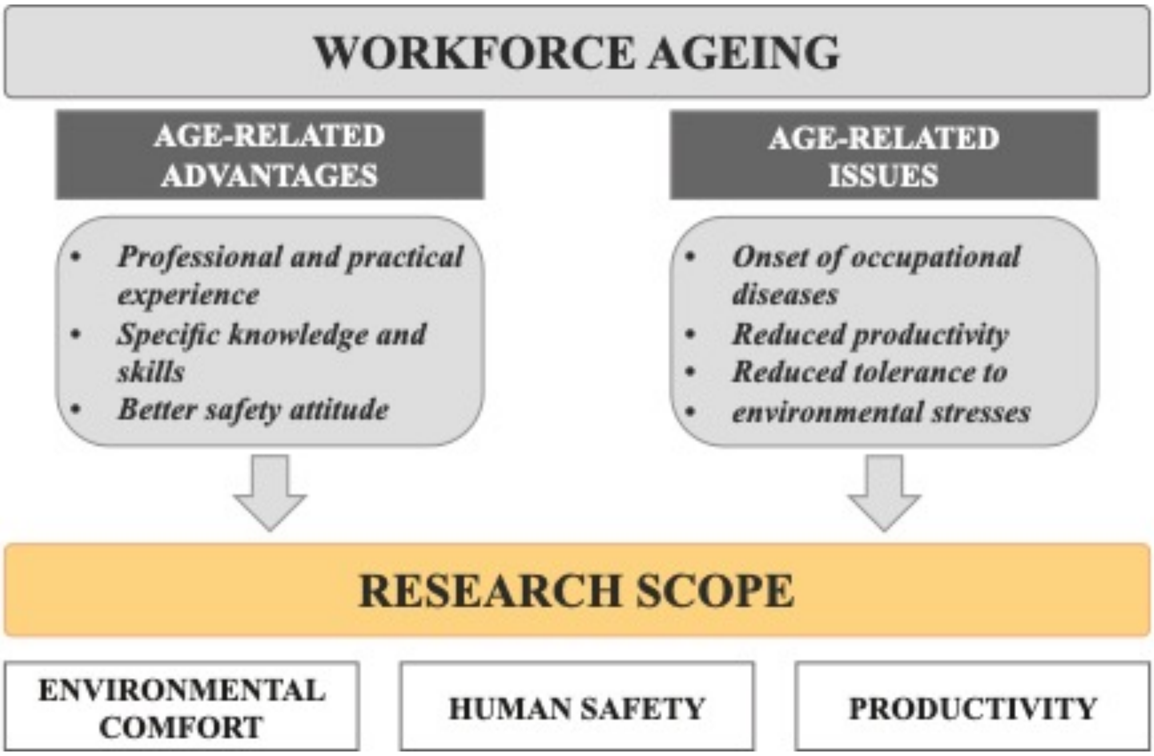

Figure 1 Research background framework.

Even if ageing, industrial performance, and microclimate strategies regarding IEQ factors are hot topics in the recent literature, almost all the contributions examine these three factors in pairs.

The research project presented in this dissertation falls within the scope of proposing an integrated analysis of the three factors (i.e., environmental comfort, human safety, and productivity).

Moreover, this thesis aims to present methods and models to integrate the age factor into comfort assessment, highlighting technical and technological solutions to prevent or at least reduce microclimate risk in industrial environments.

Based on these statements, this thesis is motivated by three research questions discussed in detail in the next section, followed by the research purpose and objectives. Then, the scope and demarcation behind this thesis, the research framework, and the adopted methodology are illustrated.

1.1 RESEARCH QUESTIONS AND OBJECTIVES

This thesis is primarily motivated by the following questions.

RQ 1. What are the relationships among IEQ factors, well-being, and worker productivity?

Following this research question, the primary purpose of this dissertation is to investigate the impact of each indoor environmental quality (IEQ) factor on worker well-being and productivity. Literature analysis shows that microclimate is one of the industry's most prevalent but underestimated risks. Therefore, this thesis explicitly explores this risk and the main issues related to achieving thermal comfort.

Hence, RQ 2 is formulated as follows:

RQ2: What are the constraints to achieving environmental comfort?

Production demands, such as product conservation, manufacturing processes, and energy saving, are the main factors hindering environmental comfort in the industrial sector. However, exceptional events like COVID-19 also create new microclimatic conditions in production compartments. Personal factors, such as worker age, can also impact the relationship between humans and the environment, decreasing workers' tolerance to environmental stress.

RQ3: Which interventions can we take to restore environmental comfort?

As a result of these research questions, the last goal of this thesis is to provide theoretical and practical solutions that assist industries in supporting the progressive ageing of the workforce. The solutions presented are intended to encourage the design of environments and workstations that ensure the well-being and productivity of workers.

The three research questions can encompass various sub-issues, given their general nature. For this reason, this thesis includes a set of research topics underpinned by specific objectives. These will be explicated in the following sections.

1.2 SCOPE AND DEMARCATIONS

The scope of the research previously introduced makes it essential to delimit the research area by defining the boundaries. The research presented in this thesis suggests limitations related to the set of selected topics, the model to assess thermal comfort, and the thesis structure.

First, the research introduces but does not detail all the factors that determine the quality of the indoor environment. This thesis delves into thermal comfort and microclimate risk concepts, presenting reference standards, models, and experiments that analyze the relationship between thermal comfort and workers' age. Indoor air quality and acoustic and visual comfort are mentioned but not explored in depth.

Second, the comfort research and experimentation in the thesis refer principally to global models and Fanger's model. This model is investigated and used as the basis for model development and thermal chamber experimentation to integrate workers' age's influence on the thermal environment's response. As much as Fanger's model has limitations when applied in real-world settings, it constitutes the foundation of thermal comfort research and is therefore investigated and discussed.

Finally, although the background of the research started from the pros and cons of population ageing, this aspect is brought back as a "constraint" in the analysis practiced by this thesis, together with production and product needs and the work environment. The worker benefits sought in this thesis (i.e., well-being, comfort, and productivity) must be compared with production and environmental needs.

Therefore, the framework and research activities proposed in the following sections start with a general analysis of environmental quality factors and how they influence worker well-being and productivity. Then, this thesis introduces the other crucial aspects that affect environmental comfort and the solutions to restore workers' comfort.

The introduced demarcations both identify the research path and expose the limitations of this thesis.

1.3 RESEARCH FRAMEWORK

The research presented in this dissertation has been developed within the framework illustrated in Figure 2, where the research topics and levers corresponding to each research question are identified.

A research lever is proposed to address RQ 1. This lever explores the main factors that hinder environmental comfort in the industrial sector. Given the demarcations mentioned in the previous section, the research focuses on thermal comfort.

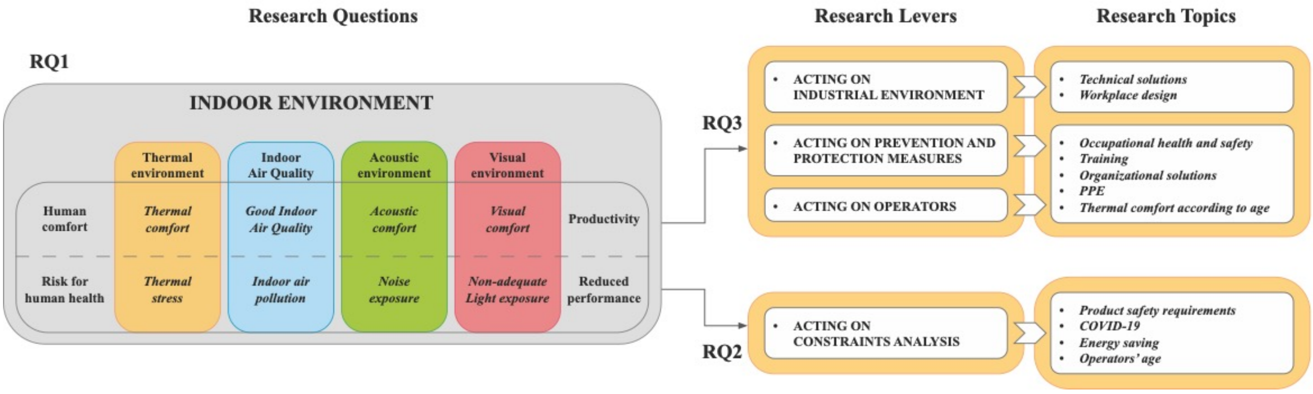

Figure 2 Research framework.

Accordingly, the research analyzes environmental requirements for industrial product safety and quality, focusing on perishable products and energy-saving strategies for products that do not require a controlled environment. In addition, microclimate strategies implemented to limit the spread of pathogens and viruses (i.e., COVID-19) are presented. Finally, the research focuses on the ageing of the working population and the challenges this trend poses within the industrial sector.

Three research levers are proposed to address *RQ 3*. The first concerns the study and application of technical solutions and the redesign of the work environment to improve environmental conditions.

The second lever relates to preventive measures, such as information, education and training, and protective measures (i.e., technical, organizational, and personal protective devices) that industrial workers can adopt.

Finally, the third research lever addresses the analysis of comfort needs and reactions to uncomfortable conditions of older workers (over 45).

1.4 RESEARCH ACTIVITIES

The research activity concerning the introduced research levers led to outcomes summarized in Figure 3. These outcomes contribute to the research scope following the two research sub-questions and have been obtained by adopting different perspectives.

From an operational perspective, some results support the improvement of momentary industrial environmental conditions. In contrast, others enable strategic design to improve the microclimate of industrial environments in the long term (strategic perspective).

The research outcomes generated to address *RQ 2* include the distinction between production and operator requirements, the environmental strategies for exceptional events, and the framework for workforce ageing.

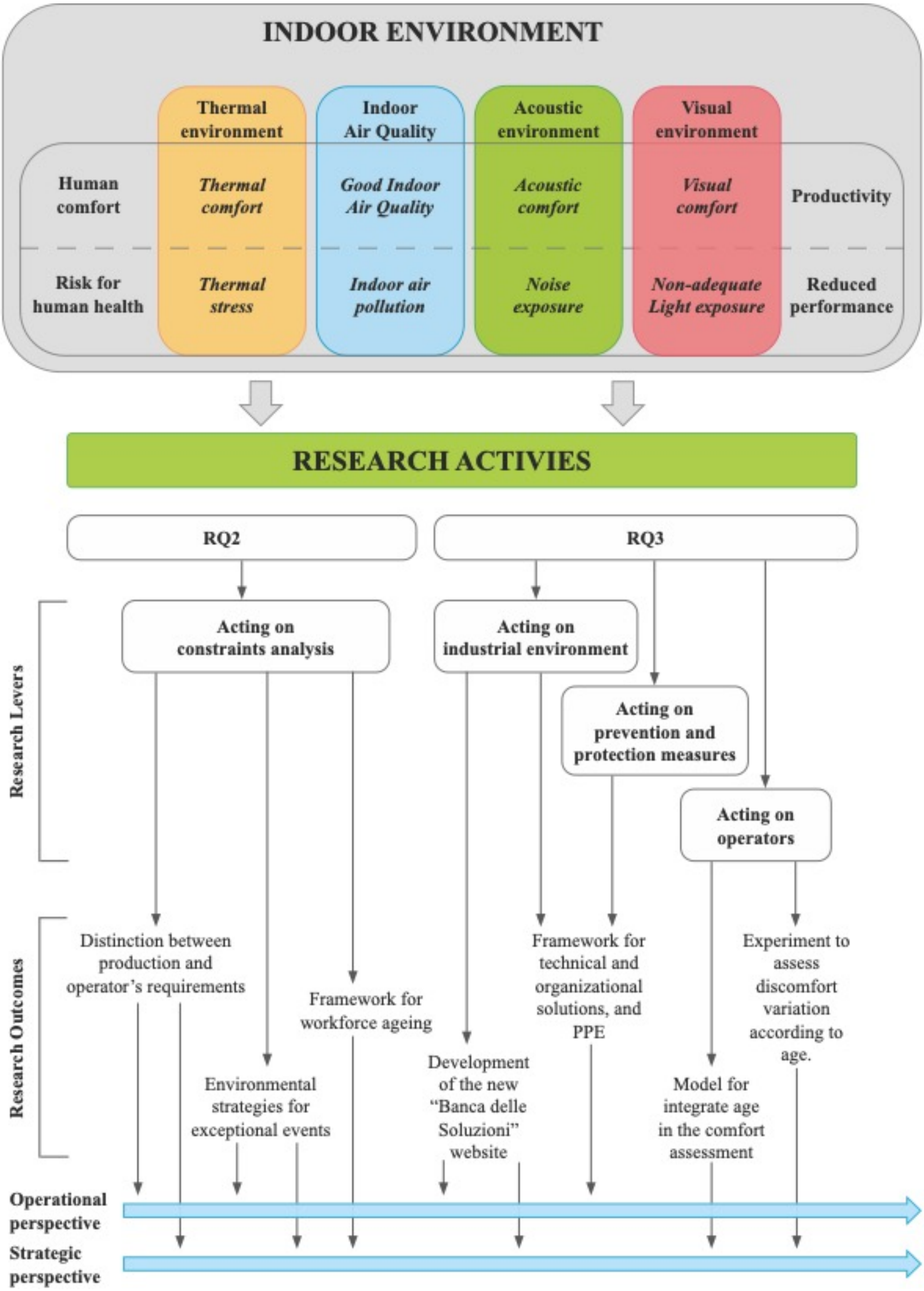

Figure 3 Outcomes of the research activity.

As illustrated in Figure 3, the first result has an impact on both perspectives, as it allows for environmental strategies that are both valuable: specific if we consider the industrial sector and scalable if different products correspond to similar processing or storage requirements.

The second outcome significantly impacts the short-term perspective because it allows for determining microclimate strategies that address a specific problem. However, these strategies can be reshaped to cope with other events from a strategic perspective. The third outcome primarily impacts the long-term strategic perspective because it needs resources and a change of view to be adopted.

The research outcomes generated to address *RQ 3* include the development of the "Banca delle Soluzioni" website, the framework for technical and organizational solutions, and PPE, the model for integrating the age factor in the comfort assessment, and the experiment to assess discomfort variation according to operators' age. The first result impacts both perspectives, as the project, already in place since 2014, is a well-established reference point for companies needing technical solutions to reduce ergonomic, microclimate, and confined environment risks. However, as an ever-expanding project, it also has a strategic impact.

The second outcome only impacts the operational perspective since technical, organizational solutions and personal protective equipment vary widely depending on the context and the operators involved. Therefore, the proposed solutions need to be readjusted strongly because of the risk analysis at the individual workplace.

The third and fourth results are mainly of strategic value in that they should be further elaborated to enable their use in the short term. However, their further elaboration is essential in an industrial context characterized by an ageing workforce.

1.5 THESIS OUTLINE

This thesis was developed following the research framework presented in the previous sections. The defined research levers and themes were arranged in a sequence of chapters, as shown in Figure 4.

Chapter 1 introduces this dissertation by outlining the area of investigation, the research questions and objectives, the research framework, and the thesis outline.

Chapter 2 presents an overview of the main factors that characterize indoor environmental quality (IEQ).

Figure 4 Thesis outline.

The chapter presents a literature review detailing, per factor, its influence on human well-being and productivity. Moreover, Section 2.2 analyzes thermal comfort and microclimate risk, presenting its main reference standards, the factors affecting it, and the leading evaluation indices. Finally, Section 2.3 concludes the chapter by highlighting key outcomes and conclusions.

Chapter 3 addresses *RQ 2* by exploring the three research topics underpinning the strategic lever, as illustrated in Figure 4. The chapter analyzes the main factors hindering thermal comfort in industrial environments. Section 3.1 delves into product, production, and energy-saving requirements that result in microclimate risk to operators. Section 3.1.1 focuses on analyzing three types of warehouses and related risks.

Specifically, cold storage warehouse and severe cold environmental risk, controlled atmosphere warehouse and suspected pollution environments, and uncontrolled temperature warehouse and severe hot environmental risk. Section 3.2 discusses the microclimate strategies adopted to cope with exceptional events and their impact on workers' health.

Moreover, Section 3.3 presents a literature review addressing the ageing of the workforce population and the impact of age in achieving thermal comfort. Finally, in section 3.4, relevant conclusions are drawn, and the outcomes of the research activity are provided.

Chapter 4 addresses *RQ 3* by exploring four research topics underpinned by three strategic levers, as illustrated in Figure 4. The chapter proposes technical and technological solutions with digital tools, a model, and an experiment to restore the thermal comfort of industrial operators.

In particular, the model and experiment address older workers and lay the foundation for microclimate risk safety management in an ageing work population. Section 4.1 presents the "Banca delle Soluzioni" project focusing on technical and technological solutions to cope with microclimate risk. Section 4.2 explores the organizational and technical solutions to improve operators' health in severe cold environments (section 4.2.1), in controlled atmosphere environments (section 4.2.2), and severe hot environments (section 4.2.3). Section 4.3 presents a model for incorporating the age of workers into the thermal comfort index.

In addition, the section illustrates a thermal chamber experiment focused on analyzing the psychological and physiological responses of older workers subjected to thermal discomfort conditions.

Finally, Chapter 5 concludes the thesis by illustrating the results obtained, managerial insights, and proposing potential future developments.

Readers interested in further exploring the research topics presented in the thesis are invited to consult the list of appended papers.

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2. ENVIRONMENTAL QUALITY OF WORKPLACES

This chapter addresses RQ. 1, focusing on the mutual relationships between IEQ factors and workers' well-being and productivity. The analysis shows how deviation from the suggested values of the IEQ factors presented strongly affects workers' well-being, reducing their performance and industrial productivity. Each factor can have an influence singly or in combination with other physical factors, complicating the human-environment relationship. This chapter presents an overview of these relationships, as comprehensive as possible. However, in subsequent sections, the thesis focuses on thermal comfort and the parameters that influence it, as the analysis shows that microclimate risk is one of the industry's most prevalent but underestimated risks.

As people spend a third of their lives at work and, in most cases, indoors, examining the factors that affect the internal work environment becomes important. The continuous and dynamic interaction between people and the working environment surrounding them produces physiological and psychological effects on operators, affecting their well-being, safety, and performance (Ismail et al., 2009; Stefanović et al., 2019). Numerous studies underline how comfort and well-being in the workplace bring positive results in terms of satisfied employees and high working performances (Isa and Atim, 2019; Kralikova and Koblasa, 2018; Szabo and Kajtar, 2018; Wu et al., 2020).

Although there are numerous factors influencing the working environment, the Indoor Environmental Quality (IEQ) factors must be considered as they directly influence the perception of the indoor environment through the senses and the occupants' physical and mental state (i.e., comfort and health) (Sugg et al., 2019).

Employees' comfort and satisfaction strongly depend on:

- Thermal comfort or indoor climate that includes parameters such as humidity, air velocity, and temperature.
- Indoor air quality: a complex phenomenon including odors, indoor air pollution, fresh air supply, etc.
- View, illuminance, luminance ratios, and reflection determine visual or lighting quality.
- Acoustic quality is determined by external and internal noise and vibration.

In addition, ergonomics plays an essential role in the perception of comfort, dealing with the design of objects, systems, and environments. Therefore, ergonomics encompasses all components of IEQ (Tagliabue et al., 2021).

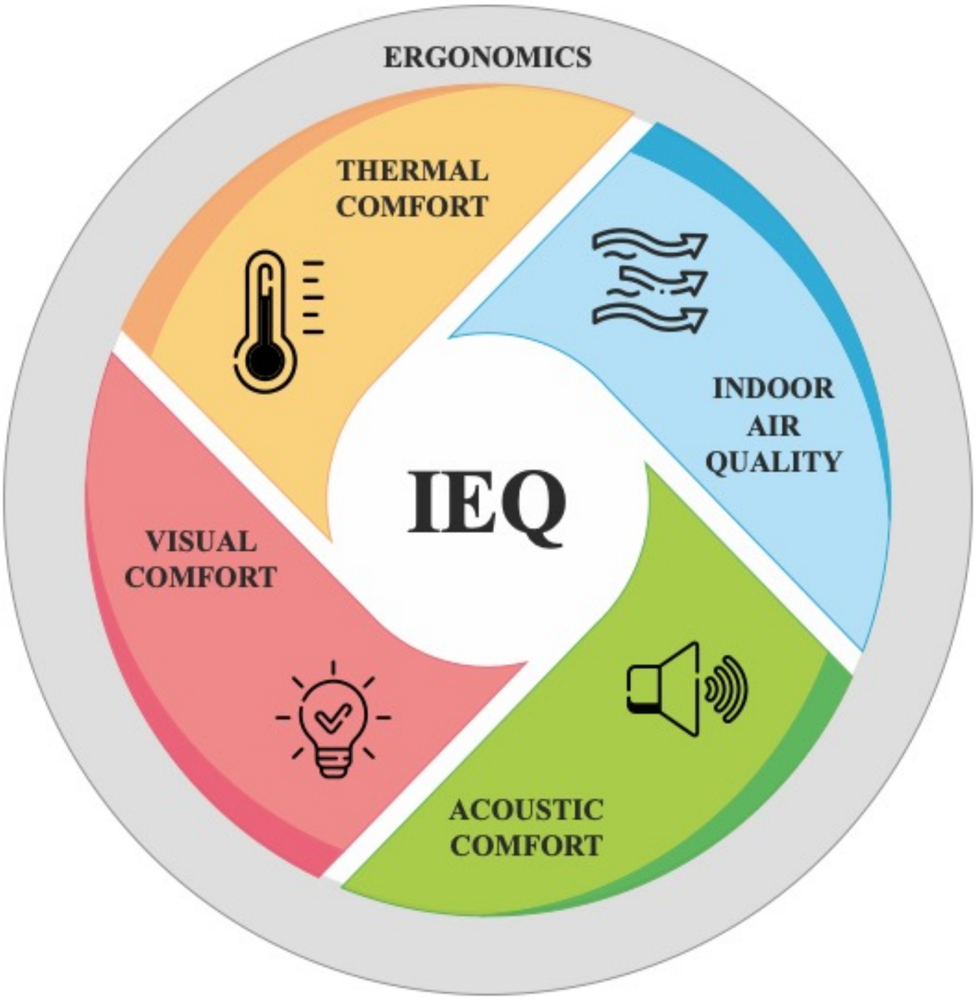

Figure 5 Indoor Environmental Quality (IEQ) factors.

On the other hand, unsatisfactory working conditions (i.e., thermal stress, indoor air pollution, non-adequate light exposure, noise, and poor ergonomics) can profoundly degrade learning and workers' performance (Mofidi and Akbari, 2016; Wang et al., 2021). The decline in work performance caused by poor IEQ leads to substantial economic loss (Wu et al., 2021).

The remainder of this chapter is organized as follows: Section 2.1 reviews the relevant literature, detailing, per factor, its influence on human well-being and productivity. Moreover, Section 2.2 focuses on thermal comfort analysis and microclimate risk, presenting its main reference standards, the factors affecting it, and the leading evaluation indices. Finally, Section 2.3 concludes the chapter by highlighting key outcomes and conclusions.

2.1 LITERATURE REVIEW: IEQ FACTORS AND THEIR INFLUENCE ON WELL-BEING AND PRODUCTIVITY

This section is organized into five parts, as many as the IEQ factors presented. Each section outlines the physical parameters that determine the IEQ factor, the values the factors must take according to the standards, and the effects on well-being and productivity due to deviation from the reference values. The ergonomic factor is only introduced, presenting its positive and negative effects on workers' health and productivity. Reference values for manual load lifting, pulling and pushing, and repetitive motion activities are mentioned but not discussed in depth.

2.1.1 Ergonomics and poor ergonomics

In August 2000, the Council of the International Ergonomics Association (IEA) officially defined ergonomics as *the scientific discipline concerned with the understanding of interactions among humans and other elements of a system and the profession that applies theory, principles, data, and methods to design to optimize human well-being and overall system performance.*

Ergonomics is strictly related to workplace design (Al Horr et al., 2016). Improper design of workplaces and tasks forces awkward postures. Repetitive movements, physically demanding tasks, and psychologically intense work increase muscle strain and cause pain, fatigue, and musculoskeletal disorders (MSDs) (Battini et al., 2018). Furthermore, poor postures such as bent wrists, arms that are raised at or above shoulder height, and prolonged periods of standing are associated with a higher risk of such injuries (EU-OSHA 2008). MSDs are associated with lower productivity and the development of workers' illnesses (Varianou-Mikellidou et al., 2019). The main consequences include damage to workers' health and financial losses to the industry (Bogataj et al., 2019). MSDs are responsible for over 40 percent of the total time lost annually.

Therefore, they are among the most expensive occupational diseases (Xu et al. 2012). The European Agency for Safety and Health at Work estimates that MSDs have an annual cost of 476 billion euros in the European Union (van den Heuvel et al., 2017).

On the contrary, integrating ergonomics in the workplace substantially benefits workers and companies, limiting these adverse effects (Chim, 2017), as explicit in Figure 6.

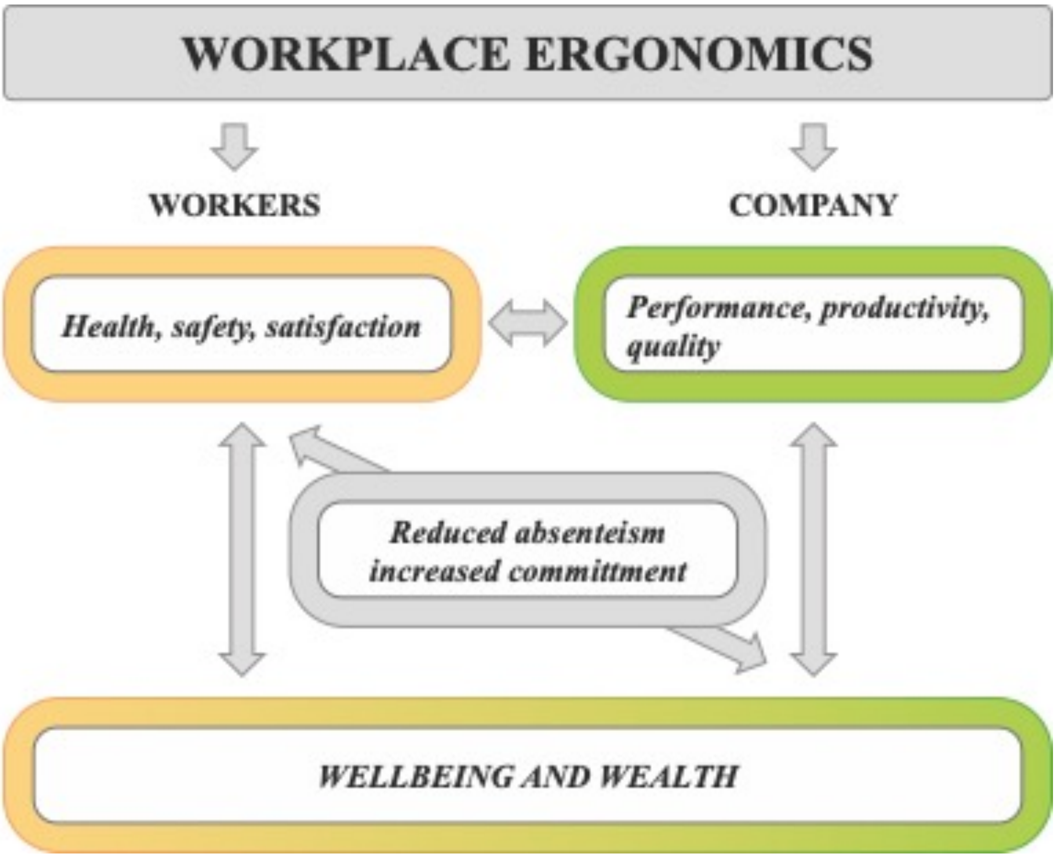

Figure 6 The ergonomics advantages for workers and companies.

Ergonomics and studying human factors aim to understand the interactions among humans and other system elements to optimize human well-being and overall system performance. The ergonomics principles should be considered in the design of workstations, staff facilities, tools, and the overall work environment, including working and non-working areas, as well as in operational phases (Digiesi et al., 2018). Moreover, Choobineh et al. (2011) recognize ergonomic training as a fundamental tool to ensure workers' well-being and performance and limit the economic impact at the industrial level. An ergonomic workplace enhances employees' satisfaction and well-being while preventing the adverse effects of poor workplace design (Walder et al., 2007).

Both employers and employees should participate in the workplace design and the re-design and provide suggestions for improving the occupational environment. The workplace design should consider the workers' physical and psychological needs and characteristics, including users with disabilities and anthropometric extremes, such as pregnant women, obese people, or anyone outside the 5th to 95th percentile range (Botti et al., 2019).

The International Organization for Standardization (ISO) fosters a workplace safety culture by providing guidelines to all those involved in the design of workplaces, workstations, and products.

The international standards, ISO 11228 and ISO 11226 establish ergonomic recommendations for manual handling tasks and work postures. The standards detail ergonomic risk assessment methods and the ergonomic approach to eliminate or reduce biomechanical overload risk. The ISO 11228 series addresses ergonomics for manual handling activities such as lifting and carrying (ISO 11228-:2022), pulling and pushing (ISO 11228-2:2009), and high-frequency load handling (ISO 11228-3:2009). ISO 11226 (ISO 11226-2:2019) is the International Standard for the evaluation of static working postures without any or only with minimal external force exertion, considering other parameters such as the body angles and the holding time, i.e., the duration that a static working posture is maintained.

These standards aim to address the application of ergonomics principles to workplace design and redesign. Corrective measures and controls are taken to avoid manual activity when the recommended limits are unmet. Alternatively, ergonomic risk can be reduced by modifying working conditions and providing auxiliary equipment.

2.1.2 Acoustic quality and noise

Noise is an unwanted sound with frequency, level, and temporal variability characteristics that negatively affect hearing health (Seidman and Standring, 2010). The perception of noise is determined by sound pressure, which is the change in atmospheric pressure due to the sound wave. The unit of measurement that identifies noise is the decibel (dB). The human ear can perceive sounds/noise varying between the threshold of audibility (about 10dB) and the pain threshold (about 140/150 dB).

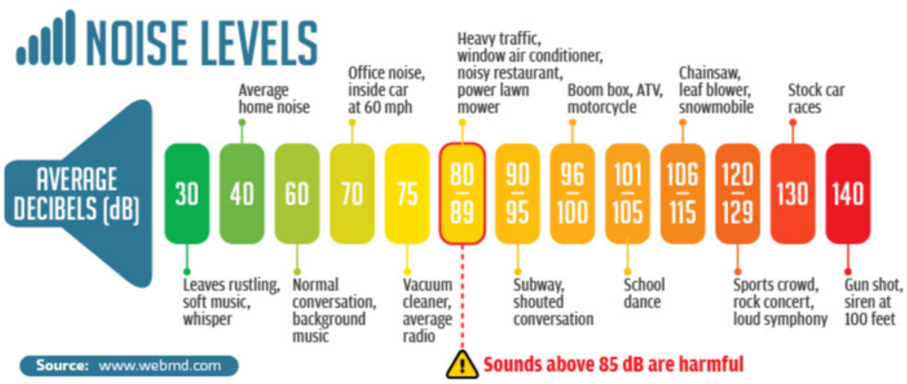

Figure 7 Noise level decibel chart.

In Italy, the Legislative Decree 81/08 establishes the limit levels for noise exposure. In particular, the allowed daily noise exposure level is 80-85 dB(A), while 87 dB(A) represents the limit level that must never be exceeded.

Article 190 of Legislative Decree 81/08 requires the employer to conduct a noise assessment to identify workers exposed to the risk and implement appropriate health prevention and protection measures.

The noise hazard depends not only on the intensity but also on the duration of exposure.

The standard defines maximum exposure levels for an average eight-hour workday in workplaces. Figure 8 associates the various daily (L_{EX},8h) and peak (L_{picc}) exposure limits with risk levels as defined by ISO 1999.

L_{EX},8h without PPE	**Peak level (L_{picc}) in Db**	**Attention index (IA)**	**Risk level**
L_{EX},8h ≤ 80	L_{picc} ≤ 135	0	insignificant risk
80 < L_{EX},8h ≤ 85	135 < L_{picc} ≤ 137	1	low risk
85 < L_{EX},8h ≤ 87	137 < L_{picc} ≤ 140	2	medium risk
L_{EX},8h > 140	L_{picc} > 140	3	high risk

Table 1 Daily (L_{EX},8h) and peak (L_{picc}) noise exposure limits according to UNI ISO 1999:2015.

This standard allows the predictive calculation of corresponding damage to a given long-term noise exposure, indicating that exceeding exposure and duration limits can generate stress and anxiety up to permanent damage such as hearing loss (UNI ISO 1999:2015).

The extent of damage also depends on other factors such as individual susceptibility, interpersonal variability, the subject's age, and previous and concomitant ear diseases (Bellomo et al., 2010).

Although all employers are required to conduct a noise risk assessment, in many industries (e.g., agriculture, construction, engineering, food and beverage, woodworking, foundries, and entertainment), noise levels continue to regularly exceed limit values, negatively impacting workers' health and productivity (Schneider, 2005).

In Italy, noise is still one of the major causes of occupational disease reported to the Italian Workers’ Compensation Authority (INAIL). Although it is a decreasing risk (Pizzuti et al., 2018), the

European Environment Agency (EEA) reports a total of 16,900 people exposed to high levels of noise in the industrial sector.

The EEA is an EU body committed to establishing a monitoring network to control European environmental conditions. Based on the European indicators for noise pollution defined under the Directive 2002/49/EC relating to the assessment and management of environmental noise – the Environmental Noise Directive (END), the EEA mapped the noise levels within European industries. These data, depicted in Figures 8a and 8b, show the number of people exposed to different noise thresholds in the daytime (8a) and nighttime (8b).

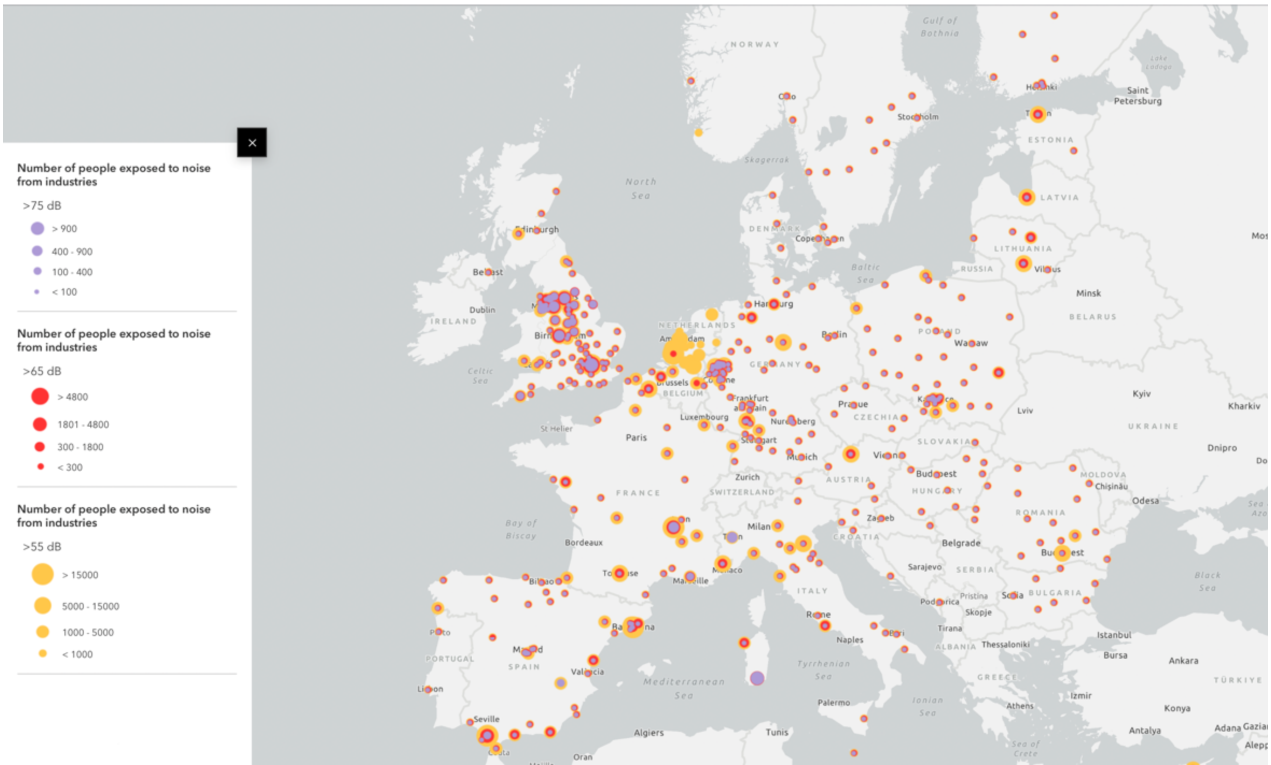

Figure 8a Number of people exposed to noise in European industries during the day.

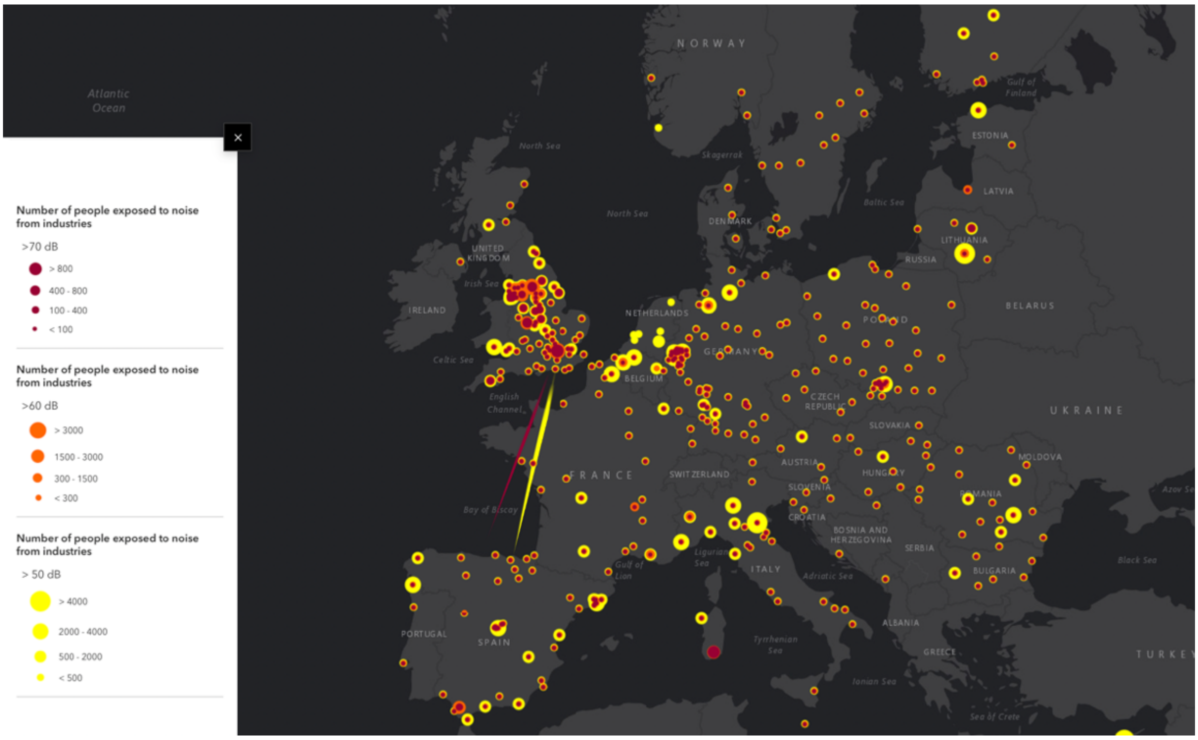

Figure 8b Number of people exposed to noise in European industries at night.

High noise levels at the workplace are responsible for increased blood pressure, disturbed sleep patterns, headache, hypertension, cardiovascular diseases, weariness, and psychological stress (Isa and Atim, 2019; Salata et al., 2018). Loud noises significantly reduce work performance (Lamb and Kwok, 2016), but even mild noise impairs performance by reducing operators' ability to concentrate (Khoshbakht et al., 2021). Moreover, both internal noise caused by operating machinery and noise from outside the building (transport/traffic) are responsible for the decline in performance.

Noise from outside can be countered using sound-absorbing building materials and interior design. However, the primary source of noise in the industrial environment concerns indoor noise and gas flows within ducts. In this case, the primary solution involves the installation of cylindrical or parallelepiped industrial silencers.

Both devices consist of a metal casing containing sequences of sound-absorbing materials. The differences concern the presence of perforated metal baffles in cylindrical silencers and perforated protective plates in the case of parallelepiped silencers. These devices are placed inside ducts, turbines, and ventilation systems (cylindrical or square/rectangular). Their operation involves energy absorption by fluid contact with sound-absorbing materials, causing a drastic reduction in residual sound pressure levels downstream of the silencer (Evdokimova and Rumyantseva, 2020).

2.1.3 Visual and lighting quality and non-adequate light exposure

Visual comfort is “a subjective condition of visual well-being induced by the visual environment” (Antoniadou and Papadopoulos, 2017). The main factors contributing to visual comfort are lighting and the view.

Light affects the occupant’s perception of the environment. The light characteristics can make the environment pleasant, bright, and warm, or cold and dark. Figure 9 illustrates the main photometric quantities (i.e., luminous intensity, luminance, and illuminance).

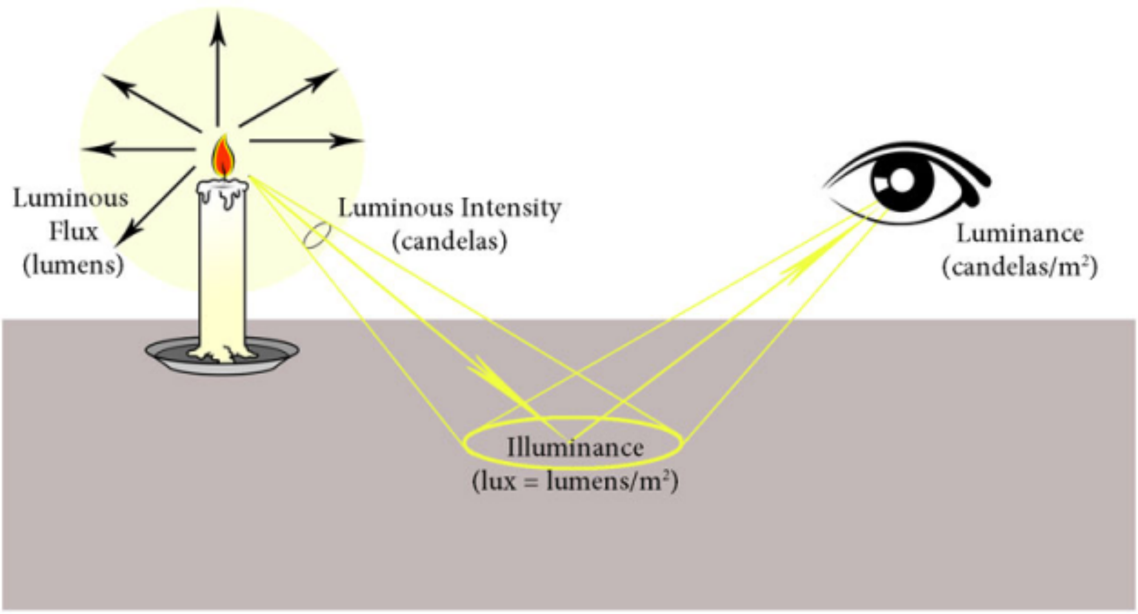

Figure 9 Representation of photometric quantities and their measurement units.

Luminous intensity refers to the overall brightness without considering the area of the light source. Luminous intensity has historically been measured in terms of the visible radiation emitted by a candle flame; therefore, its unit of measurement has been the Candela (cd) (Berlin and Adams, 2017). Today, 1 cd is defined as 1/683 W/sr at a frequency of 540 x 10^{12}Hz (Bohgard, 2009).

Then, luminance describes the light emitted by the light source and is measured in candela per m2 (Cd/m2) (Kroemer, 1997). Luminance differences result in different levels of brightness. Finally, illuminance represents the amount of light reflected from an illuminated surface.

In addition to photometric quantities, the design of working environments must also consider contrast, glare, and reflections.

Contrast is the difference in luminance or color that makes an object visible against a background of different luminance or color. Higher contrast provides greater clarity or readability (Mofidi and Akbari, 2016). Glare refers to the objective reduction in visual performance and the subjective disturbance caused by high luminance or high contrasts in the field of view. Glare is always undesirable because it causes high discomfort in viewing objects and affects the retina (Sun et al., 2019). Reflectance refers to the ability of a surface to reflect light and depends on the material or color. It is the percentage (%) of reflected light compared to incident light. In workplaces, walls and ceilings are usually lightly colored to promote light diffusion in the room, while machinery and equipment are dark in color to limit glare and reflections (Makaremi et al., 2019).

Lighting in spaces consists of two sources: daylight and artificial light.

Daylight is considered a fundamental component of the sustainability of industrial buildings, both for the benefit of workers' health and productivity and for the potential energy savings (Turan et al., 2020). People naturally prefer sunlight over artificial light due to physiological and psychological reasons. Above all, daylight is considered the best light source as it offers optimal visual conditions (Yang and Nam, 2010). Moreover, natural light strongly influences melatonin production, keeping the circadian rhythm of the human organism regular.

The benefits of this mechanism concern regulating hormonal levels, sleep-wake rhythm, and metabolism. In addition, daylight directly affects the workplace's thermal state as windows absorb and transfer significant solar radiation into the indoor environment.

However, natural light should be balanced with artificial sources in industrial environments to reduce worker dissatisfaction (Al Horr et al., 2016). In fact, on one side, a low level of lighting can lead to eye discomfort; on the other, excessive direct sunlight can cause glare, resulting in visual discomfort, fatigue, and headache (Hamedani et al., 2020).

The UNI EN 12464-1:2021 standard provides guidelines on the correct illumination level in indoor workplaces. Table 2 shows the maintained illuminance ($\bar{E}_m$) required, the minimum illuminance uniformity (U_o), and the Unified Glare Rating limit (R_{UGL}) according to different activities performed in some industrial areas in compliance with the standard.

Sector	**Type of task/activity area**	$\bar{E}_m$	U_o	R_{UGL}
Logistics and warehouses	Unloading / loading area	200	0,4	25
	Packing / grouping area	300	0,5	25
	Central logistics corridor (heavy traffic)	300	0,6	25

Ceramics, tiles, glass, glassware	Enamelling, rolling, pressing, shaping simple parts, glazing, glass blowing	300	0,6	25
	Grinding, engraving, glass polishing, shaping precision parts, manufacture of glass instruments	750	0,7	19
	Precision work, e.g., decorative grinding, hand painting	1000	0,7	16
Electrical and electronic industry	Cable and wire manufacture	300	0,6	25
	Winding large coils	300	0,6	25
	Winding small coils	750	0,7	19
	Rough assembly works, e.g., large transformers	300	0,6	25
	Precision assembly works, e.g., measuring equipment, printed circuit boards	1000	0,7	16
Cement, cement goods, concrete, bricks	Drying	50	0,4	28
	Preparation of materials; work on kilns and mixers	200	0,4	28
	General machine work	300	0,6	25

Table 2 Examples of minimum illuminance values required in different industries according to UNI EN 12464-1:2021.

Proper daylight and artificial light management ensure that tasks are performed efficiently and effectively (Varianou-Mikellidou et al., 2019). Adequate control of the lighting system allows for differentiating the lighting conditions based on the activities carried out, increasing the contrast to make objects more visible and avoiding glare (Mofidi and Akbari, 2016).

Conversely, improper lighting conditions contribute to eye strain, watery eyes, headaches, and blurred vision, causing difficulty perceiving letters. Errors resulting from a lack of understanding of instructions significantly drop performance (Lamb and Kwok, 2016) and significant safety issues (Bai and Wicaksono, 2020).

Based on connectivity and big data, modern lighting systems vary the intensity and color of the LED lights per the variation of natural light. This process allows the minimization of the variation of light perceived by the operators, protecting their visual performance.

In addition to lighting, the literature points out that visual comfort is also influenced by the pleasantness of the work environment (Castaldo et al., 2018). The layout of rooms and furnishings, the outdoor view, and the presence of elements that recall nature are crucial in ensuring workers' well-being.

Windows offers visual information, such as weather, nature, and surrounding activities, impacting occupants' productivity (Heerwagen and Orians, 1993). Besides, the vegetation outside the building, visible through the windows, helps reduce workers' stress and anxiety (Ko et al., 2020). At the same time, the presence of plants or elements that recall nature positively affects the occupants' satisfaction within industrial spaces. Elzeyadi's (2011) study shows a correlation between decreased worker absenteeism and the introduction of biophilia in offices. Nature in working environments positively influences productivity, negatively affects the occupants' stress, and represents a sustainable but untapped solution to improve indoor air quality (Al Horr et al., 2016). Plants, through the process of photosynthesis, can absorb CO_2 and volatile compounds produced by indoor furniture and synthetic materials. In addition, plants increase indoor air humidity levels by generating water vapor (Smith and Pitt, 2011).

2.1.4 Indoor air quality and indoor air pollution

Indoor Air Quality (IAQ) is a complex entity to measure because it depends on interdependent physical factors such as humidity, temperature, and atmospheric contaminants. Such parameters are influenced by external conditions, building conditions (e.g., material, structure, and construction), heating, ventilation, and air-conditioning systems (HVAC), and interior space arrangement (Zhu et al., 2020).

Indoor air humidity (IAH) is a primary parameter (e.g., relative (RH) or absolute (AH)) in defining IAQ. IAH represents the relationship between perceived air dryness and potential health effects on occupants. The ASHRAE standard (ASHRAE, 2010) established that humidity levels outside the 30-60% range adversely affect the occupants' health and performance. The minimum recommended IAH level in industrial environments is 30-40% (Wolkoff, 2018).

However, uncomfortable temperatures and pollutants (e.g., dust) alter the perception of dry air, which can occur even at relative humidity levels of 50 percent (Byber et al., 2016). When RH levels fall outside the 40-60% range, adverse effects on workers' health and productivity occur due to biological and chemical factors summarized in Figure 10 (Alsmo and Alsmo, 2014).

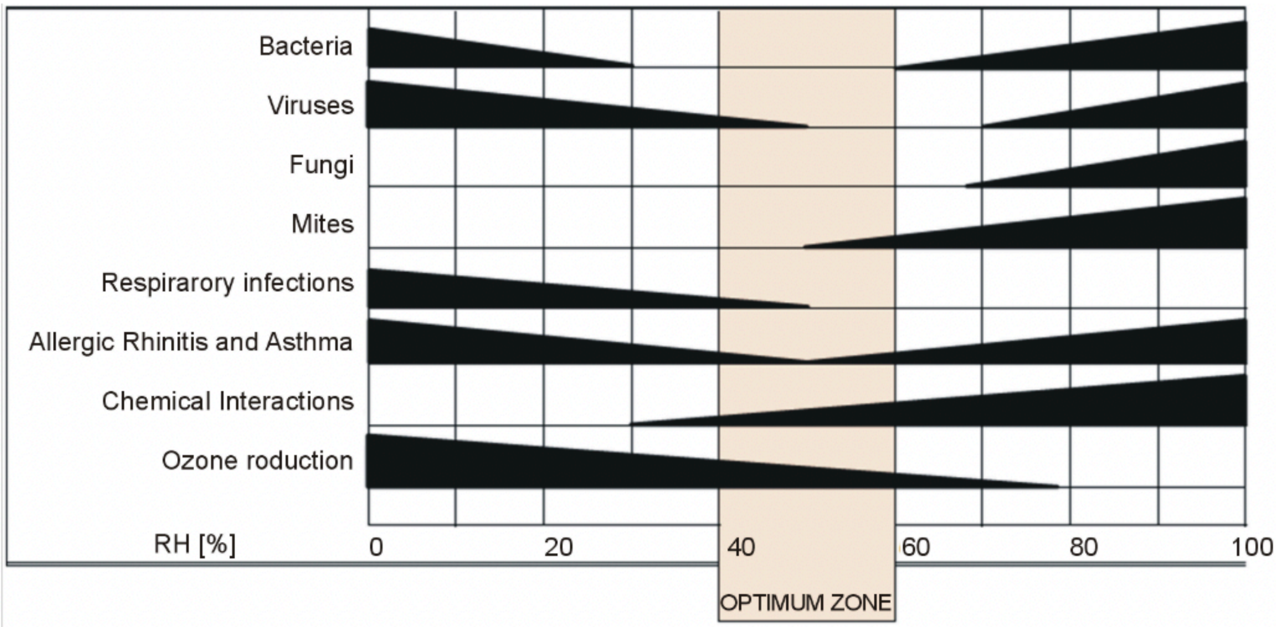

Figure 10 Biological and chemical factors impacting occupants' health when RH levels fall outside the optimum zone (i.e., 40-60%) from the Alsmo and Alsmo study (2014).

Low humidity levels within industrial environments cause the so-called "dry air" perception, a sensation of sensory irritation like a cold, while prolonged exposure leads to Sick Building Syndrome (SBS) (Zhao et al., 2011; Dalton et al., 2018). The main symptoms include dryness, itching, pain and burning in the eyes, irritated nose, and sinusitis.

Prolonged exposure to low humidity leads to respiratory irritation, headaches, lethargy, and mental fatigue (Al Horr et al., 2016). In addition, the intensive drying of the upper airway mucous membranes decreases their protective functions against sensory irritants, e.g., oxidants, particles, bioaerosols, and infections. In contrast, an increase in IAH relieves the perception of "dry air" and the symptoms of dry eyes and upper airways. Byber et al. (2016) consider an IAH of 45% optimal for the self-cleaning function of the airways.

However, even high IAH levels can negatively affect workers' health and performance. The study by Bai and Wicaksono (2020) shows that by keeping the temperature constant at 35 ◦C (95 ◦F), operator performance does not vary significantly by varying the relative humidity percentage between 50% and 75%. However, for relative humidity values above 75%, a significant performance deterioration is observed in slower reactions. In addition, an IAH between 60% and 90% promotes mold growth, which seems to have correlations with SBS (WHO, 2010).

Finally, IAH affects the emission rate of pollutants from building materials, increasing or decreasing their environmental presence (Byber et al., 2016).

IAH and IAQ can be managed by increasing the ventilation rate (VR) through ambient air dilution to reduce the concentration of atmospheric pollutants emitted by indoor sources (Sun et al., 2019). As a result, the ventilation rate is an efficient IAQ monitor in a building. A good IAQ corresponds to high ventilation rates (about 25 l/s per person), as shown in Figure 11.

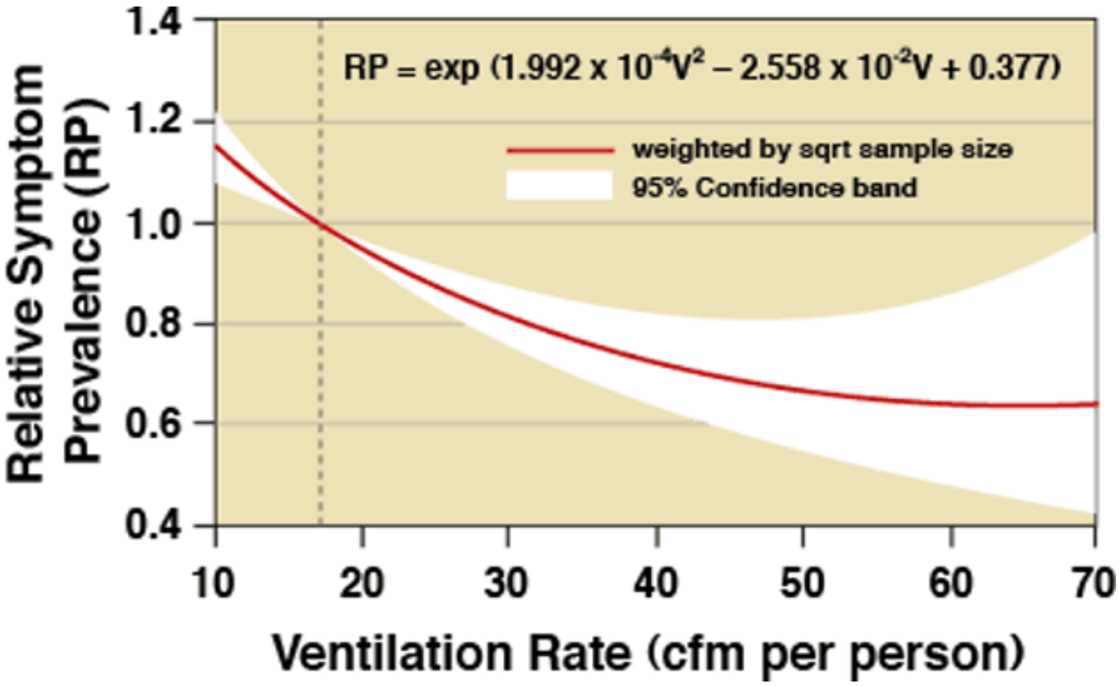

Figure 11 Estimating the relative prevalence (RP) of BSS symptoms as a function of ventilation rate.

Figure 11 shows the estimated relative prevalence (RP) of BSS symptoms as a function of ventilation rate. RP = 1 corresponds to the minimum ventilation rate (8 L/s per person) required for work environments by ASHRAE in 2010. Increasing the ventilation rate from 8 to 24 L/s per person reduces RP from 1.0 to about 0.67.

On the other hand, reduced ventilation rates are associated with lower IAQ and lead to symptoms attributable to SBS (Kotek et al., 2015). These symptoms result in a lack of concentration, reduced working capacity and task performance, and increased sickness absence, resulting in decreased industrial productivity (Ben-David et al., 2018; Reinhold and Tint, 2009; Stazi et al., 2017).

Franco and Schito (2020) highlight that increasing VR reduces SBS symptoms and improves occupants' performance with decreased absenteeism. Improving IAQ brings benefits to both occupant and building performance.

Higher ventilation rates in a building can result in a financial return ten to sixty times higher than annual energy and maintenance costs (Al Horr et al., 2016). Fisk et al. (2012) quantitatively estimated the benefits and costs of increasing ventilation rates in offices. The study demonstrates an annual economic benefit of $13 billion by increasing minimum ventilation rates from 8 to 10 l/s per person and $38 billion by increasing ventilation rates from 8 to 15 l/s per person.

Introducing “clean” external air can occur naturally, through the opening of the windows, or mechanically, with ventilation systems. The main advantage of natural ventilation concerns the ability to improve IAQ and thermal comfort in hot climates without consuming a significant amount of energy (Salcido et al., 2016).

Furthermore, opening the windows increases the particle output fraction by about 38% and helps reduce aerosol deposition on individuals in the environment by about 80% (Abuhegazy et al., 2020). However, window opening time should be optimized according to the number of people and activities to avoid overcooling, especially in cold industrial environments or loss of cooling/heating energy (Morawska et al., 2020).

Natural ventilation is an effective and sustainable method to improve IAQ. However, introducing external air may not ensure the IAQ. For example, during the winter period, it is crucial to control the indoor temperature. Temperature below 18 °C increases the risk of cardiovascular and respiratory morbidity and mortality during cold seasons for regions characterized by temperate or cold climates (Wolkoff et al., 2021). A further risk factor concerns the dryness of the cold air introduced, which can cause SBS symptoms, making exposed subjects more sensitive to internal pollutants (Salata et al., 2018). In addition, outside air itself can contain contaminants (e.g., PM particles) that can affect health if inhaled outdoors or indoors. Ventilation can carry these contaminants into interior spaces (Hamilton et al., 2016).

However, high ventilation rates should be maintained in industrial environments to limit internal pollutant levels. Where natural ventilation involves risks for the occupants, air exchange must be guaranteed through mechanical ventilation systems. HVAC systems play an essential role in improving the IAQ and IAH of the building environment. Those systems can extract moisture from the exhaust air and return it to the supply air. This means that, during the winter season, they make the dry air more humid, while during the summer, they produce a cooling effect through the evaporation of the humidity in the supply airflow. However, humidity significantly impacts the energy consumption of the HVAC system.

Shehadi (2018) showed that, in an effective ventilation system, by reducing the indoor relative humidity (RH) setting from 60% to 50%, the total energy consumption increases up to a maximum of 22.4%. HVAC systems are the most expensive building tools for improving IEQ, accounting for nearly 40% of the building's total energy consumption (Zhu et al., 2020; Yuan et al., 2021). Despite the significant energy footprint, industrial occupants are often dissatisfied with their thermal comfort (Frontczak et al., 2012).

Mixed-mode ventilation (MMV) systems increase IAQ with predominantly natural ventilation and HVAC systems. MMV employs the combination of natural ventilation from manually or automatically controlled windows and mechanical air conditioning to provide air distribution and a form of cooling only when necessary. Their primary goal is to maximize the building's internal thermal comfort, avoiding unnecessary energy use (Salcido et al., 2016). In HVAC systems, the control of the IAH increases significantly, as does the energy expenditure of the building.

On the other hand, in MMV systems, the energy expenditure is lower thanks to the introduction of air through the windows opening; however, this makes it difficult to adjust the IAH. In this case, separate air humidifiers can be used, which intervene locally at the environmental level. These humidifiers can be of different types: those that produce steam by thermal evaporation, cold atomizers that nebulize water through a high-frequency fan, and ultrasonic atomizers that create steam through ultrasonic waves (Byber et al., 2016).

The ventilation, conditioning, and humidification systems, while representing the leading technologies for the improvement of IAQ, can be a source of microbial spread (e.g., viruses, bacteria, fungi, molds) and volatile compounds, with consequent health problems for workers, e.g., infections, allergic reactions, SBS symptoms.

High Efficiency Particulate Air filters (HEPA) are added to the heating and ventilation systems to limit the spread of pathogens in different environments. Such filters require accurate cleaning, maintenance, and replacement operations to maintain their efficiency. Inside the humidification systems, adding bioacids to the nebulized water prevents the growth of pathogens. However, these substances can cause irritation or allergic reactions in exposed subjects.

2.1.5 Thermal comfort and thermal stress

In the late 19th century, thermal comfort was introduced as an environmental factor contributing to IAQ and indoor comfort. Thermal comfort is closely linked to ventilation (Akimoto et al., 2010).

Environments characterized by poor IAQ and uncomfortable thermal effects are often poorly ventilated environments. (Billings et al, 1898; Janssen, 1999).

Thermal comfort refers to the thermo-hygrometric perception of humans toward the environment (Salata et al., 2018). The American Society of Heating, Refrigerating, and Air-Conditioning

Engineering (ASHRAE), through Standard 55, has defined thermal comfort as "a condition of mind that expresses satisfaction with the thermal environment."

Due to its psychological and physiological nature, achieving thermal comfort is complex (Li et al., 2018). Thermal comfort depends on several physical parameters, which create a thermal state and subjective human responses to that thermal state. Figure 12 depicts the environmental (i.e., air temperature, air humidity, mean radiant temperature, and air speed) and personal factors (i.e., metabolic rate or activity level and clothing insulation) influencing thermal comfort.

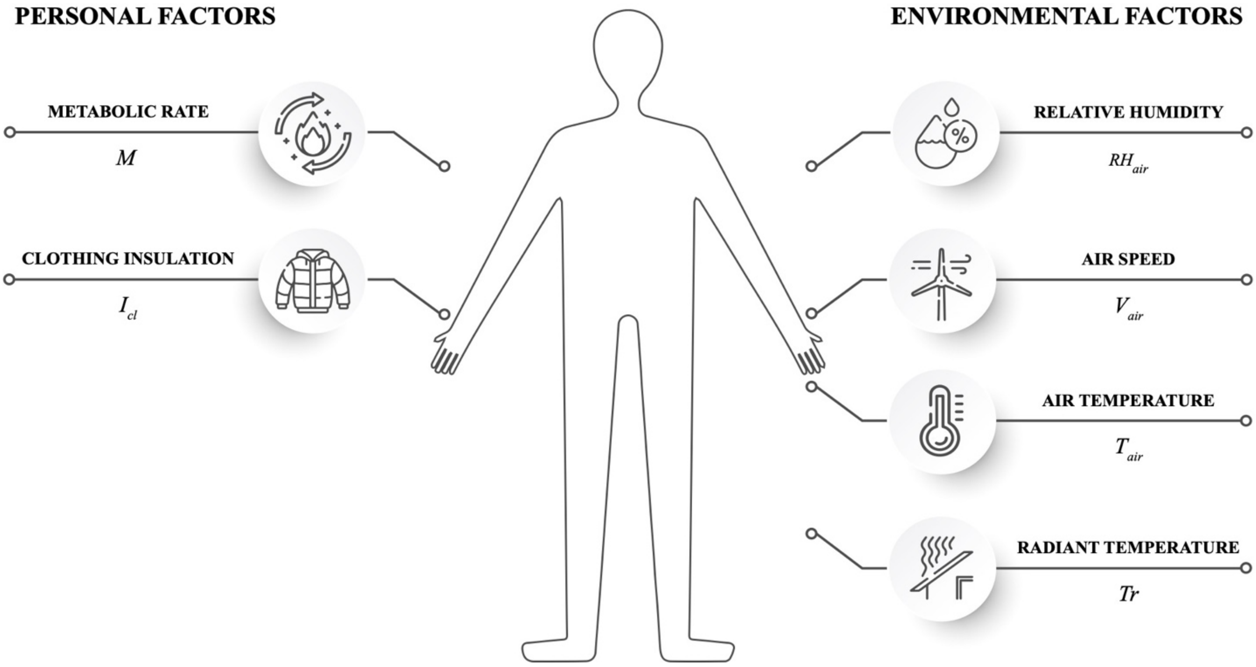

Figure 12 *Environmental and personal factors that influence thermal comfort.*

Traditional thermal comfort analysis methods use the energy balance of the human body to determine the heat transfer between the body and the environment (Prek, 2006).

Table 3 defines human-environment heat transfer parameters within the energy balancing equation.

Parameters	
S	Change in internal energy, which is the difference between the thermal power acquired and dissipated by the human body [W]
M	Metabolic rate [W]
W	Mechanical power required to perform mechanical work [W]

C_{RES}	Heat power exchanged in respiration by convection [W]
E_{RES}	Heat power exchanged in respiration by evaporation [W]
K	Heat power exchanged by conduction [W]
C	Heat power exchanged by convection [W]
R	Heat power exchanged by radiation [W]
E	Heat power transferred by transpiration and sweating [W]

Table 3 Parameters influencing human-environment heat transfer within the energy balancing equation.

The analytical formulation of the change in internal energy as the difference between the heat power acquired and dissipated by the human body is shown in the following equation:

$$S = M - W \pm C_{RES} \pm E_{RES} \pm K \pm C \pm R - E \qquad (1)$$

The individual terms in equation 1 have a positive sign if there is a gain of energy and a negative sign if there is an energy loss. Table 4 displays the change in body temperature and thermal sensation as a function of the S parameter.

Thermal energy			**Body temperature**	**Thermal sensation**
S=0	Thermal equilibrium	No change in energy	Constant	Neutrality
S>0	Input thermal power greater than output thermal power	Positive change in energy	Increases	Warm
S<0	Input thermal power lower than output thermal power	Negative change in energy	Decreases	Cold

Table 4 Change in body temperature and thermal sensation as a function of the S parameter.

As shown in Table 4, equation (1) can take the following values:

- S=0 when there is a lack of energy change within the body and represents the thermal equilibrium condition. In this case, the temperature tends to remain constant, and the sensation is thermal neutrality.
- S>0 when the heat input to the body is greater than the heat output. This positive change in internal energy causes an increase in core temperature, resulting in a sensation of warmth.
- S<0 when the heat input to the body is lower than the heat output. Such an adverse change in internal energy decreases core temperature, resulting in a cold sensation.

Thermoregulation maintains physiological core body temperature by balancing heat production and loss, regardless of environmental conditions. The body implements physiological mechanisms to maintain thermal neutrality (S=0), including sweating, shivering, and vasodilation (Tansey and Johnson, 2015). A healthy individual generally maintains an internal body temperature of 37 +/- 0.5°C (98.6 +/- 0.9°F), which allows for the proper function of the body's metabolic processes (Hymczak et al., 2021).

However, prolonged exposure to thermal stress conditions can impair the thermoregulatory system, causing a series of effects ranging from aspects of a perceptive type (comfort/discomfort) and performance aspects up to aspects involving physiological elements and even the vital functions of the individual himself (Isa and Atim, 2019). In this field, the study proposed by Ormandy and Ezratty (2012) shows that keeping the environment's temperature within the range of thermal comfort implies the protection of workers' health.

Table 5 depicts the physiological effects caused by different degrees of thermal discomfort (i.e., hot and cold). Exposure to high and low temperatures is associated with increased risk for various cardiovascular and respiratory diseases in the work environment.

COMFORT ZONE	**SLIGHTLY BEYOND COMFORT ZONE**	**DISCOMFORT**
Warm	**Moderate heat**	**Extreme heat**
• Increased peripheral blood flow • Skin temperature rises • Drop in muscle tension	• Sweating • Loss of fluids and salt • Tiredness • Decreased performance and alertness • Increased risk for errors	• Painful cramps • Impaired function of stomach and intestines • Heat regulation failure

	• Increased risk for accidents	
Cool	**Moderate cold**	**Extreme cold**
• Reduction of blood flow to skin, constricted blood vessels • Decrease in performance due to thick clothing	• Shivering • Decreased fine motor function • Decrease in sense of touch	• Disorientation • Apathy • Weaker breathing • Frostbite

Table 5 Physiological effects of heat and cold at different intensities.

In particular, high temperatures cause an increase in the body 'core' temperature, leading to fatigue and decreased muscle endurance. Prolonged exposure to hot temperatures provokes heat cramps, heat exhaustion, and heat stroke (Ilangkumaran et al., 2014).

Cold temperatures increase vasoconstriction and lower tissue temperature (Gasparrini et al., 2015). Moreover, cold exposure affects the respiratory and musculoskeletal systems, resulting in numbness, decreased manual dexterity, and reduced strength. Moreover, prolonged exposure to cold causes skin disorders (e.g., rash and hives) and cold-associated trauma such as Raynaud's phenomenon, frostbite, trench foot, chilblains, and hypothermia (Thetkathuek et al., 2015).

Nico et al. (2015) highlight that employees working in adequate hygrothermal conditions are more productive, attentive, and less prone to absenteeism and complaints, significantly reducing the risk of accidents during working hours. On the other hand, thermal stress from both cold and heat negatively affects workers' performance in industrial environments by reducing cognitive capacity and work rate (Cai et al., 2018; Lamb and Kwok, 2016).

Furthermore, thermal stress affects the workers' efficiency, leading to poor decision-making and process errors that increase the risk of accidents (Tagliabue et al., 2021). Literature studies defined 21-25°C as a stable temperature range for office productivity, while workers' performance decreases by 2% with each 1°C increase in the 25-30°C temperature range (Al Horr et al., 2016: Seppänen et al., 2006; Wyon and Wargocki, 2020) .

2.2 ASSESSING MICROCLIMATE

The term microclimate or thermal climate describes environmental parameters and their interdependence within the environments in which an individual lives or works (Parson, 2003). Figure 13 illustrates the indoor environmental parameters that influence the microclimate:

- air temperature (T_{air});

- mean radiation temperature (mean of Tr_1 to Tr_6);
- air velocity (V_{air});
- relative humidity (RH_{air}).

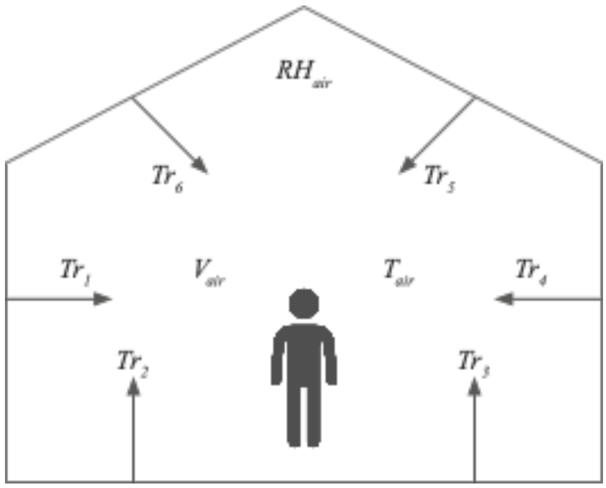

Figure 13 Thermal parameters of the thermal comfort factor: Tr represents the radiant temperature of a surface, RH_{air} is the relative humidity of the indoor air, V_{air} is the air velocity, and T_{air} expresses the air temperature.

The average energy of the microscopic motions of a single particle in the system per degree of freedom determines the system's temperature. The temperature measurement units are the Celsius and Kelvin scales for thermodynamic temperature.

The mean radiant temperature is the temperature of a uniform envelope with which a black sphere at the test point would have the same radiation exchange as it has with the real environment.

Air velocity is the rate of change of position (displacement per unit time) expressed in meters per second (m/s). Velocity is a vector physical quantity defined through speed and direction.

Humidity is the amount of water vapor in the air. Absolute and relative humidity are different ways of expressing the water content in a particle of air. Specifically, relative humidity is the ratio (in percent) of the partial pressure of water vapor in a gaseous mixture of air and water vapor to the saturated vapor pressure of water at a given temperature. The relative humidity is expressed as a percentage.

In Italy, microclimate is now recognized as a physical risk agent under Legislative Decree 81/2008. However, unlike the assessment of other physical agents, the legislation requires that the assessment consider the activity performed by the worker without providing quantitative guidance on the limit values of microclimate parameters. Specifically, Title VIII and Title II-Annex IV deal with the risk of microclimate exposure in the workplace, while Article 181 defines microclimate risk assessment as an employer's obligation. In addition, the problem approach, the investigation methodology, and the relevant reference standards depend on the thermal environment type. Therefore, thermal environments are categorized as moderate and severe.

"Moderate" environments are environments in which the thermal exchanges between subject and environment allow the achievement of conditions close to thermal equilibrium, that is, thermal comfort, according to Section 2.2.1. These environments are free of constraints that would compromise the achievement of comfort, and consequently, they are defined as moderate according to 1.9.2 of Annex IV of Legislative Decree 81/2008. The assessment of moderate environments focuses on defining the degree of worker discomfort.

Whereas, in severe environments, the analysis aims to prevent thermal stress according to Section 2.2.2. "Severe" environments are those in which environmental conditions result in a thermal imbalance in the exposed subject, representing a health risk factor. As severe environments are characterized by production requirements that determine restrictions on microclimatic parameters, they are also defined as constrained environments. Finally, severe environments are, in turn, divided into hot and cold environments, depending on thermohygrometric characteristics.

The International Organization for Standardization (ISO) specifies several procedures for microclimate assessment, displayed in Figure 14. In particular, the UNI EN ISO 7730:2006 standard contains the analytical determination and interpretation of thermal comfort by calculating the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) indices and local thermal comfort criteria, applicable in moderate environments.

Section 2.2.1 displays Fanger's model for PMV and PPD calculations. For hot severe environments, Figure 14 highlights the UNI EN ISO 7243: 2017 standard dedicated to Heat Stress Evaluation using Wet Bulb Globe Temperature (WGBT) index and the UNI EN ISO 7933: 2005 for Analytical Determination and Interpretation of Heat Stress by Calculating Predictable Thermal Stress (PHS). For severe cold environments, the primary reference standard is the UNI EN ISO 11079: 2008 for the Determination and Interpretation of Cold Heat Stress using Required Clothing Thermal Insulation (IREQ) and Local Cooling Effects. Section 2.2.2 presents WGBT and IREQ methods.

In addition, Figure 14 highlights supporting standards and specific standards for industrial environments.

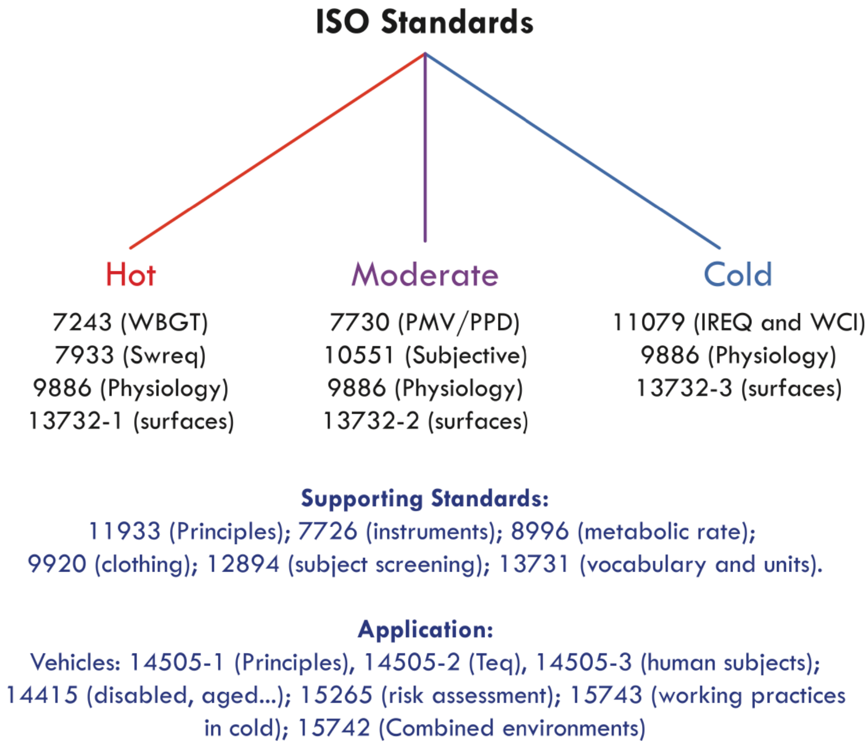

Figure 14 ISO standards for different aspects of the ergonomics of thermal environments

2.2.1 MODERATE ENVIRONMENTS

Moderate environments are characterized by the absence of constraints that can compromise the achievement of thermal comfort and, consequently, the health of the exposed individuals.

The most widely used indices are derived from a theoretical approach based on applying the heat balance equation to the human body. The PMV and PPD models are the most widely used, developed by Ole Fanger in the 1970s and contained in ISO 7730:2005.

Fanger's model predicts the number of people who will be satisfied with the temperature within a large population (Fanger, 1973). The PMV represents the mean value of the thermal sensation votes of a group of people occupying a specific environment on a 7-point thermal sensation scale from −3 (cold) to 3 (hot), as depicted by Table 6.

Value	Thermal Sensation
+ 3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral

- 1	Slightly cool
- 2	Cool
- 3	Cold

Table 6 Seven-point thermal sensation scale, from UNI EN ISO 7730:2005.

The PPD quantifies the percentage of occupants whose thermal sensation vote differs from the PMV value. The analyzed population is often not satisfied with the thermal environment corresponding to PMV=0 due to variations in personal preferences (Salata et al., 2018). For this reason, thermal comfort is measured in the workplace by analyzing the number of complaints. Therefore, the PPD graph often shows a U-shaped curve, as highlighted in Figure 15.

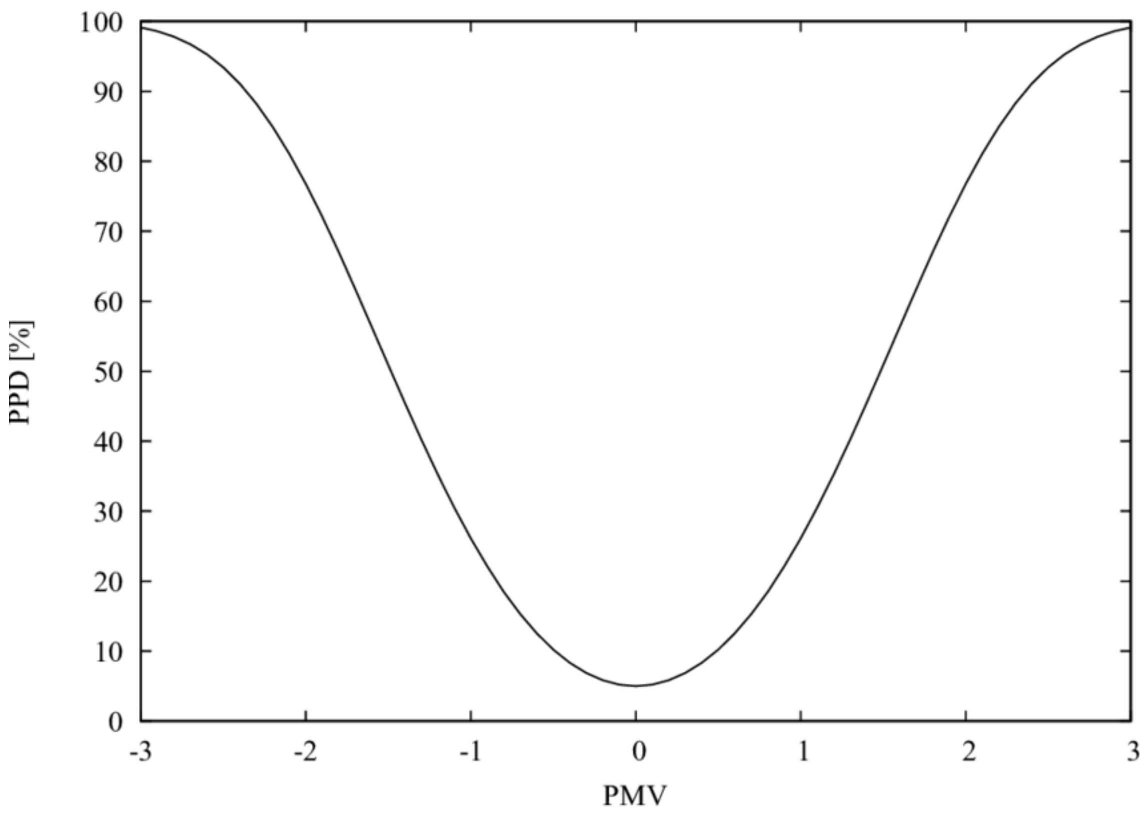

Figure 15 The relationship between PMV and PPD according to UNI EN ISO 7730:2005.

Figure 15 shows that even in the optimal condition (PMV=0), there is still a percentage of dissatisfied people of 5%.

The ANSI/ASHRAE Standard 55-2020, the UNI EN ISO 7730:2005, and the UNI EN 16798-1:2019 recommend that the optimal indoor temperature is defined when PPD is lower than 10%, which corresponds to PMV values between −0.5 and 0.5. Table 7 highlights the matches between PMV, PPD, and the reference categories.

Category	Thermal state of the body as a whole	
	Predicted Percentage of Dissatisfied PPD [%]	Predicted Mean Vote PMV
I	<6	- 0.2 < PMV < + 0.2
II	<10	- 0.5 < PMV < + 0.5
III	<15	- 0.7 < PMV < + 0.7
IV	<25	- 1.0 < PMV < + 1.0

Table 7 Default categories for designing a mechanical heated and cooled building, defined in Annex B "Default criteria for the indoor environment" in the UNI EN 16798-1:2019 standard.

The PMV calculation considers all the environmental and personal factors presented in Section 2.1.5, Figure 12. The detailed equation is given in ISO 7730:2005 p.3, while below is equation (2) for calculating PMV in its simplest form.

$$PMV = (0.303 * e^{-0.036M} + 0.028) * L \quad (2)$$

Where M = activity and L = heat load.

According to UNI EN ISO 7730:2005, PMV values should only be used for values between –2 and +2, and only if the six main parameters lie in the following ranges:

- M = metabolism: 46–232W/m2;
- Id = thermal resistance of clothing: 0–0.310m2 °C/W;
- ta = air temperature: 10°–30°C;
- tr = mean radiant temperature: 10°–40°C;
- Va = air velocity: 0–1m/s;
- Pa = partial water vapor pressure: 0–2700Pa.

Then, PPD can be calculated with the equation (3).

$$PPD = 100 - 95 * e^{[-(0.03353*PMV4+ 0.2179* PMV2)]} \quad (3)$$

This value will indicate the estimated percentage of people who find the neutral temperature too hot or too cold.

By construction, the standard applies only to healthy young men and women in moderate indoor thermal climates. Therefore, this model must be adapted to individuals with different personal characteristics (e.g., older age, presence of disease, etc.).

2.2.2 SEVERE HOT AND COLD ENVIRONMENTS

Severe environments present constraints related to production needs or environmental conditions that do not allow for interventions to achieve comfort conditions. In severe environments, the primary objective involves safeguarding the safety and health of workers. Their thermoregulation system can be significantly stressed to keep the core temperature within physiological limits.

In such environments, safety strategies include assessing the risk of exposure and training the individuals involved on the specific risk and proper work procedures.

Thermal stress assessment in severe hot environments involves using the WGBT index in compliance with the standard UNI EN ISO 7243: 2017 and the PHS according to UNI EN ISO 7933: 2005. This section delves into the WGBT index but not the PHS index because the latter's applicability is limited to cases where workers do not use protective clothing.

The WGBT index or method, developed in 1957, allows for assessing the presence or absence of heat stress caused by a hot environment, either indoor or outdoor, on an adult subject, either male or female (Yaglou and Minard, 1957).

This method considers the ambient dry temperature (T_{air}), naturally ventilated wet bulb temperature (T_{nw}), and globe temperature (T_g).

The WGBT index is calculated using the following equations with (4) or without (5) sun exposure.

$$WGBT = 0.7 * T_{nw} + 0.2 * T_g + 0.1 * T_{air} \quad (°C) \quad \text{With sun exposure} \quad (4)$$

$$WGBT = 0.7 * T_{nw} + 0.3 * T_g. \quad (°C) \quad \text{Without sun exposure} \quad (5)$$

Then, the effective index ($WGBT_{eff}$) is calculated by adding the corresponding Clothing Adjustment Value (CAV) to the result, according to equation 6.

$$WGBT_{eff} = WGBT + CAV. \quad (°C) \quad \text{Without sun exposure} \quad (6)$$

Table 8 shows the CAV's values of different types of work clothing, according to UNI EN ISO 7243: 2017 ensemble.

Ensemble	Comment	CAV [°C-WBGT]
Work clothes	Work clothes made from a woven fabric is the reference ensemble.	0
Cloth coveralls	Woven fabric that includes treated cotton.	0
Non-woven SMS coveralls as a single layer	A non-proprietary process to make non-woven fabrics from polypropylene.	0
Non-woven polyolefin Coveralls as a single layer	A proprietary fabric made from polyethylene.	2
Vapour-barrier apron with long sleeves and long length over cloth coveralls	The wrap-around apron configuration was designed to protect the front and sides of the body against spills from chemical agents.	4
Double layer of woven clothing	Generally taken to be coveralls over work clothes.	3
Vapour-barrier coveralls as a single layer, without hood	The real effect depends on the level of humidity and in many cases the effect is less.	10
Vapour-barrier coveralls with hood as a single layer	The real effect depends on the level of humidity and in many cases the effect is less.	11
Vapour-barrier over cloth cov-eralls, without hood	—	12
Hood[a]	Wearing a hood of any fabric with any clothing ensemble.	+1

The CAVs are added to the measured WBGT to obtain $WBGT_{eff}$.

NOTE For high vapour resistance clothing there is a dependence on relative humidity. The CAVs represent the likely high value.

[a] This value is added to the CAV of the ensemble without hood or respirator.

Table 8 WBGT CAVs for different clothing ensembles, in °C-WBGT, defined in Annex F "Clothing adjustment values (CAVs)" in the UNI EN ISO 7243: 2017 standard.

Finally, the resulting $WGBT_{eff}$ is compared with the reference values for energy metabolism of the different activity classes according to Table 9.

Table 9 shows the $WBGT_{eff}$ reference values for acclimatized and unacclimatized people for five classes of metabolic rate, according to UNI EN ISO 7243: 2017 ensemble.

Metabolic rate (class) (see Table E.1 for description)	**Metabolic rate** W	**WBGT reference limit for persons acclimatized to heat** °C	**WBGT reference limit for persons unacclimatized to heat** °C
Class 0 **Resting metabolic rate**	115	33	32
Class 1 **Low metabolic rate**	180	30	29
Class 2 **Moderate metabolic rate**	300	28	26
Class 3 **High metabolic rate**	415	26	23
Class 4 **Very high metabolic rate**	520	25	20
The values for $WBGT_{eff}$ given here are provided for harmonization with existing national standards. As those standards are revisited in the future, the values from Figure A.1 or the related equations may be considered. The newer values will generally differ by ± 1 °C.			

Table 9 $WBGT_{eff}$ reference values for acclimatized and unacclimatized people for five classes of metabolic rate, defined in Annex A "**Reference values of the WBGT heat stress index**" in the UNI EN ISO 7243: 2017 standard.

If the values of $WBGT_{eff}$, determined for the hot environment under investigation, are higher than the reference values in Table 9, it is necessary to:

- reduce the heat stress by appropriate methods (control of the environment, activity level, time spent in the environment under consideration);
- conduct a more detailed heat stress analysis using ISO 7933 (PHS model).

Exposure to severe cold environments can result in cooling of the body as a whole or cooling of individual parts (especially extremities such as hands, feet, and head). The reference standard for evaluating cold environments is UNI EN ISO 11079, which applies to different exposures (i.e., continuous, intermittent, or occasional) and indoor or outdoor work. Figure 16 displays the procedure for evaluating cold environments in compliance with the standard.

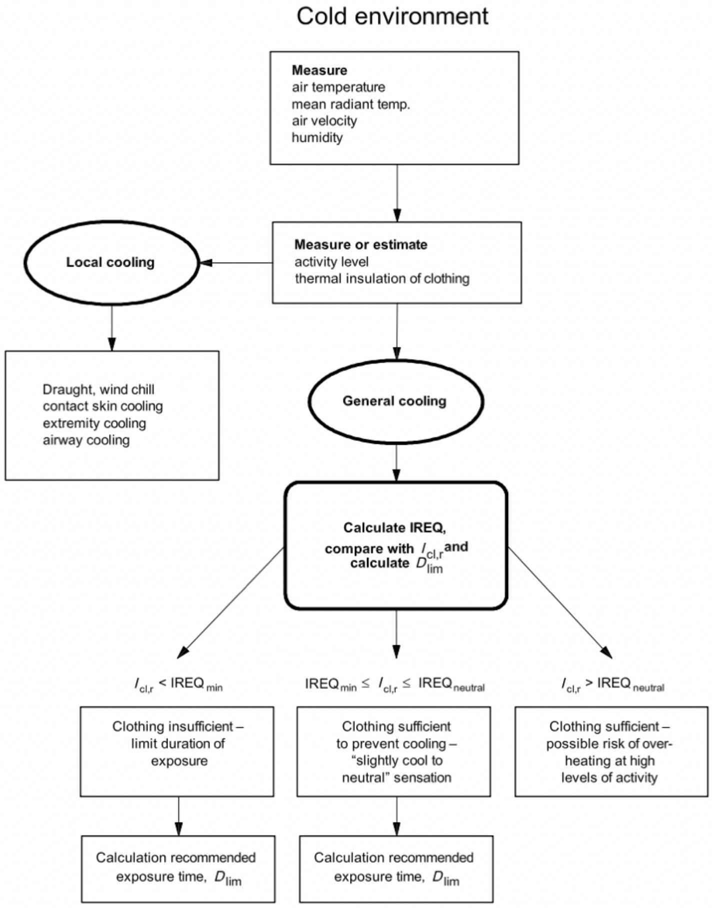

Figure 16 Procedure for evaluation of cold environments, defined in the UNI EN ISO 11079: 2008 standard.

According to Figure 16, the standard assesses the:

- global cooling through quantification of the IREQ index;
- local cooling of individual parts of the body.

This section delves into the IREQ index rather than the local cooling because the former represents the most widely used analytical tool for assessing overall discomfort in severe cold environments. The IREQ index represents the thermal insulation required to maintain the body in thermal equilibrium under the examined thermal conditions, considering the body core and skin temperature.

The IREQ index is derived by solving the heat balance equation under two conditions of thermoregulation system activation, resulting in two distinct values:

- $IREQ_{min}$ is the thermal insulation value that ensures minimum acceptable conditions, i.e., with the presence of a noticeable but tolerable cold feeling
- $IREQ_{neutral}$ is the thermal insulation value that ensures thermally neutral conditions.

These indices are then compared with the resulting thermal insulation value $I_{cl,r}$ calculated according to UNI EN ISO 9920: 2009. The three conditions featured in Table 10 can occur from the comparison.

Condition	Interpretation	Action
$I_{cl,r} > IREQ_{neutral}$	Warm, overheating zone	Reduce clothing insulation
$IREQ_{min} \leq I_{cl,r} \leq IREQ_{neutral}$	Neutral, regulatory zone	No action required
$I_{cl,r} < IREQ_{min}$	Cold, cooling zone	Increase clothing insulation or calculate the exposure limit duration D_{lim} and the recovery period D_{rec}

Table 10 Conditions resulting from comparing clothing insulation and IREQ indices with actions to be taken according to the UNI EN ISO 11079: 2008 standard.

In the case of $I_{cl,r} < IREQ_{min}$, the standard requires the calculation of the exposure limit duration (D_{lim}) to prevent the progressive cooling of the body and the recovery period (D_{rec}) required to reestablish the normal thermal equilibrium of the body.

Håkan O. Nilsson, Hannu Anttonen, and Ingvar Holmér designed a computational software to solve the equations for two IREQ indices and the D_{lim} and D_{rec}.

Figure 17 represents the main interface of the IREQ 2008 ver 4.2 software available at the following link: https://www.eat.lth.se/fileadmin/eat/Termisk_miljoe/IREQ2009ver4_2.html.

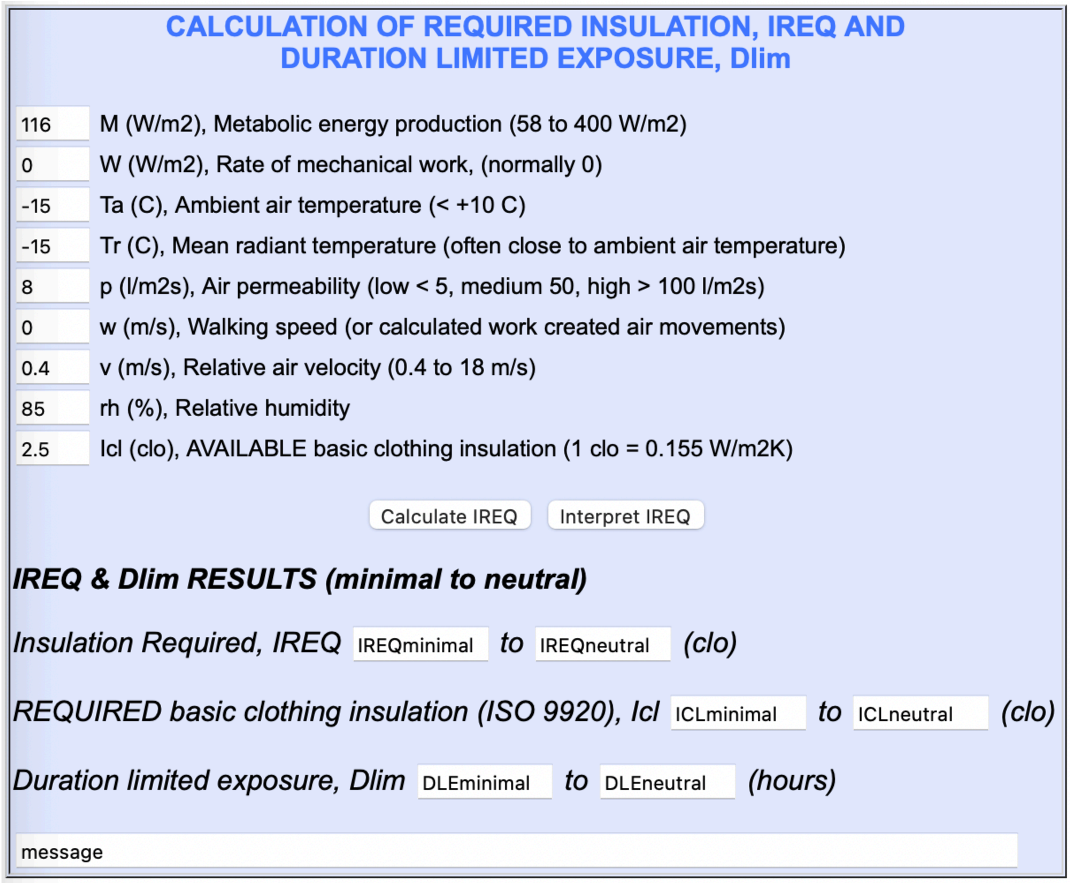

Figure 17 Interface of the IREQ 2008 ver 4.2 software, developed by Håkan O. Nilsson, Hannu Anttonen, and Ingvar Holmér.

2.3 CONCLUDING REMARKS

The continuous and dynamic interaction between people and the work environment produces physiological and psychological effects on operators. Literature analysis allowed us to outline an overall picture of the positive and negative influence of each Indoor Environmental Quality (IEQ) factor on the health and productivity of workers.

Several studies (Akimoto et al., 2010; Lan et al., 2011; Kershaw and Lash, 2013) stress the close correlation between the indoor environment and work performance. Good IEQ determines employee comfort and satisfaction, effectively reducing complaints and improving work productivity (Wu et al., 2020). Minimal stress levels and improved performance indicate an individual's suitability for the work environment. On the other hand, unsatisfactory working conditions (e.g., poor ergonomics, poor indoor air quality, uncomfortable thermal conditions, poor lighting, and noise) cause an increase in occupational injuries and absenteeism, and a reduction in work capacity, degrading the performance of workers and industry (Wu et al., 2021).

In addition, adequate IEQ can prevent the symptoms of sick-building syndrome (SBS), proving to be a critical strategy for safeguarding vulnerable populations (e.g., older workers and people with cardiovascular or respiratory diseases) in industrial environments (Al Horr et al., 2016). Still, the relationship between IEQ factors and operator well-being and productivity is highly complex.

Despite the benefits of good IEQ, industrial environments often do not allow operators to achieve comfort. On the one hand, to safeguard product quality and safety requirements; on the other hand, due to the absence of thermal comfort models and indices dedicated to sensitive individuals characterized by an altered physiological thermoregulatory capacity.

Chapter 3 investigates the main factors hindering comfort within the industry, focusing on microclimate and thermal comfort. Chapter 4 proposes technical and technological solutions together with digital tools, a model, and an experiment to restore the thermal comfort of industrial operators.

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3 CONSTRAINTS IN ACHIEVING ENVIRONMENTAL COMFORT

This chapter addresses RQ. 2, focusing on the main factors hindering environmental comfort. The analysis shows the extreme complexity of managing indoor environmental quality (IEQ) factors within industrial environments, first, because of the conflict between operator comfort conditions and production and energy needs. Second, by analyzing how the advent of COVID-19 has influenced the change in recommendations for safety in industrial environments. Finally, by investigating how the personal variables of operators complicate environmental management.

This chapter presents an overview of the factors that act as constraints in achieving environmental comfort within the industry as comprehensively as possible. However, the chapter shifts from analyzing general comfort for industrial workers to individuals considered frail due to advanced age and disease onset.

The absence of thermal comfort models and indices dedicated to fragile individuals, characterized by altered physiological thermoregulatory capacity, contrasts with the worldwide trend toward an ageing working population. Therefore, the third section of the chapter aims to analyze the relationship between the work environment and the workers' ageing.

The content of this chapter is based on the following research papers:

- Caporale, A., Botti, L., Galizia, F.G., Mora, C., 2023. Working in warehouses with adverse microclimatic conditions: technical solutions and evaluation models. Submitted paper as a chapter for the book “Warehousing and material handling systems for the digital industry. The new challenges for the digital circular economy”. Springer
- Caporale, A., Botti, L., Galizia, F.G., Mora, C., 2022. Assessing the impact of environmental quality factors on the industrial performance of aged workers: A literature review. Saf. Sci. 149, 105680. https://doi.org/10.1016/j.ssci.2022.105680
- Caporale, A., Botti, L., Galizia, F., Mora, C., Ferrari, E., 2021. The impact of microclimate strategies for the improvement of indoor air quality on well-being and productivity of industrial workers.

Managing physical risks, such as ergonomic and microclimate factors, in industrial environments can be challenging due to production and energy demands. This chapter will consider microclimate risk within the logistics industry, particularly in storage warehouses since these environments are characterized by energy constraints and limitations related to products and production processes.

In fact, to ensure the safety of perishable products in the food processing industry, storage temperatures need to be maintained at levels that may not prioritize operator comfort (Laguerre et al., 2013). Moreover, warehouses designed for non-perishable products often do not have cooling systems to minimize energy consumption, resulting in high temperatures during summer months (Akkerman et al., 2010; Rohdin and Moshfegh, 2011; Wu et al., 2021).

Furthermore, unforeseen situations can lead to the implementation of new regulations in work environments. For instance, keeping windows open during winter as a preventive measure against influenza has also proven effective in reducing coronavirus transmission (Abuhegazy et al., 2020). However, this strategy may result in thermal discomfort and irritations to exposed individuals due to cold and dry external air, making them more vulnerable to respiratory diseases (Castaldo et al., 2018; Li et al., 2018; Salata et al., 2018; Wolkoff, 2021).

In industry, the personal variables of operators can also act as constraints in achieving comfort. The ageing process, a multifaceted progression leading to physical and cognitive deterioration, substantially diminishes an individual's ability to withstand environmental strains (Eaves et al., 2016). Within the work environment, older employees' diminished capacity to cope with prolonged periods of stress can contribute to cardiovascular disease and musculoskeletal disorders (Choi, 2015; Varianou-Mikellidou et al., 2019). Given the global trend toward an ageing workforce, industries must implement measures that enable older workers to continue in their positions for as long as possible while prioritizing their safety, well-being, and productivity (European Commission 2021).

However, there is a lack of research evaluating how environmental discomfort conditions affect operators based on age. This limitation hampers the development of new technical, technological, and organizational solutions to address this issue. Therefore, industries must gather information and study how environmental conditions impact worker productivity and safety (Caporale et al., 2022).

The remainder of this chapter is organized as follows: Section 3.1 illustrates the distinction between production and energy requirements and environmental stress conditions of operators, focusing on the logistics sector and warehouses. In addition, Section 3.2 highlights how unexpected events can change environmental management by presenting strategies implemented in the context of the COVID-19 pandemic. Moreover, Section 3.3. presents a literature review on the relationships among older workers' characteristics, IEQ factors, well-being, and productivity. Finally, Section 3.4 concludes the Chapter.

3.1 PRODUCT, PRODUCTION, AND ENERGY REQUIREMENTS

Environmental control is necessary to guarantee the quality of the products throughout the supply chain, i.e., from the producer to the consumer. The improper conservation and handling of goods result in deterioration and economic losses. For example, temperature-controlled environments are necessary for the storage of perishable goods, such as pharmaceutics, fruits, vegetables, dairy, and meat products, while the cold chain prevents the deterioration of these products by maintaining a controlled atmosphere, with a static temperature below -18°C or between 0°C to 15°C according to the product. In addition, low oxygen levels and high carbon dioxide levels are maintained in cold warehouses to extend the shelf-life of perishable products. On the contrary, storage warehouses without air conditioning systems are characterized by high temperatures during the summer period, presenting significant vertical temperature differences.

Despite the progressive automation of logistics processes, some activities, such as maintenance actions and material handling operations, require operator access to these hot and cold environments. Extreme heat or cold exposure can result in adverse health effects, such as illnesses, injuries, and death. Severe hot and cold environments prevent the achievement of comfort conditions and aggravate muscle strain in the manual handling of loads. Also, low oxygen levels in a controlled atmosphere prevent breathability.

This section analyzes environmental risk factors associated with warehouses and the effects on operator safety and well-being. This analysis aims to define technical solutions and evaluation models to safeguard operators during material handling or maintenance activities in severe hot, cold, or controlled environments. These solutions will be shown in Chapter 4.

3.1.1 Warehouse environmental condition management

The increasing consumer attention to product safety and quality poses new challenges for logistics (Accorsi et al., 2018). Product safety refers to reducing the likelihood that their use will cause illness, injury, death, or adversely affect people, property, or equipment (Marucheck et al., 2011). Quality indicates the combination of product attributes and characteristics that significantly determine the degree of acceptability to a user (Bremner, H.A., 2000). Therefore, improving the efficiency of operations and ensuring safety and quality are critical levers for industries and all supply chain operators. Conversely, improper storage conditions and handling of goods lead to deterioration and economic losses (Lipińska et al., 2019).

Industries aim to ensure the safety and quality of all goods intended for consumers, focusing on perishable products (i.e., food, beverages, and pharmaceuticals) (Lejarza and Baldea, 2022). In recent years, European laws regulated the distribution of perishable products to ensure their safety and protect the consumers' health (European Commission, 2013; European Parliament and Council, 2002).

The quality attributes of perishable products generally decrease with time as part of the normal metabolism of the product (Hertog et al., 2014). The quality changes can be microbiological (growth of microorganisms), physiological (e.g., ripening, senescence, and respiration), biochemical (e.g., browning reactions, lipid oxidation, and pigment degradation), and physical (e.g., moisture loss) (Laguerre et al., 2013). Moreover, the environmental stress experienced by products during the entire supply chain endangers their safe conservation (Jedermann et al., 2014; Li et al., 2014). Acting on environmental conditions during storage, transportation, and handling can limit the loss of quality (Baruffaldi et al., 2019). However, environmental control impacts the workers' health (Caporale et al., 2022).

Figure 18 summarizes the research, highlighting how environmental control strategies to safeguard product safety and quality strongly impact the operators' health. The framework summarizes the relationships between the three research threads: product, warehouse, and operators, which will be detailed in the following paragraphs. Furthermore, this study proposes prevention and protection strategies to guarantee operators' access and activities in severe hot and cold environments characterized by environmental stress and confined spaces characterized by toxic and flammable gases and low oxygen levels.

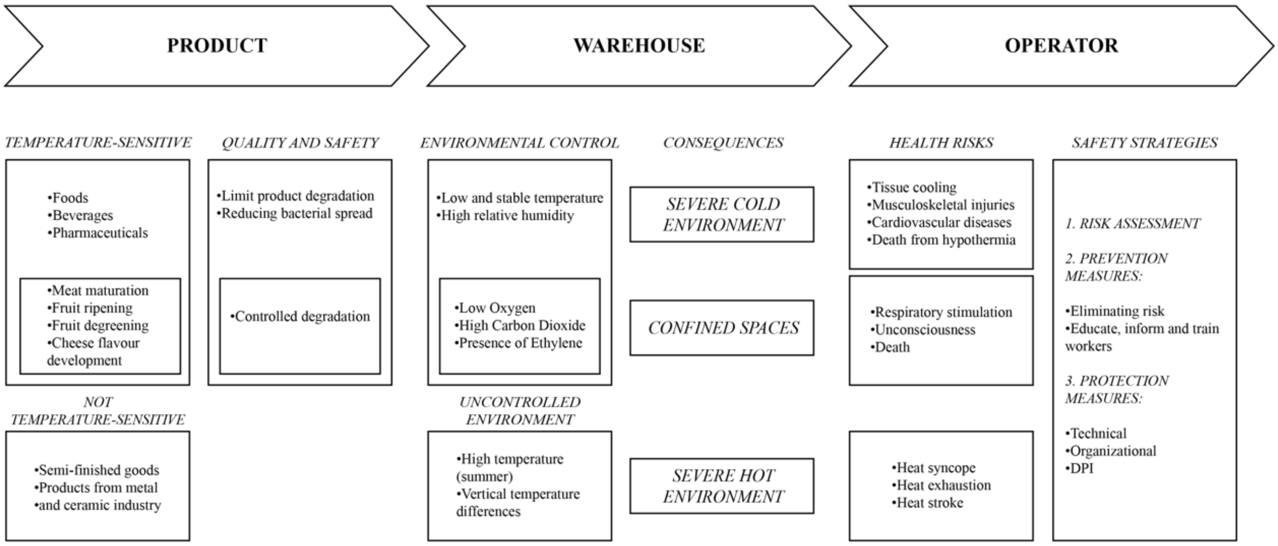


Figure 18 Visualization of the research framework: product quality and safety, environmental strategies, risks for operators, and strategies for prevention and protection in severe hot/cold and confined environments.

The effective management of environmental conditions (i.e., temperature, humidity, levels of oxygen, and carbon dioxide) is significant for improving product shelf life in the warehouse and other nodes along the supply chain where products pause most of the time. Among the environmental factors, the storage temperature proved to be strategic in controlling the physicochemical properties of perishable products (Bogataj, M., 2005). Temperature control affects product quality by limiting product degradation and safety by reducing the spread of potentially harmful bacteria (e.g., Salmonella and Escherichia coli) (Meneghetti and Monti, 2014). The terms perishable or temperature-sensitive are interchangeable, as these products require temperature-controlled environments to ensure quality and reduce losses (Hsiao et al., 2017).

A temperature-controlled supply chain is generally called a "cold chain" (Ma and Guan, 2009). Perishable products could undergo three cold chains (i.e., fresh, chilled, and frozen) classified according to temperature and quality degradation management. The frozen chain completely stops the microbial spread by operating mainly at -18°C. However, some goods (e.g., ice cream) require an even lower temperature of −25°C (Giannakourou and Taoukis, 2019). In the chilled chain, temperatures vary in the range of 0°C-15°C according to the products' needs. Such temperatures allow the safe storage of food while preserving its organoleptic characteristics. Finally, the fresh chain operates at 12°C-18°C to preserve fresh tropical products from chilling injuries (Kerbel and Madrid, 2020). The perishable products (e.g., canned goods) that do not require strict temperature control undergo the ambient chain (i.e., between 15°C to 25°C or up to 30°C, depending on climatic conditions) (Akkerman et al., 2010).

Conversely, some perishable products must undergo processing to achieve the quality desired by the end consumer without incurring health risks (Jayas and Jeyamkondan, 2002). The maturation of meat, the ripening or degreening of fruit, and the flavor development in cheese require temperature and humidity monitoring and storage in a Controlled Atmosphere (CA) to ensure controlled degradation management (Kenneth et al., 2016). CA involves the provision and maintenance of well-defined environmental conditions during storage. Controlling ambient temperature, relative humidity, ethylene, carbon dioxide, and oxygen ensures the quality and safety of these foods (James and James, 2014). Gases used in CA must reach and maintain precise concentrations within the warehouse for storage to be successful (Rama and Narasimham, 2003). Atmosphere control supplements optimal temperature and humidity ranges to preserve fruit, vegetables, and fresh produce quality and safety during post-harvest handling (Kenneth et al., 2016).

Despite continuous progress in air conditioning, temperature monitoring and control, and insulation technologies for storage facilities, indoor air temperature varies significantly among locations on different days and seasons (Armstrong et al., 2009).

Thermal stratification occurs naturally due to thermal buoyancy: warm air rises and cool air falls, creating a vertical temperature gradient (Wang et al., 2019). This phenomenon and the structural characteristics of the warehouse (e.g., high ceilings, insulation materials, exposure to sunlight, and layout) affect the temperature distribution at different heights, limiting the ability to provide safe conditions for storing goods (Porras-Amores et al., 2014). In addition, the location of structural elements (e.g., docks, doors, and windows) that generate air infiltration and operational practices (e.g., ventilation, the position of control points, and worker operations) influence temperature distribution among sites at the same height (Brinks et al., 2015).

The warehouses require much energy to maintain the product characteristics, which results in high plant operational costs (Rouwenhorst et al., 2000; Tappia et al., 2015). In addition, the high energy consumption has an environmental impact due to the CO_2 production that defines the carbon footprint of the warehouse (Bartolini et al., 2019; Zajac and Kwasniowski, 2017). The World Economic Forum (2009) estimated that warehouses account for 13% of global supply chain emissions. Most of the energy consumption inside this percentage comes from plants (i.e., heating, cooling, air conditioning, and lighting) and depends on the warehouse size (Fichtinger et al., 2015).

As cooling systems are responsible for significant energy consumption (Opalic et al., 2020), warehouses for storing products (e.g., semi-finished goods, products from the metal and ceramic industries) that are not temperature-sensitive often lack cooling systems. Uncontrolled temperature storage warehouses are characterized by high temperatures during the summer season, presenting significant vertical temperature differences (Rohdin and Moshfegh, 2011).

Despite the progressive automation of logistics processes, some activities, such as maintenance actions, goods inspection, and cleaning operations, require operators' access to warehouses (Glock et al., 2021). Workers in cold chains face severe cold environments, air movements, draught, cold working surfaces, and handling of cold products. Prolonged exposure to such conditions endangers the body's heat balance and requires external methods (e.g., adding heat retention clothing layers) to control heat loss during work (Holmér, 2009). High temperatures affect workers in uncontrolled temperature warehouses during the summer, increasing their heat and blood pressure and the risk of heart stroke (Rahma et al., 2020). Exposure to severe heat or cold does not allow the achievement of comfort conditions and can result in adverse health effects, such as illnesses, injuries, and death (Wu et al., 2021). Moreover, the combination of low oxygen (below 2%), high carbon dioxide (0.5 to 2%), and high nitrogen (approximately above 95% depending on the other gas composition) levels in the CA storage chamber fruit-friendly pose a high risk the health and safety of the workers who may access (Kolati et al., 2020). However, research on operational safety in warehouse storage operations is scarce.

This study analyses the environmental risk factors associated with warehouses and the effects on operators' safety and well-being. The aim is to investigate technical solutions and valuation models to safeguard the operators during access, material handling, cleaning, or maintenance activities in severe hot, cold, or CA environments.

3.1.2 Product versus worker safety

The growing complexity of global supply chains, coupled with the constant development of products, processes, and technologies, creates new product safety and quality challenges (Marucheck et al., 2011). In addition, the growing consumer focus on goods attributes (i.e., quality, security, sustainability, and organic and fair-trade issues) leads to a demand for products to meet quality and safety standards (Trienekens and Zuurbier, 2008).

As a result, national and international Governments are imposing new legislation and regulations to ensure safe production and processing. In Italy, Directive (EC) 2001/95, under Legislative Decree

206/2005 (Part IV, Title I of the Consumer Code) of the Ministry of Economic Development, guarantees the conformity and safety of products intended for consumers.

The European Commission published regulations on safety, standardization, technical conformity, packaging, eco-labeling, and marketing of products imported into the European Union (European Commission, 2013; European Parliament and Council, 2002). European laws focus on distributing perishable products (e.g., food, beverages, and pharmaceuticals) whose quality characteristics vary naturally over time (Hertog et al., 2014). Conversely, improper environmental conditions (e.g., low relative humidity, inadequate air temperature, and fluctuations) endanger their safe conservation and reduce their shelf-life (Jedermann et al., 2014; Li et al., 2014). Researchers and practitioners are approaching different strategies to control the warehouses' indoor environmental conditions to ensure product quality and safety and improve productivity (Bogataj, M., 2005).

However, environmental control (i.e., temperature, humidity levels, level of oxygen, and presence of gas) that guarantees the safety and quality of goods does not ensure the workers' well-being, health, and safety in warehouses (Fuentes-Bargues et al., 2019).

Despite the progressive automation of processes, warehouses still require worker access for maintenance actions, cleaning, and inspection operations (Glock et al., 2021). Accessing and carrying out activities within these environments pose severe risks to workers' health, resulting in substantial costs to the healthcare system and reduced productivity (Rohdin and Moshfegh, 2011). Exposure to cold (i.e., cold storage warehouse), hot (i.e., uncontrolled temperature warehouses during summer), or humid environments affects human physiological health.

Warehouses in which environmental conditions are constrained by production and storage needs do not allow operators to achieve thermal comfort. Thermal comfort typically refers to temperature and humidity (Sun et al., 2019) and is the mind's condition expressing satisfaction with the thermal environment (ANSI/ASHRAE Standard 55, 2017). The lack of thermal comfort causes "environmental stress," leading to adverse health effects and reduced productivity (Nico et al., 2015). Individual characteristics of the operators (e.g., age, health conditions) may worsen the response to environmental stress, strongly impacting their well-being and safety (Caporale et al., 2022).

Conditions	**Acceptable operative temperatures**	
	°C	°F
Summer (clothing insulation = 0.5 clo)		

Relative humidity 30%	24.5 – 28	76 – 82
Relative humidity 60%	23 – 25.5	74 – 78
Winter (clothing insulation = 1.0 clo)		
Relative humidity 30%	20.5 – 25.5	69 – 78
Relative humidity 60%	20 – 24	68 – 75

Table 11 Examples of acceptable operative temperature ranges based on comfort zone diagrams in ASHRAE Standard 55.

Workers exposed to cold temperatures (usually below 12°C) are more prone to respiratory, cardiovascular, and musculoskeletal disorders. Moreover, cold-associated diseases include face and skin symptoms (e.g., frostbite, trench foot, chilblains, and hypothermia) (Thetkathuek et al., 2015).

Exposure to temperatures above 28°C causes an increase in the body's 'core' temperature, leading to fatigue, decreased muscle endurance, and lack of concentration, which may lead to severe accidents (Cai et al., 2018).

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) recommends maintaining relative humidity above 30% and below 60%. The ANSI/ASHRAE Standard 55 (2017) also defines acceptable operating temperature ranges corresponding to these relative humidity levels, highlighted in Table 11. Still, in CA warehouses, the presence of toxic gases (i.e., carbon dioxide), flammable gases (i.e., ethylene), and microorganisms (e.g., fungi) pose a potentially life-threatening risk to workers (Thompson et al., 2018).

The following sections will deepen the different strategies for the environmental control of storage warehouses and the risks associated with the presence of the workers inside.

3.1.2.1 Cold storage warehouse and severe cold environmental risk

Cold storage warehouses are strategically crucial in cold chain logistics to manage the complexities of perishable or temperature-sensitive products (i.e., primary agricultural varieties, processed foods, and pharmaceuticals) (Lejarza and Baldea, 2022; Ma and Guan, 2009; Sugathadasa and Perera, 2021). The quality of agricultural varieties and processed foods is closely linked to consumers' subjective assessment of various attributes, such as taste, texture, color, and appearance (Hertog et al., 2014). On the other hand, food safety, on which consumer health depends, is regulated by standards (Zhang and Chen, 2011). For example, the Hazards Analysis and Critical Control Points

(HACCP) is a set of prevention procedures to ensure aliments' safety by reducing food-borne pathogens' levels in food production (Trienekens and Zuurbier, 2008). In contrast, the quality and safety of pharmaceutical products are overlapping characteristics defined by their long-term stability and efficacy (Bishara, 2006; Kumar and Jha, 2019). The World Health Organisation (WHO) published a technical report describing Good Pharmaceuticals Practices (GPP), which includes Good Storage Practices (GSP) for the preservation of pharmaceutical quality and safety up to the point of use (WHO, 2011).

The interactions between perishable products and the environmental conditions experienced throughout the product's life cycle determine the quality the final consumer perceives (Hsiao et al., 2018; Ma et al., 2015; Shashi et al., 2018). Among the environmental factors, temperature and relative humidity control proved to be strategic in maintaining the quality of temperature-sensitive products (Bogataj, M., 2005; Jedermann et al., 2014). Conversely, the environmental stress experienced by products exposed to non-compliant temperature and relative humidity values endangers their safe conservation, decreasing their shelf life (Li et al., 2014). Table 12 highlights the losses in quality and safety of perishable products when exposed to low humidity levels, inadequate storage temperatures, and temperature variations.

Environmental risks	**Perishable products**	**Product quality**	**Product safety**
Low humidity levels	Agricultural varieties	Moisture loss, dehydration, compromised appearance, contamination	Premature deterioration
	Processed foods	Product weight loss, contamination	Reduced shelf life
	Pharmaceuticals	Influence on water activity	Decrease the stability, efficacy losses
Improper temperature storage or	Agricultural varieties	Faster respiration rate, browining reaction, abnormal ripening	Growth of microorganisms, reduced shelf life and edibility, food-borne illness

variations in temperature	Processed foods	Senescence, textural change, freezer burn, in-package frosting	Food-borne illness
	Pharmaceuticals	Chemical and physical degradation	Reduced expired date, efficacy losses

Table 12 The impact of environmental risks on different perishable products in terms of loss of quality and safety.

Food products rely heavily on maintaining a static cold temperature to prevent large fluctuations from causing premature product deterioration (i.e., product off-flavoring, texture modifications, slime production, and spoilage) (Meneghetti and Monti, 2014; Vaikousi et al., 2008). Furthermore, high relative humidity levels limit the water deficit of food products exposed to low temperatures, thus inhibiting post-harvest quality deterioration (Zuo et al., 2022). The quality and safety of pharmaceuticals are overlapping characteristics since environmental changes do not affect them visually. However, inadequate temperature, relative humidity levels, and storage temperatures limit its effectiveness, reducing the expiry date (Bishara, 2006).

Storage conditions that guarantee the safety and quality of perishable products vary according to the individual product. For most agricultural varieties and processed food, the optimum temperature is slightly above their freezing point to inhibit the growth of potentially harmful bacteria (Meneghetti and Monti, 2014; Tashtoush, 2000). The recommended relative humidity levels are almost always above 85-90%. For pharmaceutical products, the recommended temperature is between 2 and 8°C, and relative humidity levels are between 50 and 60% (Taylor, 2001).

Table 13 shows examples of temperature and humidity conditions required to preserve the quality of individual perishable products during storage (Jayas and Jeyamkondan, 2002; Kenneth et al., 2016; Rama and Narasimham, 2003; Thompson et al., 2018).

Perishable products	**Temperature range (°C)**	**Relative humidity (%)**
Frozen chain		
Frozen fishery products, Frozen meat, Fishery products to be consumed raw, ice cream, pastry products	-30/-18	85/90
Chilled chain		

[2,3,4]Apple	-1/-4	90/95
[2,3,4]Cherries	-1/0	>95
[2,3,4]Fig	-1/0	90/95
[2,3,4]Apricot, Blackberry, Blueberries, Kiwifruit, Peach	0/5	90/95
[2,3]Coconut	0/1.5	75/85
[2,3]Orange	0/9	85/90
[1]Dairy products, fresh meat	2/4	
[4]Pharmaceutical products including vaccines and medication	2/8	50/60
Fresh chain for tropical products		
[2,4]Avocado	5/12	85/95
[2,4]Mandarin	4/7	90/95
[2,4]Fresh olives	5/10	85/90
[2,4]Passion fruit	7/10	85/90
[4]Melon	7/10	90/95
[2,4]Papaya	7/13	85/90
[2,3,4]Lime	9/10	85/90
[2,3,4]Lemon	10/13	85/90
[2,3]Cucumber	10/12.5	95
[2,4]Grapefruit	10/15	85/90
[2,3,4]Mango	10/15	90/95
[2,3,4]Banana	13/15	90/95

Table 13 Required storage conditions to maintain the quality and safety of perishable products, adapted from studies by [1]Jayas and Jeyamkondan, 2002; [2]Kenneth et al., 2016; [3]Rama and Narasimham, 2003; [4]Thompson et al., 2018.

Environmental conditions conducive to the storage of products can compromise the health, performance, and productivity of the operators involved (Laguerre et al., 2013; Wu et al., 2021). A cold working environment is a significant hazard that worsens as temperatures drop (Golbabaei et al., 2006). The medium to moderate thermal stress experienced in the fresh chain can make work performance difficult. However, in the chilled and frozen chain, the stress level approaches the human body's tolerance, increasing the risk of cold-related illnesses (Fuentes-Bargues et al., 2019).

The most severe effects of cold depend on tissue cooling. Superficial cooling of tissues causes discomfort, which can affect alertness and concentration. More profound cooling, e.g., of the extremities, impairs their functionality, causing pain, numbness, and local frostbite (Uter and Kanerva, 2019). Whole-body cooling causes a core and muscle temperature drop, affecting physical and mental performance and function (Isa and Atim, 2019). Consequently, intense work activities lead to an increase in musculoskeletal injuries. Prolonged exposure to extreme cold stress can lead to the risk of death from hypothermia (Thetkathuek et al., 2015). The effects of cold exposure depend on complex interactions between air temperature, other climatic factors (i.e., mean radiant temperature, relative humidity, and air speed), clothing insulation, and metabolic heat production (Holmér, 1993). The high relative humidity levels required to store perishable products exacerbate cardiovascular health risks in cold environments (Guo et al., 2022).

Furthermore, high relative humidity levels worsen discomfort due to low temperatures, saturating clothes, and limiting insulation capacity (Wolkoff et al., 2021). Finally, high relative humidity encourages the growth of molds and microorganisms, leading to respiratory diseases. Literature studies show that comfortable environmental conditions allow people to perform their work optimally by increasing their attention level and reducing the risk of accidents during working time (Akimoto et al., 2010; Lan et al., 2011; Nico et al., 2015).

Moreover, in 2018, Li et al. found that exposing workers to a satisfactory thermal environment can reduce the number of complaints and absenteeism. Conversely, environmental stress negatively affects productivity in manual-labor-intensive tasks (Cai et al., 2018). Prolonged exposure to severe cold environments reduces workers' physical performance due to numbness of the hands or a drop in body temperature (Rodahl, 2003).

Furthermore, cold exposure impairs tasks that require precise and controlled finger movements more than tasks that rely more on hand, arm, and shoulder movements (Ray et al., 2019). Exposure to cold has also been linked to significant declines in mental function, leading to decrements in memory, vigilance, reaction time, and decision-making (Taylor et al., 2016; Sugg et al., 2019). Finally, Bai and Wicaksono’s (2020) study highlights a significant worker performance deterioration for relative humidity values above 75%, observed as a slowdown in reactions.

3.1.2.2 Controlled atmosphere warehouse and suspected pollution environments

The cold chain, characterized by controlling temperature and relative humidity to limit or stop chemical changes in perishable products, does not allow the desired final quality for some foods (Kenneth et al., 2016). The maturation of meat, ripening or degreening of fruit, and flavor development in cheese require several temperature-controlled stages in which the desired changes can occur without undergoing modifications that are harmful to the consumers’ health.

CA storage carries out these processes (Jayas and Jeyamkondan, 2002). CA warehouses allow fresh perishable products to be stored under suitable environmental conditions to prolong the valuable marketing period of the product after harvest (Dilley, 2006). CA involves maintaining an atmospheric composition different from the air (about 78% N_2, 21% O_2, and 0.03% CO_2). Temperature control in CA is crucial to reduce fruit and vegetables' respiration and transpiration processes. Low and stable temperature levels (i.e., from 0°C to 14°C, depending on the product) prevent premature spoilage of products, ensuring their quality. Moreover, high relative humidity levels reduce water loss, significantly increasing the shelf life of fruits and vegetables (Medina et al., 2012).

In addition to the temperature and relative humidity control, the CA warehouses are equipped with special gas-tight seals to maintain an atmosphere with oxygen below 4% and CO_2 above 14% (James and James, 2014). In some cases, the CA also involves removing ethylene and adding carbon monoxide. Gases used in CA must reach and maintain precise concentrations within the warehouse for storage to be successful (Rama and Narasimham, 2003).

The regulation of these conditions limits but does not stop the two most crucial life processes (i.e., respiration and transpiration), which help reduce product metabolism and prolong goods storage life. Exposure of perishable products to low O_2 and high CO_2 atmospheres within the range tolerated by each product increases their shelf life. Conversely, too high CO_2 values or too low O_2 values may irreparably damage food (Valdez Fragoso and Mújica-Paz, 2015). Table 14 highlights the benefits of rigorously controlling CA conservation variables (i.e., temperature, relative humidity, ethylene, carbon dioxide, and oxygen).

CA storage variables	**Control range**	**Benefits**	**Product safety**	**Product quality**
Temperature control	Low (0-14°C) and stable temperature	Reduces respiration and transpiration processes, and suppresses ethylene production	Slows microbial development and prevents premature spoilage	Ensures product quality
Relative humidity control	Hight (80-95%) depending on products	Lowers the transpiration process	Prevents microbial spoilage	Reduce water loss and products wilting, and ensures shelf life

Gas control	Ethylene as low as possible, Carbon Dioxide up to 14% and Oxygen (1-4%)	Reduces respiration and ethylene production, slow down the ripening process	Slows microbial development	Guarantees the appearance of the products, their taste and nutritional value, and prolongs shelf life

Table 14 The benefits of product safety and quality resulting from correctly managing the controlled atmosphere.

The reduced oxygen, high CO2, low temperature, and high relative humidity limit ethylene levels, reducing respiration, transpiration, and product ripening. CA storage warehouses extending fruit and vegetables' lives pose a threat to operators if they accidentally enter them (Kolati et al., 2020).

Previous Section 3.1.1 sets out the risks for operators working in cold environments. Moreover, CA storage warehouses present additional health risks related to atmospheric composition. The main risk for operators is related to the low oxygen content of the atmosphere.

Oxygen content (%)	**Safe level**	**Symptoms and health effects**
23.5	Maximum safe level	
21	Typical concentration in air	Normal breathing and functions
19.5	Minimum safe level	Hight (80-95%) depending on products
15-19	First sign of hypoxia	Decreased ability to work strenuously. May induce early symptoms in persons with coronary, pulmonary, or circulatory problems
12-14		Respiration increases with exertion, pulse up, impaired muscular coordination, perception, and judgment
10-12		Respiration further increases in rate and depth, poor judgment, lips blue
8-10		Mental failure, fainting, unconsciousness, ashen face, blueness of lips, nausea, vomiting, inability to move freely
6-8		6 minutes – 50% probability of death

4-6	8 minutes – 100% probability of death Coma in 40 seconds, convulsions, respiration ceases, death.

Table 15 Oxygen content in the air and health outcomes (McManus, 2009).

The percentage of oxygen allowing normal respiratory functions is 21%, as shown in Table 15 (McManus, 2009). In a controlled atmosphere, oxygen levels below 6% (i.e., 1-4%) lead to respiratory distress followed by convulsive movements to the point of loss of consciousness in 30 seconds, cessation of breathing, and cessation of a heartbeat within minutes (Dellino, 1997). An atmosphere rich in CO_2 poses an additional health risk for operators. In fruit ripening rooms, CO_2 levels are kept above 2-5% according to the needs of individual perishable products.

However, the Occupational Safety and Health Administration (OSHA) established a Permissible Exposure Limit (PEL) for CO_2 of 5,000 parts per million (ppm) (i.e., 0.5% CO_2 in air) averaged over an 8-hour workday and designated the 40,000 ppm (i.e., 4% CO_2 in air) as the Immediately Dangerous to Life or Health (IDLH) threshold. In high concentrations (above 1.5%), CO_2 rapidly causes respiratory failure even when oxygen is at normal levels.

Symptoms are headaches, dizziness, confusion, and nausea, which can lead to loss of consciousness and death (Jacobson et al., 2019), as shown in Table 16.

Carbon dioxide (ppm)	**Carbon dioxide (%)**	**Safe level**	**Symptoms and health effects**
5.000	0.5	OSHA Permissible Exposure Limit (PEL)	
10.000	1		Possible drowsiness
15.000	1.5		Mild respiratory stimulation for some people
30.000	3		Moderate respiratory stimulation, increased heart rate and blood pressure
40.000	4	Immediately Dangerous to Life or Health (IDLH)	

50.000	5		Strong respiratory stimulation, dizziness, confusion, headache, shortness of breath
80.000	8		Dimmed sight, sweating, tremor, unconsciousness, and possible death

Table 16 Carbon dioxide level and health outcomes (OSHA).

Not only low oxygen levels and high CO_2 levels but also the presence of ethylene endanger operators who access CA warehouses. Ethylene is essential in fruit ripening. However, it has asphyxiant and anesthetic properties and is flammable. Ethylene flammability limits in the air are 3.1-32% by volume, so atmospheric levels must not reach 3.1% (Wu et al., 2013). Literature shows that in environments characterized by high humidity levels, the CO_2-enriched atmosphere is more toxic than in lower humidity conditions. However, most fruits and vegetables require humidity levels near the saturation point to limit the desiccation and shriveling of peels while improving their shelf life (Mohapatra et al., 2017). High relative humidity levels encourage the growth of microorganisms, especially fungi, that can produce chemicals harmful to the operators.

The construction of CA warehouses requires an automatic electronic gas analysis system and remote control and management with automatic computerized functions (Yahia et al., 2019). However, operators or technicians may need to enter the chamber to repair the evaporator or cooler, inspect the fruit, or perform other maintenance activities (Thompson et al., 2018). Since the atmospheric hazards assimilate CA storage warehouses into confined spaces, the entrance and activities must be designed to ensure the operators' safety.

3.1.2.3 Uncontrolled temperature warehouse and severe hot environmental risk

The perishable products (e.g., canned goods) and the goods (e.g., semi-finished goods, metal, and ceramic products) that do not require strict temperature control undergo the ambient chain (Akkerman et al., 2010). Warehouses dedicated to storing not temperature-sensitive products often lack cooling systems to save on building energy costs, resulting in high temperatures during the summer and significant vertical temperature differences (Rohdin and Moshfegh, 2011). Moreover, in the absence of ventilation or cooling mechanisms, air stratification and temperature distribution remain stable over time (Li, 2016).

In addition, both building characteristics, such as the location of structural elements (e.g., doors and windows) that generate air infiltration, and operational practices (e.g., ventilation, location of control points, and workers' operations) influence the temperature distribution between locations at the same height (Baruffaldi et al., 2019; Brinks et al., 2015).

During the warm months, the outside temperature and radiation heat the ceiling and upper layers of the warehouse, while colder air accumulates in the lower levels. Depending on external conditions and the warehouse size, the average monthly stratification reaches values between 0.3°C/m and 0.9°C/m. Porras-Amores et al. (2014) point out that in warehouses with heights above 8 meters, air stratification leads to a difference of 4°C and 10% relative humidity between the floor and ceiling, adversely affecting the storage of goods. Due to the vertical temperature difference, products stored for a long time in a warehouse experience thermal stress depending on their height (Wang et al., 2019).

Workers exposed to high temperatures in the workplace are also subject to heat stress with adverse consequences in terms of health and productivity (Rahman et al., 2020). Thermal stress highly depends on air temperature, relative humidity, mean radiant temperature, wind speed, metabolic rate, and clothing insulation (Reinhold and Tint, 2009). When the working environment does not allow for thermal equilibrium, uncomfortable conditions occur that pose risks to workers' health and safety (Varghese et al., 2020).

Exposure to heat (from weather or industrial activities) is a significant occupational health and safety issue linked to several adverse physical and psychological outcomes, including fatal illnesses (Kjellstrom et al., 2016). Workplace heat exposure causes an increase in body core temperature, leading to fatigue and decreased muscle endurance. Prolonged exposures are responsible for heat-related illnesses, such as heat stress, heat syncope, heat exhaustion, and heat stroke (Varghese et al., 2020).

High temperatures produce psychological strain on workers, leading to changes in cognition and performance and reducing worker efficiency and labor productivity (Cai et al., 2018). Moreover, heat exposure causes a lack of concentration (Kotek et al., 2015; Reinhold and Tint, 2009). Finally, Ilangkumaran et al. (2014) study reported that working in extremely hot conditions affects performance and leads to severe accidents due to poor attention toward warning signals.

High relative humidity levels worsen workers' thermal stress in severely hot environments. The high moisture content in the air does not allow sweat to evaporate to cool the body, limiting the thermoregulatory function. The body's effort to cool itself results in excessive sweating, faster and deeper blood circulation, and increased respiration (Larose et al., 2022).

The Wet-Bulb Globe Temperature (WBGT) is the most used method for assessing occupational heat stress, integrating the effects of ambient temperature, relative humidity, wind chill, and solar radiation. The WBGT method is unsuitable for assessing heat stress over brief periods with significant variations in conditions, optimal and acceptable microclimate conditions, or directional effects of heat radiation sources. However, several agencies, including the National Institute for Occupational Safety and Health (NIOSH) and the International Organization for Standardization (ISO), recognized the WBGT as a safety index for setting limits in industrial workplaces (NIOSH, 2016; UNI EN ISO 7243:2017; Yi and Cjan, 2017).

The American Conference of Governmental Industrial Hygienists (ACGIH, 2022) determined the Threshold Limit Value (TLV) and the Action Limit (AL) as initial screening tools to evaluate whether a heat stress situation may exist based on WBGT, workload, and work/rest regimen.

Work (%)	**Light workload**		**Moderate workload**		**Heavy workload**		**Very heavy workload**	
	TVL (°C)	**AL (°C)**	**TVL (°C)**	**AL (°C)**	**TVL (°C)**	**AL (°C)**	**TVL (°C)**	**AL (°C)**
75 to 100	31.0	28.0	28.0	25.0	N/A	N/A	N/A	N/A
50 to 75	31.0	28.5	29.0	26.0	27.5	24.0	N/A	N/A
25 to 50	32.0	29.5	30.0	27.0	29.0	25.5	28.0	24.5
0 to 25	32.5	30.0	31.5	29.0	30.5	28.0	30.0	27.0

Table 17 ACGIH's Screening Criteria for TLV and AL for Heat Stress.

The limiting levels are in Table 17. TLV shows the temperature at which there is a heat hazard present for an acclimatized worker, while the AL is the temperature at which there is a heat hazard present for a non-acclimatized worker. The TLV and AL limits suggest the need for temperature and humidity control in each industrial process and in all locations where operators are present to avoid heat stress and safeguard workers' health and productivity. Neither the TVL nor the AL provides criteria values for continuous Heavy and Very Heavy work and 25% rest because of the extreme physical strain.

Warehouses are complex environments characterized by various processes and operations requiring efficient management (Halawa et al., 2020). The purpose of warehouses is to satisfy customers by maintaining the quality and safety of goods, especially perishable products (Chen et al., 2017). Environmental control (i.e., temperature, humidity levels, level of oxygen, and presence of gas) in CA and cold storage ensure the preservation of goods. However, environmental strategies do not guarantee the workers' well-being and safety (Fuentes-Bargues et al., 2019). Research on warehouse management has recently started focusing on operator safety to limit accidents (Hofstra et al., 2018). The previous Sections illustrated the risks associated with the operators' access and activities in cold stores, CA storage rooms, and uncontrolled temperature warehouses.

Chapter 4 will deepen the regulations governing the operator's safety and the prevention and protection measures for operators exposed to severe hot and cold environments, oxygen-deficient atmospheres, and toxic or flammable gasses.

In addition, Chapter 4 will illustrate some of the technical solutions of the “Banca delle Soluzioni" project, a free online access database for researchers and practitioners (www.bancadellesoluzioni.org).

The following two sections address additional limitations to achieving environmental comfort in the workplace. Section 3.2 discusses strategies for managing unexpected events (i.e., the COVID-19 pandemic) and their impact on workers wellbeing. Finally, Section 3.3 highlights how workers' age impacts the environmental stress response, complicating the human-environment relationship.

3.2 UNEXPECTED EVENTS MANAGEMENT

In recent years, in industry, the adoption of effective microclimate strategies for improving Indoor Environmental Quality (IEQ) has been considered an important topic for its effects on workers' health and safety (Wu et al., 2020). Still, recently, it is more relevant than ever in light of the coronavirus pandemic. COVID-19 has shifted the scientific community's attention to studying new microclimate strategies to reduce respiratory virus transmission within industrial settings. Experimental studies showed that increased ventilation and controlled relative humidity levels influence the buoyancy of the expiratory clouds ejected during human respiratory (Abuhegazy et al., 2020). The result is a reduced contamination range of the suspended droplets containing the respiratory viruses.

Existing literature describes eight Indoor Environmental Quality (IEQ) factors that characterize indoor air quality, including ventilation, relative humidity level, thermal comfort, and light in the workplace. The National Institute of Health (ISS) has recently defined a set of strategic implementation measures aimed at improving indoor air quality in industrial environments and ultimately containing the transmission of SARS-CoV-2.

In addition, the American Occupational Safety and Health Administration (OSHA) recommended increasing the ventilation rate of industrial environments through natural or artificial ventilation. However, these microclimate variations can cause heat stress, discomfort, and other adverse effects on workers' health and safety (Reinhold and Tint, 2009; Kershaw and Lash, 2013; Ilangkumaran et al., 2014; Gasparrini et al., 2015; Nico et al., 2015; Castaldo et al., 2018; Salata et al., 2018; Wolkoff, 2018). Based on these premises, this section presents the microclimatic strategies for reducing COVID-19 infections adopted in the industry. The objective is to investigate their impact on the well-being and productivity of industrial workers.

3.2.1 Microclimate strategies in the context of COVID-19 pandemic

COVID-19 is caused by the SARS-Cov-2 coronavirus, with more than 770 million infections recorded worldwide from February 2020 to date, as depicted in Figure 19.

This pandemic represented a global health crisis and an international economic threat due to the massive closures needed to contain the spread of the virus (Kabadayi et al., 2020). In such a scenario, work represented a decisive dimension in the context of the Sars-Cov-2 pandemic.
Therefore, recent discoveries on the dynamics of infection transmission allowed for constant updating of guidelines in the industrial field.

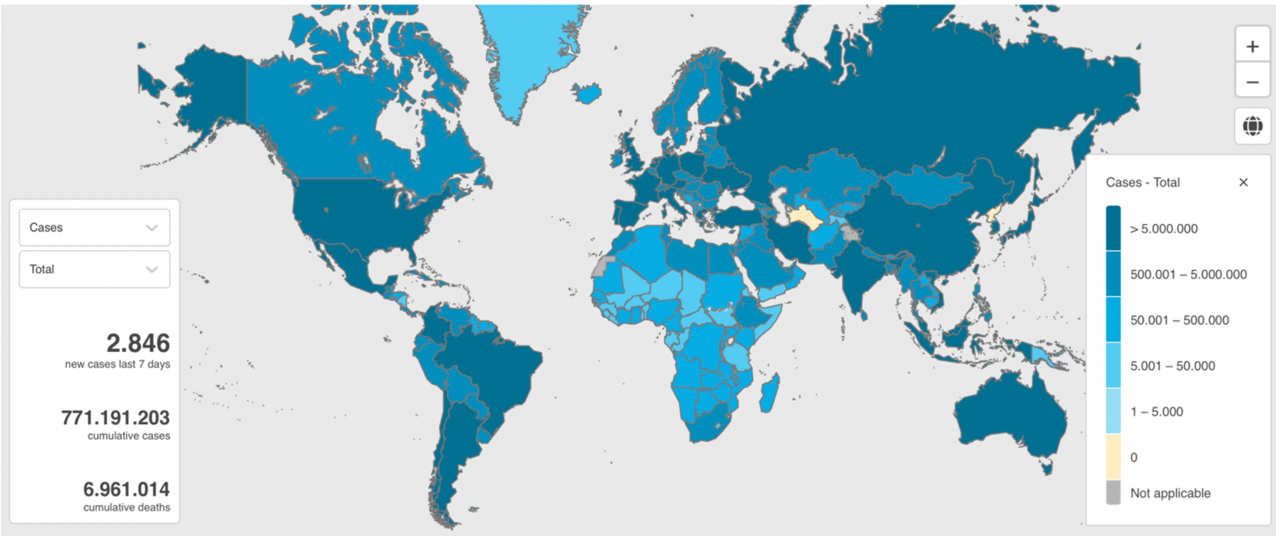


Figure 19 Overview of the worldwide distribution of coronavirus cases confirmed by the World Health Organization (WHO).

Coronavirus transmission occurs mainly through inhalation of SARS-CoV2-laden droplets and aerosol particles through direct contact with an infected person or a contaminated surface (Jayaweera et al., 2020). Effective mitigation measures require a clear understanding of droplets and aerosols transport, surface retention, and evaporation kinetics in different environments and conditions (Mittal et al., 2020). In indoor environments, some generated particles exit the system through ventilation; some are deposited on the room's surfaces and can return in suspension, and others can be inhaled directly. The mitigation measures aim to reduce virus transmission by maximizing the fraction of particles leaving the system and minimizing aerosol deposition to humans.

Abuhegazy et al. (2020) showed that the total fraction of particles depositing on the source individual, the ground, and the surfaces close to him increases significantly with increasing particle size. In November 2020, a study published by the Centers for Disease Control and Prevention (CDC) showed that asymptomatics were the largest transmission channel.

In this regard, the scientific community has highlighted the importance of ventilation and indoor humidity levels in combating the spread of the virus in indoor environments. Ventilation promotes the escape of infected particles. At the same time, increased indoor air humidity (IAH) increases the size and weight of particles, accelerating their deposition and limiting their resuspension. In addition, a higher IAH increases the occupants' mucociliary clearance, decreasing the infectivity of viruses and pollutants.

Thanks to these key findings, there has been a succession of documents and guidelines from the world's leading health and safety authorities to counter the spread of coronavirus in the workplace.

The International Labor Organization (ILO) primarily mandated employers to conduct risk assessments to ensure that industries met strict employee health and safety criteria. At the same time, in February 2020, OSHA published a guidance document, "Guidance on Preparing Workplaces for COVID-19," which would allow different industries and non-industries to reopen production sectors (OSHA, 2020). That document suggested adequate ventilation of industrial environments as the main action to contain bio-aerosol transmission. Later, the European Agency for Safety and Health at Work (EU-OSHA) and the researcher of the ISS, through the report Covid-19 n5/2020 Rev (R.I.S.S., 2020), stressed the importance of improving IAQ as a virus mitigation strategy by keeping doors and windows open to promote air exchange.

However, keeping windows open during the winter period results in overcooling of the indoor environment with adverse health effects on occupants (Salcido et al., 2016; Morawska et al., 2020). Section 2.1.4 highlights that maintaining temperatures below 18 °C during cold seasons increases the risk of cardiovascular and respiratory issues, resulting in illness and mortality. Another concern is that introducing cold air through natural ventilation can cause dryness, leading to discomfort, such as irritation of mucous membranes, eyes, and skin. This heightened sensitivity makes occupants more susceptible to internal pollutants.

To ensure adequate air exchange and maintain stable air temperature and relative humidity, the Italian Association of Air Conditioning, Heating, and Refrigeration (AiCARR), in its "Protocol for Reducing the Risk from the Spread of Sars-CoV-2 in the Operation and Maintenance of Existing Air Conditioning and Ventilation Systems," suggests the use of Mixed-mode ventilation (MMV) systems, maximizing the amount of outside air supplied. These systems, by combining the function of local air recirculation with the introduction of outside air, save energy compared to classical Heating, Ventilation, and Air Conditioning (HVAC) systems.

However, to reduce indoor contamination due to recirculation and the introduction of outdoor pollutants, such systems require the use of High-Efficiency Particulate Air (HEPA) filters or treatment or abatement technologies (e.g., ultraviolet lamps) (AiCARR, 2020).

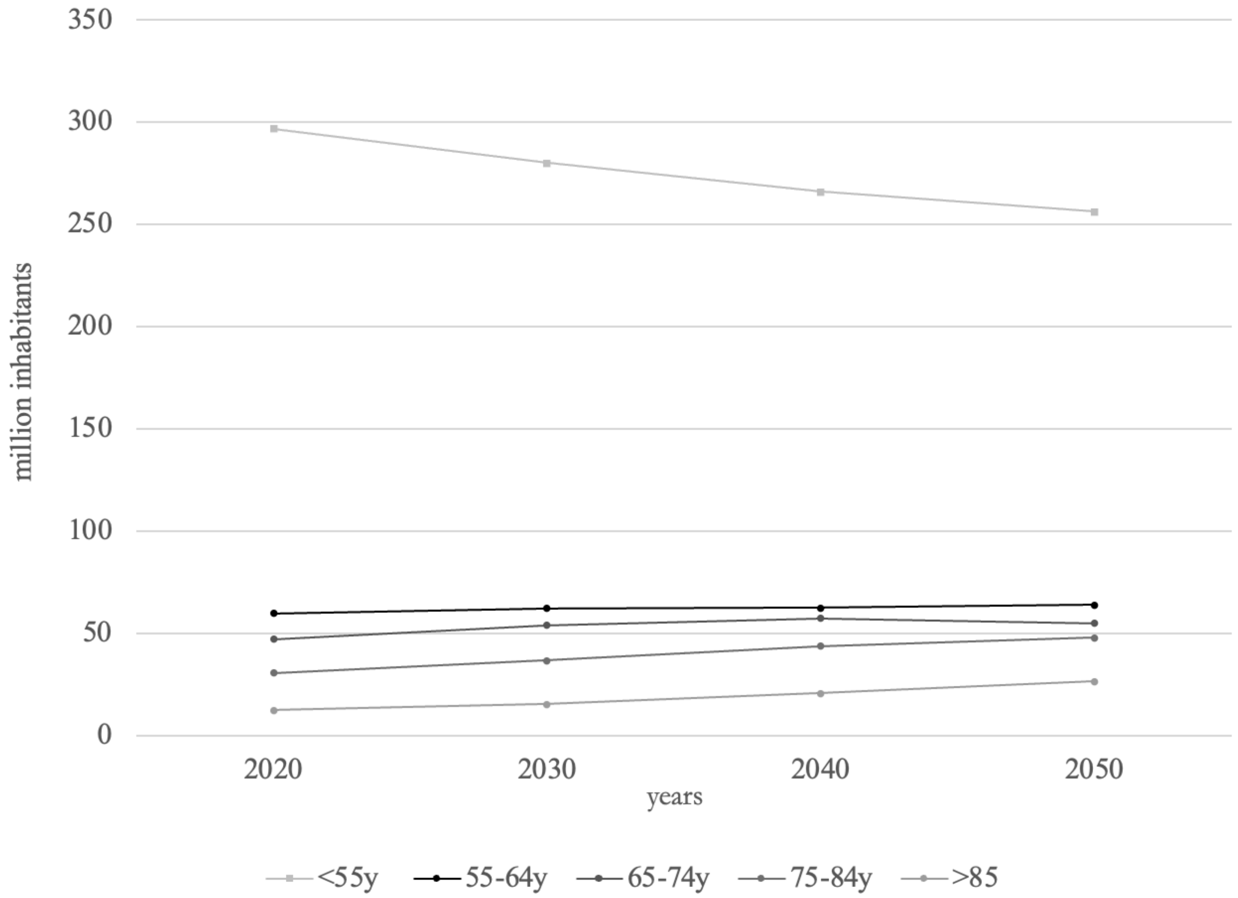
In conclusion, the strategies employed for indoor control in industrial workplaces during the COVID-19 pandemic have implications beyond this health crisis, offering valuable insights and approaches for mitigating the spread of other pathogens in indoor settings. These strategies encompass a range of environmental and control measures that can enhance IAQ and reduce infectious agent transmission, promoting a healthier and safer indoor environment.

3.3 OPERATORS' AGEING

People worldwide are living longer (Eaves et al., 2015). The increase in life expectancy and the decline in fertility rates led to a rise in the share of older people in the total population. The population of aged people (65 years or more) in the EU-27 will increase significantly, rising from 90.5 million at the start of 2019 to 129.8 million by 2050. By contrast, the projections suggest that 13.5 % fewer people under 55 will live in the EU-27 by 2050. People living longer than before also work longer (Dimovski et al., 2019). Forecasts on the ageing of the workforce estimate that nearly one-fifth of workers will be aged 50 and over by 2050 (Eaves et al., 2016).

Figures 20 and 21 compare data on the population ageing (over 55) in the EU-27 countries with the increase in the percentage of aged workers (50-64 years) in the total workforce. Figure 20 shows the decrease in people aged less than 55 years (light lines) and the increase in the population over 55 in EU-27 (dark lines). In 2019, people aged 55 or older accounted for just over one-third (33.6 %) of the EU-27 population. Forecasts by the Statistical Office of the European Union (EUROSTAT) in

2020 show that the share of this age group (i.e., 55 years or older) in the EU-27 population will reach



40.6 percent by 205

Figure 20 Population developments by age class, EU-27, 2020-2050 (EUROSTAT, 2020).

Figure 21 shows the data from the European Commission (2021) report "The 2021 Ageing Report". The trend foresees an increase in the share of aged workers (50-64 years) from 18% in 2019 to about 21% in 2045.

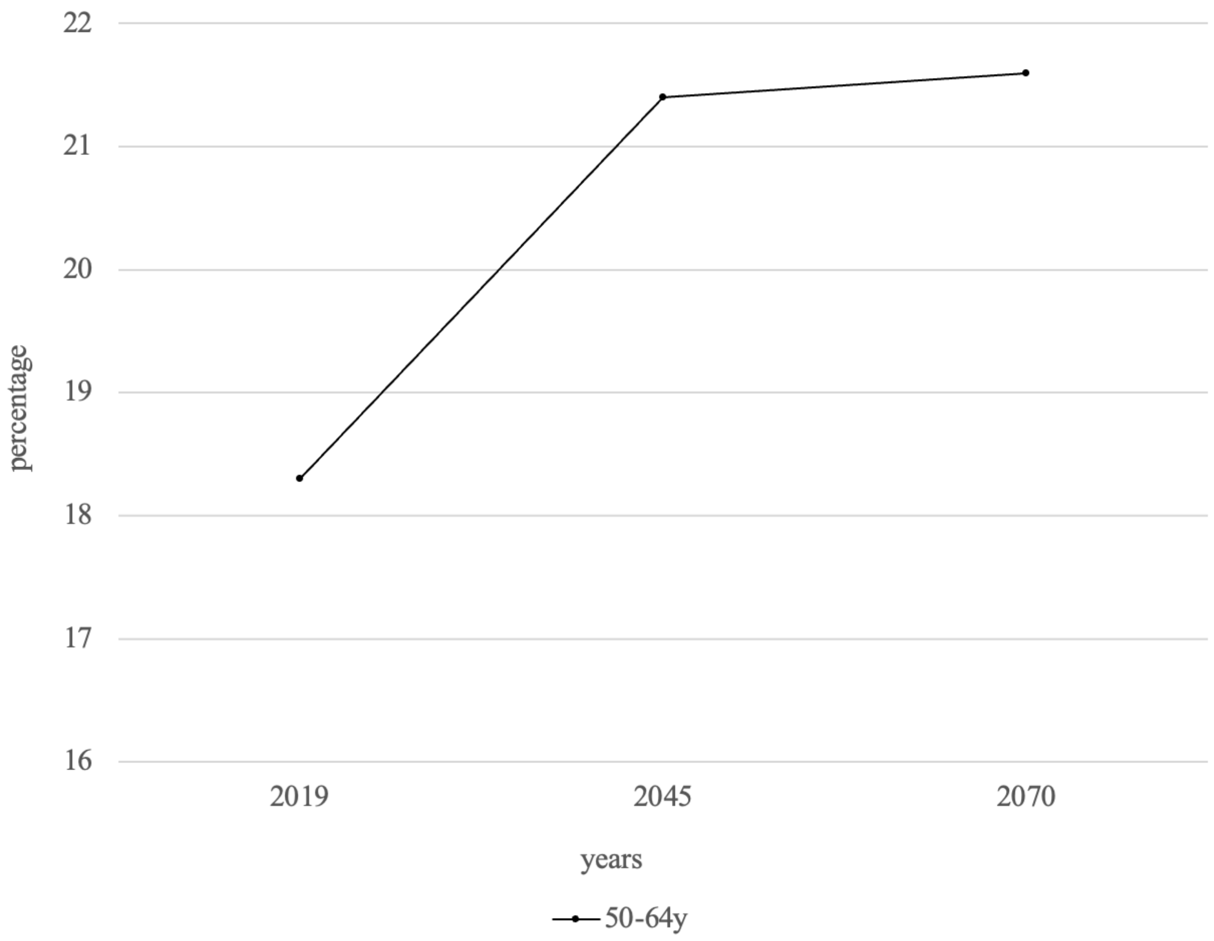


Figure 21 Percentage of aged workers (50-64y) on the total employment (20-64y) in Europe (European Commission, 2021).

On the one hand, a long-lasting working life offers opportunities for industries thanks to the expertise and knowledge gained by aged workers over the years. In this context, current employment policies encourage employees to continue working longer than previous generations (Parkes, 2016). On the other hand, postponing the retirement age increases the risk of exposure, hence the probability of developing occupational diseases (Varianou-Mikellidou et al., 2019). In fact, as workers age, many tasks they used to complete efficiently may become increasingly difficult due to a decline in mental and functional abilities (Choi, 2015). Moreover, the extension of working life, in most cases indoors, requires assessing the factors that determine the quality of the indoor environment. Stefanović et al. (2019) argue that IEQ affects workers' well-being, ability, and health. The potential negative impact concerns worker performance, defined as accomplishing a given task measured against known preset standards of accuracy, completeness, cost, and speed (Al Horr et al., 2016). The decline in worker performance affects economic growth and manufacturing efficiency (Digiesi et al., 2020). However, worker well-being and performance are complementary factors. Production systems supporting aged workers ensure high operator performance maintenance (Battini et al., 2018; Bogataj et al., 2019).

The World Health Organization (WHO), the International Labor Organization (ILO), and continental institutions such as the European Agency for Safety and Health at Work (EU-OSHA) provide guidelines and recommendations for companies supporting the active ageing of the working population. These Occupational Health and Safety Management System (OHSMS) guidelines suggest promoting active ageing as the opportunities arising from the elderly population heavily depend on their good health (WHO, 2016). ILO (2019) suggests investing in ergonomic improvements of the working places/processes and providing a better working environment to enable the continuing participation of aged workers in the labor market. From an organizational point of view, the EU-OSHA publication "Healthy Workplaces for All Ages Promoting a Sustainable Working Life" (2016) offers solutions and design ideas for improving work shifts, introducing job rotation, reducing physical workload, and increasing rest times.

According to these guidelines, the existing literature presents some studies investigating how the age factor strongly affects industrial workers' performances (Van Den Heuvel et al., 2010; Case et al., 2015; Guo et al., 2015; Kurtzer et al., 2020; Pan et al., 2020). Moreover, recent studies highlighted that age represents a crucial risk factor in the worker's response to IEQ factors as individual differences in the sensitivity to changes in environmental stressors, making difficult the interaction between people and industrial environments (Mofidi and Akbari, 2016; Mofidi and Akbari, 2017; Castaldo et al., 2018; Pigliautile et al., 2020). However, current literature lacks studies collecting, categorizing, and discussing such contributions to pave the way for an integrated analysis among the three factors, i.e., age, IEQ, and performance. Based on these premises, Section 3.3 proposes a systematic review of these contributions to fill this gap.

The remainder of this paper is organized as follows: Section 3.3.1 analyses the characteristics of the working population with a focus on ageing and how this phenomenon impacts workers’ capacities within the industry. Section 3.3.2 introduces the research approach adopted for the literature review, while Section 3.3.3 analyses the impact of age, performance, and environmental quality factors in pairs. Finally, Section 3.4 presents final remarks and future opportunities for research.

3.3.1 Aged workers in industrial processes

The decline in fertility and the increase in life expectancy at birth are behind the sharp rise in the elderly population worldwide (Calzavara et al., 2020). The economic pressures of these demographic trends are pouring into pension systems, forcing workers to postpone their retirement age (Case et al., 2015). According to EUROSTAT (2020) data, the percentage of people aged 55 years or more over the total number of persons employed in the European Union increased from 11.9 % to 20.2 % between 2004 and 2019. The Organization for Economic Co-operation and Development (OECD) defines older people as 65 (OECD, 2021). However, literature studies on the ageing of the workforce define "aged workers" starting from 50 (Eaves et al., 2016; Parkes, 2016; Digiesi et al., 2020).

In both cases, the chronological age cannot express the complex and continuous ageing process due to individual variability. The concept of age has a further dimension known as "functional age" (Varianou-Mikellidou et al., 2019; Varianou-Mikellidou et al., 2021). Functional age measures how well a person can operate in a specific environment or at a particular job compared with others of the same chronological age (Kowalski-Trakofler et al., 2005).

Next, subsection 3.3.1.1 describes the changes due to the ageing process, highlighting the natural age-related declines in functional and cognitive abilities. Although ageing leads to substantial physical and psychological changes, aged workers are relevant to the industry. Subsection 3.3.1.2 presents the age-related advantages within industrial environments.

3.3.1.1 Age-related decay

The EU-OSHA (2016) defines *age* as a multi-dimensional biological, psychological, and social change process. These changes correspond to a decline in overall physical and mental health. However, individual factors such as lifestyle, pre-existing disabilities, and fitness level make it non-universal (Lilley et al., 2018). Many ways exist in which capacity decay occurs in aged workers.

After age 50, increased muscle weakness affects joint flexibility and mobility (Choi, 2015). Moreover, changes in the locomotor system, associated with repeated demands on the same joints, make age a significant factor in developing Musculoskeletal Disorders (MSDs) (Claudon et al., 2020). Between the ages of 51 and 62, musculoskeletal disorders among workers can increase by 15% in physically demanding tasks (Kenny et al., 2008). Boenzi et al. (2016) suggest that MSDs cause numerous health problems, including back pain and work-related upper limb disorders. With increasing age, the greater severity of injuries increases the probability of contracting diseases. Furthermore, as aged workers cannot recover, the need for substitute workers often arises (Thompson et al., 2015).

In addition to muscle fatigue, potential causes of injury for aged workers include sensory impairment. Hearing loss leads to the possibility of missing alarms or other signals (Bogataj et al., 2019). Vision becomes compromised due to a hardening of the eye's lens (Eaves et al., 2015), impacting the ability to adapt to changes in light conditions and making the eye more sensitive to glare (Silverstein, M., 2008). Balance changes increase the risk of slips, trips, and falls (Choi, 2015).

Finally, the altered perception of hot and cold temperatures due to changes in the cardiovascular system and pathologies (Crawford et al., 2010) causes a decline in the thermoregulation phenomenon (Case et al., 2015). Due to ageing, the reduction in fluid intelligence affects multiple cognitive abilities, including thinking, reasoning, problem-solving, remembering, and decision-making (Digiesi et al., 2020). Mental deterioration impacts adapting to changes and learning new concepts and technologies (Dimian et al., 2016). Aged workers need more time to process information, complete tasks on time, and participate in training than younger workers (Calzavara et al., 2020).

The ageing process leads to physiological and cognitive changes that can challenge working in later life (Eaves et al., 2016). Ensuring favorable conditions for aged workers means protecting an industrial asset despite the factors listed. Subsection 3.3.1.2 describes the benefits that older workers bring to industries.

3.3.1.2 Age-related advantages

Aged workers are a valuable resource for national and global economic growth thanks to their professional and practical experience (Dimian et al., 2016), specific knowledge, and skills (Bogatai et al., 2019). Aged workers are familiar with their work environment and know how to perform complex tasks. These characteristics, combined with a better safety attitude and a more conscious use of personal protective equipment, allow aged workers to identify potentially critical situations quickly (Han et al., 2019).

Within industries, older workers are considered a relevant asset for the organization (Case et al., 2015; Kurtzer et al., 2020) thanks to their loyalty, expertise (Kralikova and Koblasa, 2018), and autonomy, and many companies prefer to keep them as long as possible (Choi, 2015). The study by Calzavara et al. (2020) highlights how experience is one of the determining factors in influencing workers' performance. Thanks to their expertise, aged workers can compensate for physical decay by transferring their knowledge and skills to younger workers (Eaves et al., 2015).

3.3.2 Research method

The search for articles included search strings in scientific databases, mainly Scopus (scopus.com) and Google Scholar (scholar.google.com). The aim was to find relevant contributions simultaneously addressing at least two of the three topics of interest, i.e., aged workers, IEQ factors, and industrial performance. In this way, the selected literature contributions dealt with aged workers and performance, aged workers and IEQ factors, and IEQ factors and performance. The analysis included the most relevant contributions published between 2000 and 2021. During the articles screening phase, search strings included the words *ageing or aged* and *worker*/workforce*, combined first with *performance* and then with *Indoor Environmental Quality (IEQ)*. Finally, the word *performance* was combined with *Indoor Environmental Quality (IEQ)*.

The first screening of the articles enhanced the studies presenting industry-oriented perspectives. The review considered those published in international ISI/Scopus journals, exploring the variation in the aged workers' performance. Moreover, the paper collection phase collected contributions that dealt with the impact of IEQ factors on the performance of industrial workers. The paper selection also considered articles providing valuable information on the impact of microclimatic factors on the aged workers' well-being. Contributions belonging to the thematic areas related to engineering, psychology, neuroscience, medicine, environmental sciences, and energy were analyzed.

The saturation point was reached in the article search phase when duplicates of articles began to appear continuously. The selected articles were categorized according to the belonging to a specific electronic database (ED). The central EDs identified are Elsevier (sciencedirect.com), MDPI (mdpi.com), Taylor & Francis (tandfonline.com), Wiley (wiley.com), and ASCE Press (ascelibrary.org). Globally, 58 articles were selected for this review. Such articles deal with issues related to industrial workers' well-being and performance. Some considered the impact of the age factor; others focused on factors that determine the quality of the indoor environment.

The following graphs provide some relevant metrics for the classification of the paper database. Figure 22 shows the temporal distribution of the selected articles. Figure 23 and Figure 24 show the publication sources and the EDs to which the articles belong. These last two figures contain only the academic journals and the most representative EDs of the analyzed papers.

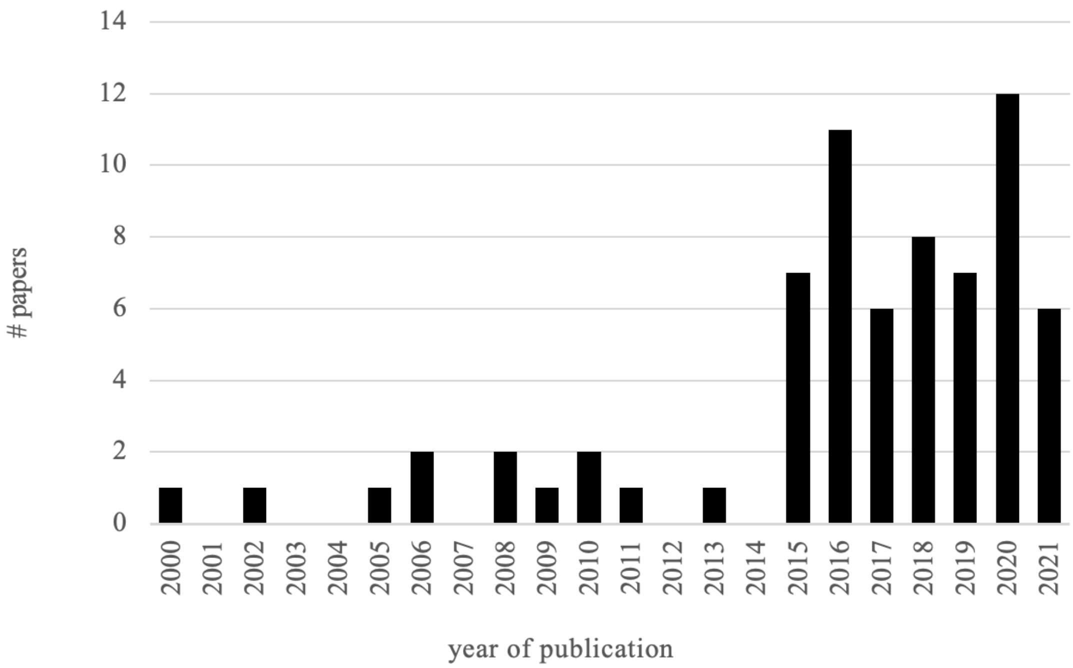


Figure 22 Paper database, classification per year of publication.

In Figure 22, up to 82% of papers are published starting from 2015, demonstrating growing attention for the aged workers' management and the quality of the working environment.

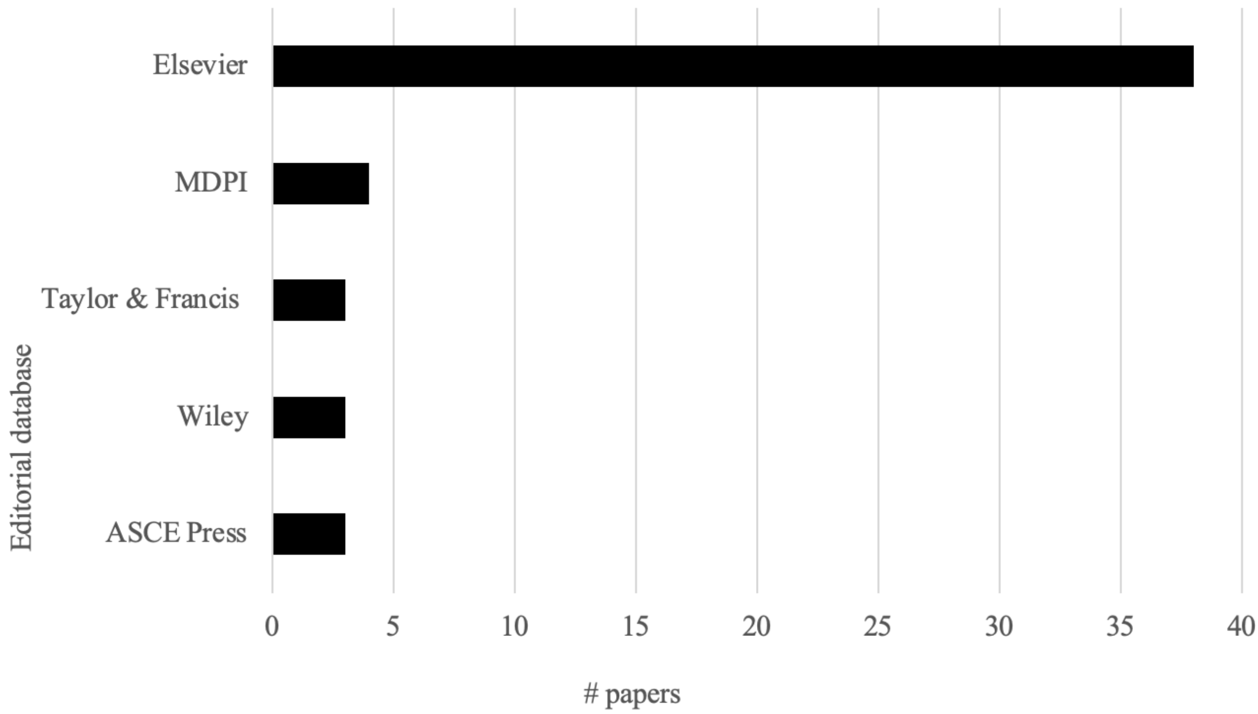


Figure 23 Paper database, classification by ED.

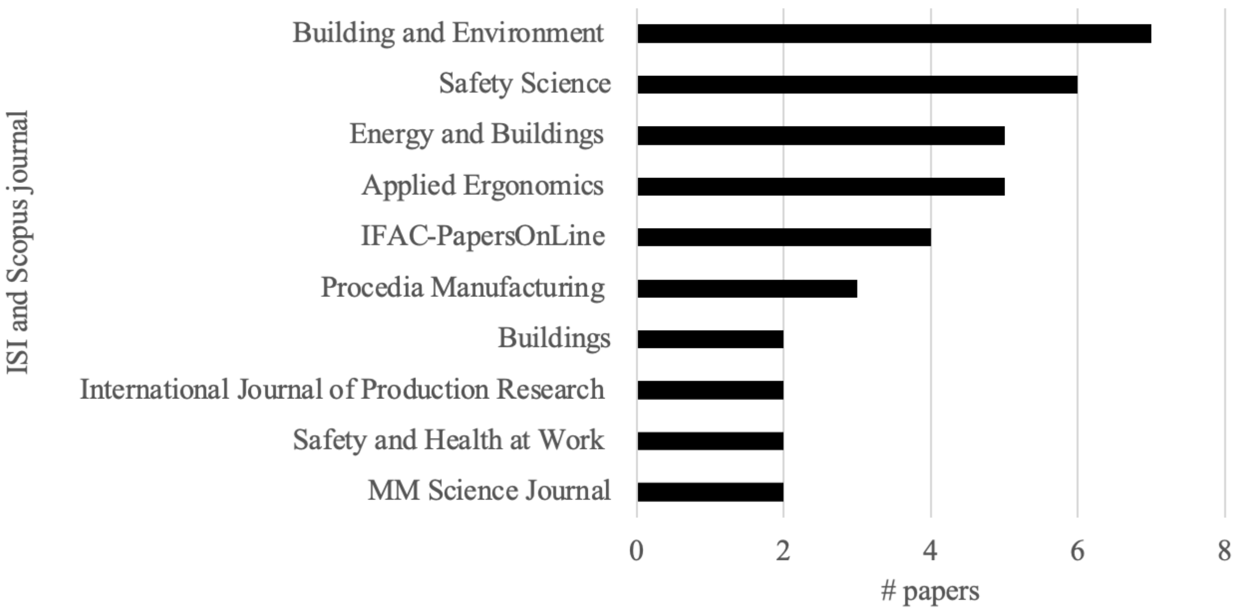


Figure 24 Paper database, classification per journal of publication.

In Figure 24, *Building and Environment, Safety Science, Energy and Building* and *Applied Ergonomics* collect up to 32% of the considered publications, representing the privileged target to publish innovative papers about the impact of environmental quality factors on the industrial performance of aged workers.

Finally, Figure 24 highlights the disciplinary sectors investigated in this review to analyze the impact of environmental factors on the performance of older workers. The analyzed topic considers contributions from the following subject areas: Engineering, Phycology, Neuroscience, Environmental Science, Energy, and Medicine.

3.3.3 The relation among age, performance, and IEQ factors

The existing literature investigates the variation in the performance of industrial workers in the field of safety science (Stefanović et al., 2019). Some of the studies relate the performance decline to the ageing of workers (Van Den Heuvel et al., 2010; Case et al., 2015; Guo et al., 2015; Kurtzer et al., 2020; Pan et al., 2020). Others to the change in IEQ factors (Lamb and Kwok, 2016; Ben-David et al., 2017; Steinemann et al., 2017; Kralikova and Koblasa, 2018; Szabo and Kajtar, 2018; Sun et al., 2019; Tagliabue et al., 2021). At the same time, other studies highlight that age represents a crucial risk factor in the worker's response to IEQ factors (Mofidi and Akbari, 2016; Mofidi and Akbari, 2017; Castaldo et al., 2018; Pigliautile et al., 2020).

Over the years, many papers have been published examining pairs of these three factors, i.e., age, performance, and IEQ factors. However, articles collecting, categorizing, and discussing such contributions to pave the way for an integrated analysis among such three factors are missing but highly expected.

Table 18 details the correspondence between the collected papers and the three factors mentioned above. A check mark indicates that the document in the row addresses the topics in the corresponding columns. The table indicates the publication date and the corresponding reference for each paper. The Age and IEQ factors columns contain subcategories for more effective classification of the research contributions. The Age column distinguishes contributions that treat functional decline from cognitive decline resulting in sensory impairments.

The IEQ factors column divides the publications according to the investigation of one or more inadequate IEQ factors, i.e., ergonomic working conditions, air temperature (T_{air}), relative humidity (RH), ventilation rate (VR), lighting, and noise. Multiple matches indicate a multi-perspective focus and partial overlaps between search topics.

However, no previous study relates all the subcategories of the factors, i.e., age, IEQ, and performance.

Author(s)	**Year**	**Age**		**IEQ factors**						**Performance**
		Functional decline	Sensory impairment	Poor ergonomic	Inadequate T_{air}	Inadequate RH	Inadequate VR	Inadequate lighting conditions	noise	
Salthouse	2000	✓	✓							✓
Van Someren et al.	2002		✓		✓					
Kowalski-Trakofler et al.	2005	✓	✓	✓						✓
Bortkiewicz et al.	2006	✓			✓					✓
Seppänen and Fisk	2006				✓		✓			✓
Kenny et al	2008	✓	✓							✓
Silverstein	2008	✓	✓							✓
Ismail et al.	2009			✓	✓	✓	✓	✓	✓	✓
Van Den Heuvel et al.	2010	✓								✓
Choobineh et al.	2011			✓						✓
Case et al.	2015	✓	✓	✓						✓
Choi	2015	✓	✓	✓						✓
Guo et al.	2015	✓	✓							✓
Kotek et al.	2015				✓	✓	✓			✓
Thetkathuek et al.	2015	✓			✓					
Thompson et al.	2015	✓								✓
Al Horr et al.	2016				✓	✓	✓	✓	✓	✓
Boenzi et al.	2016	✓		✓						
Dimian et al.	2016		✓							✓
Eaves et al.	2016	✓	✓	✓						✓

Hamilton et al.	2016						✓			✓
Lamb and Kwok	2016		✓		✓	✓		✓	✓	✓
Mofidi and Akbari	2016				✓		✓	✓		✓
Nunes	2016	✓								✓
Parkes	2016		✓	✓	✓		✓	✓	✓	✓
Ben-David et al.	2017						✓			✓
Botti et al.	2017	✓		✓						
Mofidi and Akbari	2017				✓		✓	✓		✓
Stazi et al.	2017				✓		✓			✓
Steinemann et al.	2017			✓	✓		✓	✓	✓	
Battini et al.	2018			✓						✓
Ben-David et al.	2018						✓			✓
Castaldo et al.	2018				✓			✓		✓
Digiesi et al.	2018	✓		✓						
Kralikova and Koblasa	2018				✓	✓	✓			✓
Lilley et al.	2018	✓	✓							✓
Szabo and Kajtar	2018				✓					✓
Bogataj et al.	2019	✓	✓	✓					✓	✓
Dimovski et al.	2019	✓	✓							✓
Isa and Atim	2019				✓		✓	✓	✓	✓
Shuang et al.	2019	✓		✓						
Sun et al.	2019				✓	✓	✓	✓		✓
Varianou-Mikellidou et al.	2019	✓	✓	✓				✓	✓	✓
Weng and Kau	2019				✓		✓			✓
Bai and Wicaksono	2020			✓	✓	✓	✓	✓	✓	✓
Calzavara et al.	2020	✓	✓		✓			✓		✓
Claudon et al.	2020	✓		✓						✓
Franco and Schito	2020						✓			✓

Kurtzer et al.	2020	✓	✓							✓
Pan et al.	2020	✓								✓
Pigliautile et al.	2020				✓					✓
Varianou-Mikellidou et al.	2020	✓	✓	✓						✓
Botti et al.	2021	✓		✓						
Khoshbakht et al.	2021								✓	✓
Ma and Qu	2021	✓	✓							✓
Tagliabue et al.	2021			✓	✓	✓	✓	✓	✓	✓
Varianou-Mikellidou et al.	2021	✓	✓							✓
Wang et al.	2021			✓	✓	✓	✓	✓	✓	✓
This paper	2021	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 18 Literature contributions classification.

Table 18 presents the papers in chronological order, allowing tracking of the rise and evolution of each topic by the literature. The discussion of the streams is in the following of the present Section 3.3.3. Chapter 2 discussed the relationship between worker well-being, productivity, and IEQ factors. Therefore, section 3.3.3 is devoted to the relationship between age and productivity and age and IEQ.

Table 18 shows the correspondence between the literature and the topics investigated. The reading of Table 18 shows that no contribution in the literature deepens the relationships between all the subcategories of the three macro topics covered. The contents collected and categorized during the literature analysis are represented in Figure 25. The schematic map organizes the literature contributions and gaps, highlighting pairs of relationships between ageing workers, IEQ factors, and performance.

The schematic of Figure 25 helps to structure the present review. Following the research aim, the map categorizes the factors included in the review (i.e., ageing, IEQ factors, and performance), detailing their subcategories. Furthermore, it combines the three factors in pairs, considering the contributions of the literature presented in Table 18.

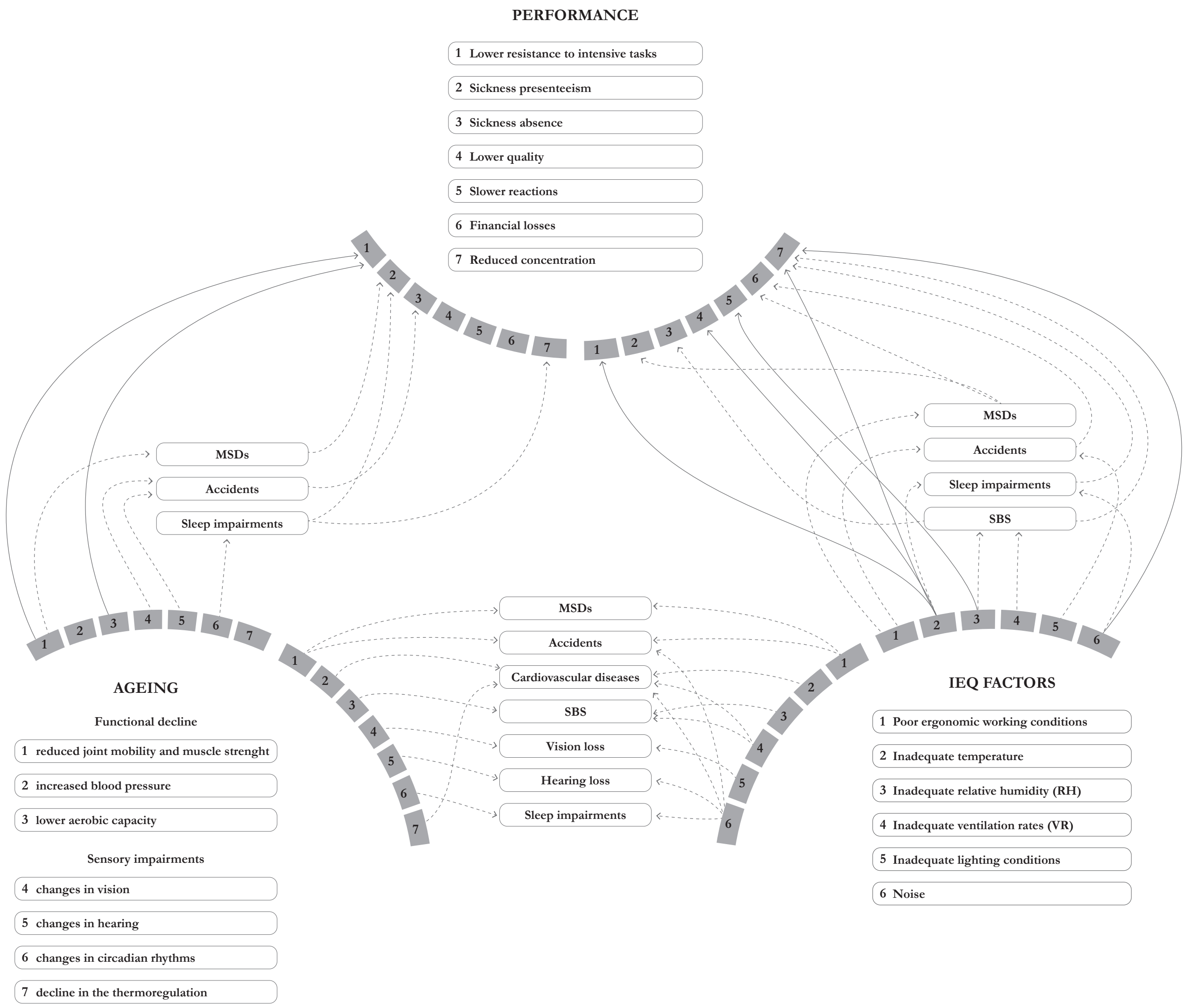


Figure 25 Summary representation of literature results and gaps. Continuous lines indicate the direct influence of subcategories while the dashed lines indirect ones.

The map illustrates the relationship between the ageing of workers and the decline in performance, the impact of IEQ factors on worker performance, and the relationship between ageing and IEQ factors. The direct influence of the subcategories belonging to different factors is represented by a continuous line (e.g., reduced joint mobility and muscle strength due to ageing directly affect workers' performance due to lower resistance to intensive tasks).

Conversely, dashed lines indicate indirect influence (e.g., changes in hearing due to ageing indirectly affect performance as they increase the risk of accidents and consequently cause sickness absence). The arrow indicates the direction in which the influence occurs. As explained below, the following subsections describe in detail the content of Figure 25.

Section 3.3.3.1, "Age and Performance," presents the impact of the decline in physical and physiological capabilities of ageing on industrial performance. This section delves into both the effect of functional decline (e.g., reduction in joint mobility, muscle strength, and aerobic capacity) on task performance and the consequences of cognitive decline on job performance.

Section 3.3.3.2, "Age and IEQ factors," states how age-related decline reduces tolerance to environmental stresses. This section presents literature contributions according to functional or cognitive decline and the impact of IEQ factors.

3.3.3.1 Age and performance

Forecasts for the near future indicate an increase in the number of workers over the age of 65 and close to retirement, in the European population; while the share of workers aged 50-64 appears to remain unchanged. On the contrary, the number of young workers entering the labor market is decreasing due to a decline in births and longer training courses (European Commission, 2021).

Consequently, the main strategies to maintain a positive relationship between yield and invested resources are two. On the one hand, reducing the number of workers corresponds to a greater demand for employment in terms of hours and services (Pan et al., 2020).

Aged workers may find themselves working closer to their maximal capacities, with a higher risk of chronic fatigue and musculoskeletal injuries (Kenny et al., 2008). On the other hand, it becomes necessary for aged workers to stay longer in industries (Nunes, 2016). However, the gap between employer demand and workers' productive capacity is increasing (Ma and Qu, 2021). In addition, aged workers may encounter health problems more frequently than younger workers as they are subject to a decline in physical, physiological, and cognitive abilities (Case et al., 2015).

Health problems cause a reduction in performance at work. At the same time, work performance may decrease because workers cannot be at work due to health problems. Thus, work performance loss due to health problems consists of two main components, i.e., sickness absence (i.e., days off work) and sickness presenteeism (i.e., reduced performance at work) (Van Den Heuvel et al., 2010). The literature highlights how the decline in physical and physiological capabilities and differences in psychological attitudes and behavior affect performance (Guo et al., 2015; Kurtzer et al., 2020).

Functional decline and performance

As people age, physiological changes occur, and such a decline in functional capabilities potentially affects any task (Varianou-Mikellidou et al., 2020). Case et al. (2015) study suggests a noticeable reduction in joint mobility over the years. The study shows a musculoskeletal strength decrease in the whole body from 30 years old, dropping by 30% around 60. The consequent loss of movement speed and the maximum and rapid power negatively impact the resistance to physical work (Thompson et al., 2015).

The study by Varianou-Mikellidou et al. (2019) shows that lesser endurance combined with lower aerobic capacity after age 40 affects the ability to perform a physically intense task or physical work over extended periods or under strict time constraints. Aged workers need flexible pacing conditions and more breaks during tasks to safeguard their performance, reducing the biomechanical load (Claudon et al., 2020). Boenzi et al. (2016) study states that job rotation solutions that minimize aged workers' load compensate for their decreased ability to meet stressful tasks.

Conversely, changes from low to high job demand, job strain, or night shifts are associated with the onset of sleep impairments. Poor sleep quality among aged workers affects concentration, increasing workplace accidents (Parkes, 2016). Age makes workers more vulnerable to accidents. In addition, the ability to recover quickly after an injury decreases (Karimi and Taghaddos, 2020). However, numerous studies highlight that age does not affect the likelihood of accidents but their severity (Choi, 2015; Lilley et al., 2018; Shuang et al., 2019; Jilcha Sileyew, 2020).

Eaves et al. (2015) collect guidelines to ease healthy ageing in the workplace. Aged workers propose improving facilities and personal protective equipment and structuring effective knowledge transfer systems. Hartless et al. (2020) state that educating the workforce to understand their physiological changes could proactively reduce the industry's hazards. Dimovski et al. (2019) consider safety training and technological updating as the key elements to help workers retain their positions and stay longer. At the same time, continuous training allows aged workers to transfer their knowledge to inexperienced young workers. Knowledge transfer addresses the problem of ageing and long-term skills shortages (Eaves et al., 2015).

Sensory impairment and performance

As workers age, the decline in physical skills causes a reduction of cognitive abilities with a strong influence on the human sensory perception and some mental processes, such as those requiring spatial abilities, problem-solving, and processing of complex stimuli (Silverstein, M., 2008; Dimovski et al., 2019). According to Salthouse (2000), physiological performance peaks between ages 20–30 and then declines by approximately 1% yearly. As a result of these changes, the ability of an individual to perform stressful activities declines with age, affecting work performance (Digiesi et al., 2020).

Eaves et al. (2015) highlight that visual changes impact accuracy on detailed tasks. Hearing loss leads to the possibility of missing alarms or other signals, increasing the risk of accidents (Bogataj et al., 2019). Poor or inadequate sleep quality affected by changes in the circadian rhythm and shifts is a causal factor in short-term performance decrements (Van Someren et al., 2002; Parkes, 2016). Although age affects human abilities and job performance, individuals age differently. A worker may perform tasks that another individual may struggle with (Eaves et al., 2015).

Workplace and task design must consider age classification to ensure aged workers' well-being and performance. At the same time, the workplace should respond to specific workers' needs to increase individual motivation, job satisfaction, creativity, and work performance quantity and quality (Calzavara et al., 2020).

3.3.3.2 Age and IEQ factors

The relationship between IEQ factors and the aged workers' well-being is very complex. Sensitivity to changes in environmental stressors depends on physical and subjective variables

(Mofidi and Akbari, 2017). Therefore, measurable environmental parameters alone are not sufficient to assess the occupants' comfort conditions. Castaldo et al. (2018) highlight a need for a systematic analysis of the impact of non-measurable factors, i.e., socio-psychological, physiological, and medical. Ageing, considered a complex set of processes that lead to physical and cognitive decline, significantly differentiates the physiological responses of individuals to the environment surrounding them, complicating this interaction. Although everyone ages differently, a characteristic that distinguishes the age factor is the progressive health decline (Varianou-Mikellidou et al., 2019).

This decline results in reduced tolerance to environmental stresses (Lamb and Kwok, 2016). The inability of individuals to respond to prolonged stress would result in cardiovascular (i.e., heart) diseases and Musculoskeletal Disorders (MSDs) (i.e., disorders of the nervous system, joints, ligaments, muscles, and tendons) (Isa and Atim, 2019). Van Someren et al. (2002) add a key step. Their study states that cardiovascular diseases result from impaired sleep due to age and adverse work environment combination. In addition, Parkes's (2016) study states that exposure to noise, poor lighting, inadequate temperature, and ventilation strongly contribute to sleep disturbance and insomnia.

Consequently, the deviation of IEQ factors from comfort ranges strongly affects the well-being of aged workers. At the same time, age becomes an additional risk factor in environmental stress conditions. Understanding the relationships between progressive physical and cognitive decline and critical aspects of the IEQ will allow the development of new strategies to support workforce ageing.

Functional decline and ergonomic working conditions

After age 50, individuals are subject to a decline in muscle strength (Thompson et al., 2015), limiting joint flexibility and mobility (Choi, 2015). Changes in the locomotor system make age a significant factor in the risk of developing MSDs (Claudon et al., 2020). Poor ergonomic working conditions and repeated requests on the same joints represent additional risk factors for developing MSDs (Botti et al., 2017; Botti et al., 2021).

Ageing and improper ergonomic working conditions lead to work accidents and diseases. On the other hand, applying ergonomics principles both in design (e.g., workstation design, equipment tools identification) and in operational phases (e.g., workload balance, task assignment) reduces the onset of MSDs (Digiesi et al., 2018), improving job satisfaction (Kowalski-Trakofler et al., 2005). Moreover, Dimovski et al. (2019) suggest that promoting healthy lifestyles and educational pathways to avoid the onset of MSDs allows people to remain active until retirement.

Functional decline, temperature, relative humidity, and ventilation rates

After age 30, the cardiovascular and respiratory systems change, impacting the tolerance to heat and cold (Case et al., 2015). Proper thermoregulation functioning requires that the metabolic rate, heat generated from energy in the human body, balance the rate of heat that the human body is losing (Van Someren et al., 2002). A decrease in the efficiency of the physiological response to changes in temperature (e.g., the release of sweat to decrease the temperature) prevents the achievement of thermal comfort (Lamb and Kwok, 2016).

Thermal comfort depends on temperature, relative humidity, and air movement. However, it expresses a subjective satisfaction with the thermal environment (Sun et al., 2019). The literature demonstrates how the possibility of acting on temperature control improves occupant comfort (Mofidi and Akbari, 2016; Castaldo et al., 2018).

Since most workers do not have this possibility, today's industrial workplaces are unsuitable for middle-aged and aged workers (Varianou-Mikellidou et al., 2019). Mofidi and Akbari's (2017) study states that failure to meet occupants' thermal preferences leads to adverse health effects.

Thetkathuek et al. (2015) highlight that working in a cold environment affects the respiratory system, reducing cutaneous blood flow and increasing blood pressure and heart rate. Aged workers with hypertension should avoid prolonged exposure to the cold environment due to the risk of developing cardiovascular diseases (Bortkiewicz et al., 2006).

Weng and Kau (2019) also consider inadequate ventilation rates a risk factor for aged workers as air pollutants threaten the human respiratory system and the cardiovascular system, leading to cardiovascular diseases. Older age exacerbates SBS symptoms, resulting in increased sickness absence.

Sensory impairment and lighting

Conditions of environmental stress strongly influence age-dependent muscle fatigue and cardiovascular diseases. Similarly, IEQ factors represent an additional risk factor for sensory impairment. Vision loss and workplace lighting are closely linked. Vision changes occur naturally with age, but inadequate lighting can affect vision loss. As people age, the eye lens hardens, impairing vision (Eaves et al., 2015). This phenomenon affects the ability to adapt to light conditions and makes the eye more sensitive to glare. Workplace adjustment for increasing lighting levels (e.g., installing local lighting or operational lighting to adjust themselves) compensates for the sensory loss of aged workers.

Sensory impairment and noise

The ageing sensory decline also results in high-frequency hearing loss and the inability to locate the sound source. These changes in hearing considerably impact communication, causing psychological stress. Noise exposure at the workplace is an additional risk factor affecting the operators' comfort, causing headaches, weariness, and increased blood pressure, with the risk of developing cardiovascular diseases (Isa and Atim, 2019). In addition, noisy work environments increase the risk of severe accidents since changes in hearing reduce understanding of instructions, increasing the possibility of missing alarms or other signals (Bogataj et al., 2019). A good solution is to equip offices with noise-blocking devices and equipment to prevent noise exposure and echoes. At the same time, the addition of visual cues and vibrations makes audible alarms understandable to everyone (Varianou-Mikellidou et al., 2019).

The increased life expectancy and the consequent extension of working life characterize today's workforce, generating new industry opportunities and challenges. Employers benefit from the aged workers' expertise and knowledge by postponing the retirement age. Conversely, they face an increase in occupational diseases.

The primary outcomes of Section 3.3.2 are the following:

1. The ageing process involves a progressive functional and cognitive decline that negatively impacts task execution. Older workers experience a significant reduction in joint mobility with consequent movement speed loss. Less endurance combined with lower aerobic capacity affects performing a physically intense task for prolonged periods or under strict time constraints.

2. The decline in physical skills causes a reduction of cognitive abilities, strongly influencing human sensory perception. For example, impaired vision and hearing loss have severe consequences in terms of the health of the operator. Failure to understand signals and alarms dramatically increases the risk of workplace accidents. Thus, work performance loss due to health problems consists of two components: sickness presenteeism (i.e., reduced performance at work) and sickness absence (i.e., days off work).

3. Ageing significantly differentiates the physiological responses of individuals to the environment surrounding them. The progressive functional and cognitive decline makes aged workers more susceptible to prolonged stressful situations. This aspect is responsible for cardiovascular diseases, musculoskeletal disorders, respiratory tract inflammation (SBS), significant sensory losses (visual and auditory), and sleep disturbances.

3.4 RESEARCH OUTCOMES

Chapter 3 responds to RQ2 by presenting the main factors limiting workplace environmental comfort. Several focal points emerge from the analysis considered in the research path to propose technical solutions, indices, and models. The following are the main findings to be considered when defining new strategies to support the safety of industrial workers:

1. Well-being is the core aspect that links IEQ factors, highlighted within Chapters 2 and 3, to worker productivity. The absence of environmental well-being, which can be declined

in its components of thermal comfort, IAQ, visual, and acoustic comfort, compromises workers' health and productivity.

2. Product storage needs determine the environmental conditions present in warehouses. Therefore, such environments are constrained and do not allow the attainment of comfort by operators, as defined in Section 2.2.2. This aspect can be generalized to many other industrial sectors, whether indoor (e.g., steel mills, ceramic industries, engineering) or outdoor (e.g., agriculture). In such environments, to protect the health and safety of workers, it is necessary to conduct an accurate risk assessment and incorporate technical and organizational solutions up to and including personal protective equipment.

3. The strategies adopted in workplaces to cope with the COVID-19 emergency, with proper precautions, are effective in maintaining good indoor air quality and can be extremely useful daily to cope with the transmission of influenza viruses or to ensure workers' comfort. However, the mere opening of windows or the absence and non-maintenance of filters inside facilities can compromise workers' health. Therefore, the use and routine maintenance of systems and filters are necessary to avoid thermal discomfort, inadequate air humidity, and the introduction of pathogens from outside.

4. The section on the ageing of the working population highlights the need to include the age factor in worker comfort assessments. However, as described in Section 2.2.1, no models and indices have considered this factor.

Chapter 4, devoted to solutions for restoring comfort within work environments, attempts to answer the issues highlighted here.

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4 INTERVENTIONS TO RESTORE COMFORT

This chapter addresses RQ. 3, exploring theoretical and practical solutions to restore the thermal comfort of industrial operators. The chapter delves into the "Banca delle Soluzioni" project, emphasizing the importance of this digital tool in bringing companies closer to industrial security solutions.

Then, the analysis focuses on the logistics industry, presenting technical and organizational solutions and personal protective equipment to safeguard warehouse workers' health. The proposed solutions refer to the risks analyzed in Section 3.1.2.

Finally, Chapter 4 focuses on solutions to support the ageing workforce by presenting a model that integrates the age factor within thermal comfort assessment and an experiment investigating older workers' responses to thermal stress.

The content of this chapter is based on the following research papers:

- Caporale, A., Botti, L., Galizia, F.G., Mora, C., 2023. Working in warehouses with adverse microclimatic conditions: technical solutions and evaluation models. Submitted paper as a chapter for the book “Warehousing and material handling systems for the digital industry. The new challenges for the digital circular economy”. Springer
- Caporale, A., Zaniboni, L., Wargocki, P., Mora, C., 2023. An experimental study investigating differences in acclimatization capacity and thermal preference between university students and older workers. E3S Web Conf. 396, 01048. https://doi.org/10.1051/e3sconf/202339601048
- Caporale, A., Gabriele Galizia, F., Botti, L., Mora, C., 2022. Thermal comfort prediction of aged industrial workers based on occupants’ basal metabolic rate. Soc. Occup. Ergon. 65, 120–129. https://doi.org/10.54941/ahfe1002666

The remainder of this chapter is organized as follows: Section 4.1 presents the “Banca delle Soluzioni” project focusing on technical and technological solutions to cope with microclimate risk. Section 4.2 explores the organizational and technical solutions to improve operators’ health in severe cold environments (section 4.2.1), in controlled atmosphere environments (section 4.2.2), and severe hot environments (section 4.2.3). Section 4.3 offers a model for incorporating the age of workers into the thermal comfort index. In addition, the section illustrates a thermal chamber experiment focused on analyzing the psychological and physiological responses of older workers subjected to thermal discomfort conditions.

4.1 "BANCA DELLE SOLUZIONI" PROJECT

Workplace safety is now of higher urgency than ever due to the frequent occupational injuries and illnesses on the daily news agenda, which point out the increased risks to workers' health. Some emerging risks from this perspective are biomechanical overload, the microclimate risk, and the risk of working in confined and suspected polluted environments.

On one side, Musculoskeletal Diseases and Disorders (MSDs) represent the leading cause of disability and a significant cause of sickness absence in various occupations (Battini et al., 2018). About 1.7 billion people suffer from MSDs worldwide. At the same time, the Italian Workers' Compensation Authority (INAIL) reported that these disorders reached 70 percent of the reported occupational diseases in Italy, resulting in lost productivity and high business costs.

Only recently, microclimate has been recognized as a physical risk agent under Article 180, Title VIlI of Legislative Decree 81/2008, as microclimatic conditions in a workplace can significantly interfere with occupants' activities, generating discomfort, reduced concentration, and cardiovascular disorders. Logistics, agriculture, and construction are particularly exposed to these issues (INAIL 2018). In addition, statistics show an increase in fatal injuries due to accessing confined and suspected polluted environments, with a high frequency in the construction (20.5 percent) and agriculture (19.5 percent) sectors due to exposure to hazardous gases/vapors and falls from height or depth (INAIL 2017).

International legislation on safety in the workplace suggests using control methods and tools to analyze, reduce, and, preferably, eliminate risks related to work activities (OSHA 3071: 2002, ISO 45001: 2018). Similarly, Italian legislation in Art. 15 of Legislative Decree 81/08 requires the elimination of risks or their reduction when this is not possible by adopting technological solutions and tools made available by scientific and technical progress.

In this context, implementing risk prevention and reduction actions takes on relevance, which must consider the awareness that there are technical solutions that can eliminate or reduce the adverse effects of such risks.

In 2014, the “Banca delle Soluzioni” project was born to spread the culture of prevention and awareness of technical solutions, in line with the dictates of Legislative Decree 81/08.

This project, set up in collaboration with the AUSL of Bologna, INAIL, the Labour Inspectorate, and the Fire Brigade, aims to analyze the health and safety conditions in which industrial work activities are carried out. The project initially focused on risks in confined environments and biomechanical overload, presented in 2015. In 2020, the microclimate section was born, introduced in 2023, along with redesigning the entire website and adding new areas of analysis in existing units. The online database is free to access at www.bancadellesoluzioni.org, and Figure 26 depicts its Home Page.

Figure 26 The Home Page of the “Banca delle Soluzioni” project.

“Banca delle Soluzioni” aims to represent an updated information document to guide companies in choosing automatic technical solutions capable of correcting work postures, improving the microclimate, and replacing the operator during risky activities in confined environments (Botti et al., 2016). The technical solutions contained within the project are identified through multiple search channels, such as scientific and industry literature, reports from workplace safety supervisory and control activities, and international search engines.

This collection is not intended to be an exhaustive list but is a dynamic document, an expression of the current state of technical progress.

The project addressed prevention service operators, workers, employers, safety professionals, designers, and anyone looking for practical solutions to design workstations and equipment.

Next, Section 4.1.1 details the microclimate section inside the project, showing some of the technical datasheets.

4.1.1. The microclimate section

The Microclimate section, created in 2020 within the “Banca delle Soluzioni” Project, has, together with the Confined Spaces Group and the Ergonomics Group, the purpose of analyzing and defining the state of the art on the degree of technological development related to tools and techniques suitable for eliminating risks at the source or minimizing them, in line with what is indicated within Legislative Decree 81/2008.

In particular, the work within the "Microclimate" working group aims to research materials, equipment, systems, and PPE aimed at reducing or eliminating microclimate risks and to disseminate valuable indications for the choice of effective and usable prevention and management measures for microclimate in the occupational sphere, through design criteria for work environments.

The result is the creating of an information document consisting of data sheets intended for dissemination to direct companies toward introducing structural and technological solutions capable of improving the microclimate, reducing the risks associated with inappropriate environmental conditions. Figure 27 shows the page of the Microclimate Section displaying the three areas of analysis (i.e., monitoring devices, case studies, and technical solutions) and insights related to risk description, current regulations, and design criteria.

Figure 27 The Microclimate section page.

The available data sheets cover heating and cooling systems that can be adopted in environments characterized by microclimate risk without requiring a complete renovation. Therefore, such heating and cooling systems are called localized because they allow the creation of comfort islands within industrial environments.

Section 4.2 explores the technical and organizational solutions and personal protective equipment suitable for microclimate hazards found in logistics warehouses.

4.2 ORGANIZATIONAL AND TECHNICAL SOLUTIONS

Warehouses are complex environments characterized by various processes and operations requiring efficient management (Halawa et al., 2020). The purpose of warehouses is to satisfy customers by maintaining the quality and safety of goods, especially perishable products (Chen et al., 2017). Environmental control (i.e., temperature, humidity levels, level of oxygen, and presence of gas) in the Controlled Atmosphere (CA) and cold storage ensure the preservation of goods. However, environmental strategies do not guarantee the workers' well-being and safety (Fuentes-Bargues et al., 2019). Research on warehouse management has recently started focusing on operator safety to limit accidents (Hofstra et al., 2018). The previous paragraphs illustrated the risks associated with the operators' access and activities in cold stores, CA storage rooms, and uncontrolled temperature warehouses. The following sections will deepen the regulations governing the operator's safety and the prevention and protection measures for operators exposed to severe hot and cold environments, oxygen-deficient atmospheres, and toxic or flammable gasses.

In addition, the following sections will outline some of the technical solutions of the "Banca delle Soluzioni" project that solve the risks highlighted in section 3.1.2.

4.2.1 Improving health and safety in severe cold environments

The temperatures and relative humidity levels required to preserve the quality and safety of perishable products in cold warehouses do not allow operators to achieve thermal comfort. Such warehouses are, therefore, classifiable as severe cold environments. In a severe cold environment, exposed subjects are unable, beyond certain limits, to retain heat within the body through thermoregulation mechanisms (i.e., vasoconstriction and shivering), resulting in a lowered core temperature (Thetkathuek et al., 2015). Extremely high relative humidity levels in cold storage worsen discomfort by saturating clothes, limiting their insulation capacity, and accelerating heat loss from the body (Wolkoff et al., 2021). Moreover, a heavy workload exacerbates the risk of musculoskeletal disorders (Caporale et al., 2022).

Prevention and protection measures could reduce the risk of cold injuries or illnesses. First, a risk assessment must be conducted according to the reference standards for severe cold environments: UNI EN ISO 11079:2008 and UNI EN ISO 13732-3:2009. IREQ (i.e., insulation required) is the index for assessing cold stress. This method calculates the insulation of clothing that is necessary to maintain the body's thermal balance for different physiological stress levels and the limited exposure time for certain levels of clothing insulation (Fuentes-Bargues et al., 2019; Holmér, 2009).

Prevention and protection measures are subsequently adopted based on the encountered risks. The primary prevention measures concern eliminating the risk, replacing the dangerous process with others that are not or less dangerous, and the workers' information, education, and training. In the case of severe cold environments, this measure refers to keeping workers outside the frozen and chilled chambers.

The realization of automated warehouses equipped with modular systems for the automation of storage and picking in multi-depth pallet storage represents a great solution to the operator's access problem. These shuttles, or satellites, guarantee high performance, speed, and layer storage management, significantly increasing the system's efficiency. In addition, the automation of access to and exits from the cold storage area reduces the costs of energy dispersion. Finally, these solutions are fundamental in limiting workers' time inside cold stores, safeguarding their safety. Figure 28 shows an automated storage shuttle produced by Moffett Automated Storage.

Figure 28 Automated Storage Shuttle produced by Moffett Automated Storage, CC Moffett Automated Storage.

Where operators need access to maintenance and control activities, organizational and technological protective measures and Personal Protective Equipment (PPE) apply.

Table 19 sets out the main measures applicable in severe cold environments to counter the risks due to worker exposure, according to Article 182, Paragraph 1, "Provisions aimed at eliminating or reducing risks," and Article 184, "Worker information and training" of Legislative Decree 81/08.

Prevention measures	Protection measures		
	Technical	**Organizational**	**PPE**
Reduce access and working time within the severe cold environment	Cover metal handles with thermal insulating material	Schedule work/rest times in a warm environment, job rotation	Protective clothing continuous work at or below 4°C
Information, education, and training of employees	Designing machines and tools so that they can be operated with gloves	Provide hot and sweet drinks, and warm and high-calorie foods	Hats and gloves to protect extremities

Table 19 Main risk control measures in severe cold environments, according to Article 182, Paragraph 1, and Article 184 of Legislative Decree 81/08.

Technical measures foresee the insulation of metal handles used in sub-zero climates and the design of machinery and tools to operate with PPE. For example, the design of touchpad devices must consider that operators will use them with cold protection gloves, compliant with UNI EN 511: 2006.

Organizational measures include controlled exposure to cold by alternating work and rest periods in a warm environment to allow workers to acclimatize through job rotation and regular rest breaks. Table 20 shows the maximum duration of activities within refrigerated rooms and the respective breaks in a heated restroom according to DIN 33403-5 (1997-1). Table 20 also specifies that if the permanence time is shorter than the maximum allowed, the warm-up time corresponds to a certain percentage of this duration.

Cold levels	Air temperature [°C]	Maximum uninterrupted permanence [min]	Heating duration depending on permanence [%]	Min. heating after max. permanence [min]
I	$10 \leq x < 15$	150	5	10
II	$-5 \leq x < 10$	150	5	10
III	$-18 \leq x < 5$	90	20	15
IV	$-30 \leq x < -18$	90	30	30
V	$-40 \leq x < -30$	60	100	60

Table 20 Cold exposure and rest times in a warm environment according to DIN 33403-5 (1997-1).

Organizational measures also require workers to consume hot, sweet, but caffeine-free beverages and warm, high-calorie foods. Finally, PPE requires the choice of appropriate protective clothing when working continuously at 4°C or below and using gloves and hats to protect the extremities.

Figure 29 depicts an operator wearing the PPE required for access, maintenance, and material handling operations inside cold stores.

Figure 29 Cold store operator wearing PPE (image: Freepik.com).

The choice of protective clothing depends on temperature, weather conditions, and the activity performed. Taking these factors into account allows the amount of heat and sweat generated during work to be regulated. In fact, in case of excessive sweating, clothes get wet, drastically reducing their insulating value and increasing the risk of cold injuries.

For environments with temperatures greater than or equal to -5°C, 150 g/m^2 cold weather protective clothing includes thermal undergarments, jacket, trousers or full quilted coveralls, light gloves, safety boots or shoes, and a Thinsulate hat or safety helmet.

While in a frozen environment with temperatures below -5°C, protective clothing of 235 gm includes thermal undergarments, jacket, and dungarees or full coveralls, both with knee protection, work gloves with thermal linings, insulated safety boots with thermal socks, safety helmet with thermal lining, thermal balaclava, and thermal hood.

In both cases, the given clothing weights are a recommendation. The exact requirements must be determined by risk assessment and according to the standard UNI EN 342:2017.

4.2.2 Improving health and safety in in controlled atmosphere environments

The American Occupational Safety and Health Administration (OSHA) defines "Confined Space" as an area that, by design, has limited openings for entry and exit, unfavorable natural ventilation that could contain or produce dangerous air contaminants and is not intended for continuous worker occupancy (U.S. Department of Labor, 2018). Based on this definition, OSHA further classifies confined spaces according to whether a permit is required to access them.

Permit-required confined spaces contain hazards such as a flammable atmosphere (> 10% of the lower flammable limit of any substance), an oxygen-deficient atmosphere (< 19.5%) or an oxygen-rich environment (> 23.5%), walls that converge inwards or floors that slope downwards and taper into smaller areas that could cause entrapment or asphyxiation, materials that could cause swallowing and any other hazards (e.g., electrical hazards, heat, unattended machinery) (U. S. Department of Labor, 2018).

Non-permit-required confined spaces are less hazardous than the previous ones since they do not present such characteristics (Smith et al., 2018). Based on this definition, the lack of oxygen (<4%) and the presence of toxic and flammable gases (e.g., ethylene, CO_2) that characterize CA classify such storage cells as permit-requiring confined spaces. The most insidious risk in confined environments is anoxic asphyxiation due to insufficient oxygen supply to tissues.

It takes a few breaths without oxygen to cause delayed reflexes, muscle control, inability to react, loss of consciousness, irreversible brain damage with paralysis, a comatose state, and progressive cell and neuronal death. For this reason, OSHA regulation 1910.134(b) declares confined environments to be Immediately Dangerous to Life or Health (IDLH), as they are characterized by an atmosphere that poses an immediate threat to life, would cause irreversible adverse health effects, or would impair an individual's ability to escape from a hazardous atmosphere (OSHA, 2004).

The primary prevention strategy concerns an accurate risk assessment before designing the working environment to reduce risk in confined environments and providing signs highlighting dangers in such an environment (Botti et al., 2018), as shown in Figure 30.

Figure 30 Warning sign to mark a confined space. Image by Tom Page, CC license.

Moreover, adopting technological solutions to monitor and maintain activities keeps operators out of such environments. The Confined Spaces section of the "Banca delle Soluzioni" project proposes several technologies that could replace operators in cleaning and maintenance activities, preventing their access (Botti et al., 2017; Mora and Botti, 2016; Mora and Botti, 2017).

For example, technological solutions dedicated to cleaning include Sonic Horns to clean tanks and reservoirs (e.g., boilers, filters, pharmaceutical industry tanks) containing dry material in the form of solid particles. The cleaning process involves acoustic emissions that act like short bursts of compressed air, dislodging residues from the walls. This solution, shown in Figure 31, is mainly used in potentially explosive environments.

1. TANKS AND RESERVOIRS

Sonic horns

Cleaning of tanks and reservoirs containing dry material in the form of solid particles (boilers, filters, pharmaceutical industry tanks, etc.), keeping the operator outside.

Mode of use
Cleaning through acoustic emissions that act like short bursts of compressed air. These rapid pressure fluctuations are transmitted to the dry material, which, on receiving them, breaks away from the walls and falls to the bottom of the silo by gravity or transported by the air stream.

Mobility features
Sistema fisso, non-climbing.

State of the tank
In-service

Explosive properties
Device that can be used in an explosive environment.

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Figure 31 Data sheets of sonic horns.

Finally, information, training, and instruction must be provided for the workers involved in applying procedures and using PPE. When entering a confined space cannot be avoided, technical solutions, organizational solutions, and PPE apply.

Table 21 contains measures applied in confined environments to counter exposure risks, according to DPR 177/2011 and Article 66 of Legislative Decree 81/08.

Prevention measures	**Protection measures**		
	Technical	**Organizational**	**PPE**
Risk assessment and safe working environment design and signage	Air quality monitoring	Adequate operational procedures	Gas detectors
Technological solutions to avoid operator access	Effective ventilation	Communication system	Lighting systems and special equipment
Information, education, and training of employees	Preventive cleaning of spaces	Appropriate emergency solutions	Breathing apparatus

Table 21 Prevention and protection measures in confined spaces according to DPR 177/2011 and Article 66 of Legislative Decree 81/08.

Technical measures refer to the hazard's containment within the confined environment through preventive cleaning, room ventilation management, and atmospheric composition monitoring. Organizational measures include providing adequate operating procedures to ensure the safety of operators within the environment. Furthermore, these measures include establishing a communication system that enables workers operating within the confined environment to keep in contact with those outside and to raise the alarm in the event of danger and emergency preparedness.

Finally, PPEs include portable gas detectors, appropriate non-sparking devices, shielded lighting systems in a potentially flammable or explosive atmosphere, and respirators in the presence of gases, fumes, or vapors due to the absence of oxygen.

4.2.3 Improving health and safety in severe hot environments

Warehouses without air-conditioning systems for storing non-perishable goods reach high temperatures during the summer period and significant vertical temperature differences (Rohdin and Moshfegh, 2011). These warehouses reach high temperatures and humidity levels that do not allow workers' thermal equilibrium, creating risks to their health and safety (Varghese et al., 2020). Uncontrolled temperature warehouses are classifiable as severe hot environments during the summer period.

A rise in core body temperature occurs in individuals exposed to severe hot environments. When subjects fail to dissipate the excess heat through thermoregulatory mechanisms (e.g., vasodilation, sweating), they experience pathological disorders (Kjellstrom et al., 2016). The most significant risk is heat stroke, which manifests as headache, dizziness, asthenia, and abdominal discomfort and can lead to delirium. When the core body temperature rises above 42°C, numerous organs are damaged, and death can occur in 15-25% of cases (Roelofs, 2018).

Other pathologies associated with prolonged exposure to heat are heat cramps due to the massive loss of minerals through sweating, dehydration due to loss of fluids, and heat exhaustion due to circulatory failure or collapse, which can even result in a brief loss of consciousness and can lead to heat stroke (Rahma et al., 2020).

Moreover, heat exposure in the workplace compromises worker efficiency and capacity, reduces productivity, and increases safety risks (Cai et al., 2018; Kotek et al., 2015). Risk assessment in severe hot environments concerns UNI EN ISO 7243: 2017 and UNI EN ISO 7933: 2005. The former provides an initial thermal stress estimate by calculating the synthetic risk index WBGT (i.e., Wet Bulb and Globe thermometer Temperature). The second allows a more detailed and reliable assessment using the PHS (i.e., Predicted Heat Strain) method.

Air temperature, relative humidity, radiant heat (from the sun or other sources), air movement, workload (nature of work and duration), clothing, and individual risk factors must be considered to identify the level of risk (Reinhold and Tint, 2009).

Prevention and protection measures can then be planned and implemented. The primary prevention measures concern the structural and plant design of the building. In buildings without an air-conditioning system, the correct arrangement of openings exploiting the chimney effect controls the summer temperature and limits temperature stratification by homogenizing the indoor environment (Porras-Amores et al., 2014).

Moreover, reflective or light-colored external cladding and roofing can reduce indoor temperatures. Meanwhile, information, education, and workers' training are essential for preserving their health and safety.

Finally, technological and organizational measures and PPE contain the effects of heat stress during working hours. Table 22 highlights the measures to counter the risks due to heat exposure, according to Article 182, Paragraph 1, "Provisions aimed at eliminating or reducing risks" and Article 184, "Worker information and training" of Legislative Decree 81/08.

Prevention measures	**Protection measures**		
	Technical	**Organizational**	**PPE**
Design a good airflow to encourage 'chimney effects' for dissipating heat	Installing fans (high humidity) or water coolers (low humidity)	Schedule work/rest times, job rotation	Evaporative-cooled, phase-change, hybrid-cooled garments
Clear and/or reflective cladding to reduce internal temperatures	An air-conditioned environment for workers to rest and recuperate	Provide cool water	Air-cooled garments
Information, education, and training of employees	Mechanical aids to reduce workload	Ensure trained personnel are available to manage heat injuries	

Table 22 Prevention and protection measures in severe hot environments, according to Article 182, Paragraph 1, and Article 184 of Legislative Decree 81/08.

Organizational measures include controlled heat stress by alternating work and rest periods (i.e., job rotation) to allow workers to acclimatize. Besides, workers are advised to drink cool water often. Furthermore, workers can always seek the assistance of personnel trained to handle heat injuries. Technical measures include the installation of fans in rooms with high humidity or water coolers at low relative humidity levels to promote air recirculation and evaporation of sweat. In addition, the availability of an air-conditioned environment enables workers to recover more quickly.

The "Banca delle Soluzioni" project contains data sheets for using fixed and portable coolers, shown in figures 32 and 33, respectively.

These devices base their operation on adiabatic cooling. Hot air from the room is cooled in the tank and then expelled from the system with the help of powerful motorized fans. Depending on the size of the water reservoir, these devices allow small or large rooms to be cooled. Fresheners are often combined with air extraction devices (e.g., helical fans or turrets) to increase the cooling capacity.

Compared to air conditioning systems, these devices have very low operating and maintenance costs and do not produce emissions, as they do not contain any refrigerant gases. Therefore, they are particularly suitable for installation in warehouses and industrial buildings where openings often must be maintained, making air conditioning systems untenable.

1. HOT ENVIRONMENTS

1.1. Cooling devices

Stationary coolers

Need to lower temperatures in large rooms characterised by hot and dry climatic conditions, due to solar radiation, heat input from plant and machinery, and lack of sufficient air exchange. These rooms (e.g. production halls or logistics rooms) often have to keep open spaces, making the use of air conditioning systems untenable.

Mode of use

Stationary industrial cooling equipment with a water tank used to cool and evaporate heat. The resulting cold air is expelled from the system by side, top or bottom discharge, with the help of powerful motorised fans. Systems managed remotely via control panel and/or remote control. Often combined with air extraction devices (helical fans or towers) to increase cooling capacity.

Pros

- Air filtration and temperature lowering (5-10°C) in medium to large spaces.
- Easy and versatile installation.
- Very low operating and maintenance costs
- They are emission-free, as they do not contain refrigerant gases.

Cons

- This equipment leads to an increase in indoor humidity, so it may be necessary to monitor comfort and thermal stress indices, as well as the impact on production activity (plants and materials)

Technical features

Cooling area: 200-400 square metres. The tank, with automatic loading/unloading, is between 18 and 40 litres. Power consumption: 250-1500W depending on selected speed. Degree of protection IP54, IPX4 or IP24. Noise level: 55-80dB. Some devices have OZOSYSTEM systems for water sterilisation.

Maintenance

End-of-season cleaning (washing of water distribution circuit, evaporator packs, recirculation pump and water collection tank). Covering the system and draining the water in the winter season to prevent frost damage. Every three to four years it is recommended to replace the evaporative packs

Conformity to standards

CE Certification

Cost

Purchase 2000-4500€
Installation varies from 4000€ to 7000€
Maintenance approx. 300€ per year per machine body

Figure 32 Data sheets of stationary coolers.

1. HOT ENVIRONMENTS

1.1. Cooling devices

Portable coolers

Need to lower temperatures outdoors or in small rooms, or at a single piece of machinery, in hot and dry climatic conditions due to solar radiation, heat input from plant and machinery, and lack of sufficient air exchange. In these environments (especially outdoors) it is often not sustainable to use air conditioning systems.

Mode of use

Transportable instruments for industrial cooling, indoors and outdoors, equipped with a water tank used to cool and evaporate heat. The resulting cold air is expelled from the system by side, top or bottom discharge, with the help of powerful motorised fans. Systems managed remotely via control panel and/or remote control.

Pros

- Air filtration and lowering of temperatures in the workplace (5-10°C).
- Easily transportable and usable outdoors.
- Very low operating and maintenance costs.
- They are emission-free, as they contain no refrigerant gases.

Cons

- In some versions, the water tank must be refilled manually; otherwise, a water connection is required.
- This equipment leads to an increase in internal humidity, so it may be necessary to monitor comfort and thermal stress indices, as well as the impact on production activity (equipment and materials).

Technical features

Cooling area: 50-400 square metres. Some technical characteristics are variable depending on the area being cooled: tank size between 50 and 250 litres, with manual or automatic loading/unloading; consumption between 150-1150W, also depending on the selected speed. Noise level: 52-68dB. Some devices can be equipped with UV lamps for water sterilisation.

Maintenance

End-of-season cleaning (washing of water distribution circuit, evaporator packs, recirculation pump and water collection tank).

Conformity to standards

CE Certification

Cost

Purchase 1200-2500€
Maintenance approx. 300€ per year per machine body

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Figure 33 Data sheets of portable coolers.

Moreover, mechanical aids that reduce the biomechanical overload of the operators are recommended. In this regard, the ergonomics section of the "Banca delle Soluzioni" project contains a subsection dedicated to technical solutions applicable in the retail sector (Botti et al., 2017; Mora and Botti, 2016; Mora and Botti, 2017).

Finally, PPE for preventing heat-related illnesses includes evaporative-cooled, phase-change, hybrid-cooled, and air-cooled garments. Head and neck garments (i.e., helmet-helmet, hood, bandana, neck guard, or neckband) cool the most exposed areas. Upper body devices (i.e., waistcoat, waistcoat) help protect vital organs. Wrist and ankle devices (i.e., wristband, wristlet, galoshes) ensure normal blood flow.

4.2.4 Concluding remarks

Warehouse storage conditions strongly affect product quality and safety. Several control measures for temperature, humidity, and atmospheric composition extend the life of goods to meet consumer expectations. However, these environmental conditions may conflict with the health and safety of the workers involved.

Low temperatures and high humidity levels characterize cold chain warehouses to ensure the storage of perishable products. These constraints do not allow operators to achieve thermal comfort, labeling such warehouses as severe cold environments. The same occurs in warehouses without a cooling system for storing non-temperature-sensitive products. In this case, the constraint depends on the need to save energy and results in high temperatures and vertical temperature differences during the summer, labeling such warehouses as severe hot environments. Finally, the Controlled Atmosphere (CA) composition for the maturation of meat, the ripening or degreening of fruit, and the flavor development in cheese threaten the humans that enter accidentally, identifying such warehouses as confined spaces.

Despite the progressive automation of logistics processes, some activities, e.g., maintenance actions, cleaning, goods inspection, and material handling operations, require the operators' access to storage rooms, compromising their well-being and safety.

Section 4.2 describes the environmental risks operators face in logistics warehouses, presenting the methodologies used to assess the risks. In addition, this section highlights the leading technical and organizational measures and PPE that allow operators to access and remain in areas dedicated to storing goods.

Meanwhile, sections 4.1 and 4.2 present and draw attention to the "Banca delle Soluzioni" project, which constitutes an updated database of technical and technological solutions for preventing and managing ergonomic, microclimate, and confined space risks in the industrial sector.

The application of dedicated solutions to different storage warehouses allows the maintenance of parameters that ensure the safety of goods without affecting the well-being and safety of the operators involved. The continuous updating of the project portal and collaboration with companies to analyze the application of the proposed solutions allows for quantifying the benefits for the operators involved in activities characterized by ergonomic, microclimate, and confined space risks.

Section 4.3 below presents a model and experiment for integrating the age factor into the assessment of operator comfort, constituting an innovative approach to occupational safety.

4.3 MODEL AND EXPERIMENT FOR THE AGEING WORKFORCE

The increase in life expectancy and falling birth rates drive the sharp increase in the world's elderly population. These demographic trends generate solid economic pressures on pension systems, forcing workers to postpone their retirement age (Caporale et al., 2022).

The increasing workforce ageing brings benefits and challenges to industrial structures. Industries consider aged workers as essential resources thanks to the experience and skills gained (Parkes, 2016). Conversely, the aged workers' progressive functional and cognitive decline reduces industrial performance (Varianou-Mikellidou et al., 2019).

Ageing significantly differentiates the physiological responses to the surrounding environment. Under prolonged exposure to stressed working conditions, older workers develop cardiovascular and respiratory disorders due to their limited tolerance. However, new occupational strategies have emerged to support aged workers' health, well-being, and productivity.

The World Health Organization (WHO), the International Labor Organization (ILO), and continental institutions such as the European Agency for Safety and Health at Work (EU-OSHA) provide guidelines and recommendations for industries to support aged workers through the improvement of the indoor environmental quality (IEQ) factors. The IEQ concept defines the relationship between environmental quality factors (i.e., thermal comfort, indoor air quality (IAQ), visual and lighting quality, and acoustic comfort) and the occupant's health and well-being (Stefanović et al., 2019).

Since ageing involves a decrease in the physiological response to temperature changes, among IEQ factors, thermal comfort assumes extreme importance in safeguarding their well-being. The evaluation of thermal comfort is carried out, even today, using Fanger's model, which introduces the Predicted Mean Vote (PMV) to predict the average thermal sensation of large populations (Fanger, 1970). The main limitation of the PMV concerns the inability to incorporate new relevant input variables, such as age, health status, body mass index, and contextual features (Arakawa Martins et al., 2022; Broday et al., 2019).

Section 4.3 aims to fill this gap by proposing an analytic model and an experiment. The model in section 4.3.1 allows a prediction of thermal comfort, including the age of the operators, by considering metabolism as the junction factor between changes in body thermoregulation and the energy balancing equation. Moreover, the experiment in section 4.3.2 tests thermal response and the ability to acclimatize during thermal discomfort conditions of different age groups.

Knowing the relationship between the comfort and age of operators and their physiological response to heat stress conditions enables accurate planning regarding work shifts, facility management, and provision of appropriate clothing and tools. The goal is to safeguard the health and well-being of older workers to improve their performance in industrial settings.

4.3.1 Thermal Comfort Prediction of Aged Industrial Workers Based on Occupants' Basal Metabolic Rate

People are living longer. Although everyone ages differently, a characteristic distinguishing the age factor is the progressive health decline (Varianou-Mikellidou et al. 2019). The cardiovascular and respiratory systems change after age 30, altering the thermoregulation phenomenon and limiting tolerance to environmental stresses.

At the same time, the inability of individuals to respond to prolonged environmental stress results in cardiovascular diseases (Isa & Atim 2019). Proper thermoregulation requires that the Metabolic rate (M), i.e., the heat generated from energy in the human body, balances the heat the human body is losing.

A decrease in the efficiency of the physiological response to changes in temperature (e.g., the release of sweat to decrease the temperature) prevents the achievement of thermal comfort. Thermal comfort depends on environmental parameters (i.e., air temperature, mean radiant temperature, relative humidity, and air speed). At the same time, it expresses a subjective satisfaction with the thermal environment (Sun et al. 2019). The indices used to evaluate thermal comfort derive from a theoretical approach based on applying the energy balance equation to the human body.

In 1960, Ole Fanger proposed the Predicted Mean Vote (PMV) methodology, deepened in Section 2.2, to predict the average thermal sensation of large populations on a seven-point thermal sensation scale (Fanger, 1970). The adaptability of the Fanger model makes it fundamental in the thermal comfort analysis of large populations, representing, on the other hand, one of its limitations.

In 2019, Broday et al. reported the presence of substantial disparities when comparing the PMV values to the actual thermal sensation reported by occupants. These discrepancies underline the differences in the thermoregulatory response of individuals in a given environmental condition. More recently, Arakawa Martins et al. (2022) reported that people with lower thermal sensitivity, such as aged workers, present thermal management and adaptation difficulties. The highlighted discrepancies suggest that one of the Fanger model limitations relates to incorrectly determining the users' M value (Broday et al. 2019). Section 4.3.1 aims to fill this gap by proposing a thermal comfort prediction model including the operators' age and considering M as a junction between changes in body thermoregulation and PMV calculations.

4.3.1.1 Methodology

The analytic model proposed in this paper addresses the thermal comfort prediction of industrial operators, using the Equation proposed by Harris-Benedict (1919) and revised by Mifflin and St Jeor (1990) for calculating the Basal Metabolic Rate (BMR) of individual workers.

The model proposes a detailed evaluation of PMV and PPD, considering the BMR values concerning the operators' age within the M parameter in the Fanger model. The aim is to improve aged workers' health and well-being and enhance their performance at work.

Table 23 shows the index and parameters used in the proposed model.

Index	
i	Activity index, $i = 1....n$
Parameters	
M	the Metabolic rate [W/m^2]
W	the effective mechanical power [W/m^2]
BMR	the Basal Metabolic Rate [W]
PAR	the Physical Activity Ratio
PAL	the Physical Activity Level
BSA	the Body Surface Area [m^2]
w	the person weight [kg]
h	the person height [cm]
y	the person age [years]
t_i	the duration of activity i [min]
T	the duration of the work cycle considered [min], equal to the sum of the partial durations [t_i]
P_a	the water vapor partial pressure [p_a]
t_a	the air temperature [°C]
f_{cl}	the clothing surface area factor
t_{cl}	the clothing surface temperature [°C]
t_r	the mean radiant temperature [°C]
h_{cl}	the convective heat transfer coefficient [w/(m^2 * k)]
V_{air}	the relative air velocity [m/s]
RH	the Relative Humidity expressed as the percentage [%] of the water vapor pressure to the

	saturation vapor pressure at a given temperature
I_{cl}	the clothing thermal insulation [clo]
MET	the Metabolic Equivalent of Task [met]

Table 23 Index and parameters for revised PMV model.

The analytic formulations of the models' functions are as follows.

$$PMV = [0.303 \times \exp(-0.036 \times M) + 0.028] \times \{(M - W) - 3.05 \times 10^{-3} \times [5733 - 6.99 \times (M - W) - p_a] - 0.42 \times [(M - W) - 58.15] - 1.7 \times 10^{-5} \times M \times (5867 - p_a) - 0.0014 \times M \times (34 - t_a) - 3.96 \times 10^{-8} \times f_{cl} \times [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} \times h_{cl} \times (t_{cl} - t_a)\} \quad (1)$$

$$M = \frac{BMR \times PAL}{BSA} \quad (2)$$

$$BMR_{men} = 10 \times w + 6.25 \times h - 5 \times y - 5 \quad (3a)$$

$$BMR_{women} = 10 \times w + 6.25 \times h - 5 \times y - 161 \quad (3b)$$

$$PAL = \frac{\sum_{i=1}^{n} t_i \times PAR_i}{\sum_{i=1}^{n} t_i} = \frac{1}{T} \times \sum_{i=1}^{n} t_i \times PAR_i \quad (4)$$

$$BSA = (w^{0.425} \times h^{0.725}) \times 0.007184 \quad (5)$$

$$M_{men} = \frac{(10 \times w + 6.25 \times h - 5 \times y - 5) \times \sum_{i=1}^{n} t_i \times PAR_i}{T \times [(w^{0.425} \times h^{0.725}) \times 0.007184]} \tag{6a}$$

$$M_{women} = \frac{(10 \times w + 6.25 \times h - 5 \times y - 161) \times \sum_{i=1}^{n} t_i \times PAR_i}{T \times [(w^{0.425} \times h^{0.725}) \times 0.007184]} \tag{6b}$$

Equation (1) computes the PMV values, as in the ISO 7730:2005 standard. The relationship between the M, the BMR, and the contribution of energy consumption derived from the Physical Activity Level (PAL) is in Equation (2). The Body Surface Area (BSA) subsequently divides the product between these factors. Equations (3a) and (3b) are from Mifflin and St Jeor's formulas for male and female BMR calculation, respectively (Mifflin et al. 1990).

Equations (3a) and (3b) consider individual weight (w), height (h), and age (y) in the BMR definition. Equation (4) represents the average time-weighted Physical Activity Ratio (PAR). PAR values represent the energy cost of physical activity expressed as a ratio of BMR.

The Du Bois formula for the BSA calculation is in Equation (5), given the individual weight (w) and height (h) (Du Bois and Du Bois 1989).

Equations (6a) and (6b) integrate Mifflin and St. Jeor's formulas into the male and female M equation.

The following feasibility constraints give consistency to the model:

M	46 W/m^2 to 232 W/m^2 *(0,8 met to 4 met)*	(7)
I_{cl}	0 $m^2 * K/W$ to 0,310 $m^2 * K/W$ *(0 clo to 2 clo)*	(8)
t_a	10 *°C* to 30 *°C*	(9)
T_r	10 *°C* to 40 *°C*	(10)
V_{air}	0 *m/s* to 1 *m/s*	(11)
P_a	0 p_a to 2700 p_a	(12)

The following Section applies the proposed model to three simulated work activities and discusses the main results and key findings.

4.3.1.2 Case study

This Section introduces the analytic model's application, proposing a multi-scenario analysis. This simulation involves the thermal comfort analysis of 12 operators engaged in three industrial processes. Specifically, the first Scenario investigates the operators' thermal comfort during office work. The second Scenario refers to an assembly activity. Finally, the third Scenario simulates the variation of operators' thermal comfort during a lifting activity.

The goal is to analyze the impact of the age of the operators on their thermal sensation, defined with the PMV, based on the application of the Equations proposed by Mifflin and St Jeor (3a and 3b) in the calculation of operators' M value (6a and 6b).

The multi-scenario analysis aims to compare the resulting PMVs to varying ages only. The environmental parameters (i.e., t_a, t_r, V_{air}, and *RH)* and the individual parameters (i.e., I_{cl}, *w,* and *h*) are constant in each Scenario.

The following Table 24 collects the values of the constrained parameters for evaluating PMV in each Scenario.

Individual parameters				**Environmental parameters**			
Gender	*w* [kg]	*h* [cm]	I_{cl} [clo]	T_a [°C]	T_r [°C]	V_{air} [m/s]	*RH* [%]
Male	79	176	0.5	24.5	27.5	0.10	50
Female	65	163					

Table 24 Constrained individual and environmental parameters.

Table 24 shows the environmental parameters and the thermal insulation provided by clothing, following the ranges described in UNI EN 16798-1:2019.

This standard defines the minimum quality criteria that the environmental parameters must respect to guarantee both the energy performance of the building and the operators' thermal comfort. In the three scenarios, the selected configuration simulates the optimal microclimatic conditions of an industrial environment during summer. Literature studies highlight the risks associated with the ageing of workers both during the winter and in the summer due to their reduced ability to regulate their body temperature in hot and cold environments (Calzavara et al. 2020). This multi-scenario analysis considers the summer period and represents only a first verification of the importance of the age factor in achieving thermal comfort.

The analysis of the age impact on individual environmental comfort involved the definition of 12 ideal profiles. In Table 24, the operators' weight and height values were established following the 50th mass and height percentiles of male and female Caucasian populations (Cassola et al. 2011).

The six male operators share the values of weight (79kg) and height (176cm) and differ in age (i.e., 20y, 30y, 40y, 50y, 60y, 65y). In the same way, the six female profiles share equal values of weight (65kg) and height (163cm) and different values of age (i.e., 20y, 30y, 40y, 50y, 60y, 65y).

In Table 25, the BMR in watts [W] was calculated with Equations (3a) and (3b) for men and women, respectively.

Gender	**Male**						**female**					
Age	20	30	40	50	60	65	20	30	40	50	60	65
BSA[m^2]	1.95						1.70					
BMR [W]	1785	1735	1685	1635	1585	1560	1407	1357	1307	1257	1207	1182
BMR/h [W/h]	74	72	70	68	66	65	58	56	54	52	50	49

Table 25 Hourly BMR calculation in the reference multi-scenario analysis.

Since this calculation derives the daily BMR in the following line, this result has been divided by 24, resulting in hourly BMR. The Body Surface Area (BSA) in [m^2] was calculated with the Du Bois formula (5) starting from the operators' weight and height. Values of w and h are constant in this multi-scenario analysis; therefore, BSA values are common to six males (1.95 m^2) and six females (1.70 m^2) operators, respectively.

Table 26 illustrates the M values of the 12 operators during the three scenarios.

Gender	male						female					
Age	20	30	40	50	60	65	20	30	40	50	60	65

Scenario 1: Office work												
PAR	**1.5**											
M [W/m^2]	57	55	53	52	50	49	51	49	48	46	44	43
MET [met]	0.98	0.95	0.93	0.90	0.87	0.86	0.89	0.86	0.82	0.79	0.76	0.75
Scenario 2: Assembly activity												
PAR	**2.5**											
M [W/m^2]	95	92	89	87	84	83	86	83	80	77	73	72
MET [met]	1.64	1.59	1.54	1.50	1.45	1.43	1.48	1.43	1.38	1.32	1.27	1.24
Scenario 3: Lifting activity												
PAR	**4.0**											
M [W/m^2]	152	148	143	139	135	133	137	133	128	123	118	115
MET [met]	2.62	2.55	2.47	2.40	2.33	2.29	2.37	2.29	2.20	2.12	2.04	1.99

Table 26 Calculation of metabolic expenditure for individual activities.

M [W/m^2] was calculated using Equations (6a) and (6b) considering for each Scenario $t_i = 1$ [h] and the Physical Activity Ratio (PAR) value in Table 26. The PAR values used to represent the energy costs of the selected activities are from Ainsworth et al. (1993). The M [W/m^2] value was converted to the Metabolic Equivalent of Task (MET) using the conversion formula 1 [met] = 58 [W/m^2].
The PMV values for each Scenario and operator are in Section 4.3.1.3.

4.3.1.3 Results and discussion

This Section introduces the results of applying the thermal comfort prediction model to the multi-scenario industrial case study. The aim is to verify the impact of workers' age on the individual response to the microclimatic conditions of an industrial environment during the performance of different activities.

Table 27 shows the individual parameters (i.e., gender and age) of the 12 operators involved, the values of PMV and PPD, and the reference scenario (i.e., office work, assembly activity, lifting activity).

Gender	male						female					
Age	20	30	40	50	60	65	20	30	40	50	60	65
Scenario 1: Office work												
PMV	-0.13	-0.27	-0.37	-0.52	-0.69	-0.75	-0.58	-0.75	-1.00	-1.20	-1.42	-1.50
PPD [%]	5	7	8	11	15	17	12	17	26	35	47	51
category	I	II	II	III	III	IV	III	IV	IV	IV	IV	IV
Scenario 2: Assembly activity												
PMV	0.57	0.54	0.49	0.45	0.41	0.39	0.44	0.39	0.34	0.29	0.24	0.21
PPD [%]	12	11	10	9	8	8	9	8	7	7	6	6
category	III	III	II	II	II	II	II	II	II	II	II	I
Scenario 3: Lifting activity												
PMV	1.42	1.36	1.28	1.23	1.16	1.12	1.19	1.12	1.04	0.97	0.91	0.86
PPD [%]	47	43	39	37	33	31	35	31	28	25	22	21
category	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV

Table 27 Change in PMV as worker's age increases.

The CBE thermal comfort tool (Tartarini et al. 2020) allowed the calculation of the comfort indices following the ASHRAE 55–2020, ISO 7730:2005, and EN 16798–1:2019 Standard. PMV, PPD, and category were calculated only by varying the MET values in Table 6. The values in Table 7 show that, for each of the three case studies, the age of workers significantly influences the response to the thermal environment.

The values in Table 5 show a condition of thermal neutrality for the 20-year-old male worker (PMV = -0.13) with a PPD equal to 5% in the case of office work (Scenario 1). As age increases, PPD increases, reaching 17% (category IV) for the 65-year-old male operator. The PMV negative value (-0.75) highlights the workers' thermal sensation, changing from neutral to slightly cool, as indicated in Table 1.

The 20-year-old male worker experiences a condition halfway between thermal neutrality and slightly warm (PMV = 0.57) during the assembly activity (Scenario 2). These results place him in category III with a PPD of 12%. In this case, the assembly activity produces a PAR of 2.5, increasing the operators' MET. For this reason, the PMV value of the 65-year-old operator in Scenario 2 is lower than the PMV values for the younger operators in the same Scenario.

The increased metabolic activity due to the activity carried out compensates for the cool feeling in Scenario 1.

The workers in Scenario 3 perform an intense activity (PAR 4), which places them in category IV with slightly warm to warm sensations. PMV and PPD variations are similar to those in Scenario 2. The feeling of thermal neutrality requires a warmer environment as worker age increases because of the drop in the BMR values. The metabolic decline compensates for the increase in the MET when performing intense work activities.

The results for the six female workers in Table 27 show that these operators present lower PMV values than their male counterparts of the same age and in similar environmental conditions. The environmental conditions in Scenario 1 (Table 24) are insufficient to guarantee the thermal comfort of female operators over 50 years old. The UNI EN 16798-1:2019 standard does not consider PMV values equal to or below -1.20.

Conversely, the BMR values for the female operator ensure comfortable conditions in conjunction with the medium-intensity assembly activity in Scenario 2 (PAR values equal to 2.5). In Scenario 3, all the female workers are in category IV. However, comparing their PMV values with those of male operators shows a slight improvement.

4.3.1.4 Concluding remarks

The ageing of the working population and the strategies to protect the aged workers' well-being and productivity represent fundamental issues within industrial settings. The literature highlights that all workers need favorable environmental conditions. Older workers need thermal comfort conditions to improve their health and to remain in the labor market.

The model in Section 4.3.1 proposed integration to the Predicted Mean Vote (PMV) methodology, including the age factor to calculate the Metabolic rate (M) of workers during the performance of three different work activities, i.e., office work and assembly and lifting activity. The multi-scenario analysis introduced in this section shows that the increase in age corresponds to a Basal Metabolic Rate (BMR) decline and a consequent decrease in M.

The drop in BMR values implies that, as age increases, the feeling of thermal neutrality requires higher ambient temperatures. So, in a cold or slightly cold environment, aged workers suffer more than their younger colleagues. Finally, female workers have lower BMR values than male workers. Therefore, female workers suffer more from a cold environment than male counterparts of the same age and in similar environmental conditions.

Considering the impact of changes in thermoregulation systems due to advancing age and gender in thermal comfort assessments allows for better plant management, work shift definition, and appropriate clothing and tools supply.

4.3.2 An experimental study investigating differences in acclimatization capacity and thermal preference between university students and older workers

According to Section 4.3, recent literature reported the presence of substantial disparities when comparing the PMV values to the actual thermal sensation reported by occupants in real-case scenarios set in offices or other production environments (Broday et al., 2014; Broday et al., 2019; Gilani et al., 2016; Van Hoof, 2008). In 2022, Arakawa Martins et al. stated that the inconsistency between the model's results and the registered thermal sensation relates to the PMV's inability to incorporate demographic characteristics (e.g., age, gender, and nationality).

When considering the age factor, the 2019 study of Isa and Atim highlights the decline in thermoregulatory response as one of the main factors determining the reduced environmental tolerance in older workers (45-65 years old). On the one hand, physiological changes in the cardiovascular and respiratory systems (after the age of 30 years) can reduce the effectiveness of the body's thermo-regulatory function, limiting tolerance to environmental stresses (Varianou-Mikellidou et al., 2019).

On the other hand, the inability of individuals to adapt to uncomfortable thermal environments can result in cardiovascular diseases (Gasparrini et al., 2015). Fanger's model assumes that older workers' (45-65 years old) thermal response is similar to the one provided by young adults, whose comfort temperature in winter is around 22 °C with 1 clo and in summer around 24 °C with 0.5 clo (Fanger, 1970). However, the literature suggests that older people (age 65 and over) prefer higher room temperatures than younger people (DeGroot and Kenney, 2007; Schellen et al., 2015) but lacks studies quantifying older workers' thermal preferences and ability to acclimate in thermal discomfort conditions.

Adequately adjusting the workplace temperature would be crucial to protect workers' health.

Section 4.3.2 presents an experimental study that will help understand how the thermal needs of older workers differ from students', assessing their response to thermal discomfort conditions during two temperature ramps through the evaluation of psychological responses and physiological correlates.

4.3.2.1 Experimental method

In the current study, seven college-age students and six older workers were exposed to increasing and decreasing temperature ramps at 3.5 K/h after being allowed to modify their clothing insulation to be thermally neutral at 22 °C.

ASHRAE requirements regarding the maximum operative temperature change allowed (i.e., 2.2 K/h) were not met since the study aimed to test how participants react to thermal discomfort conditions (ANSI/ASHRAE Standard 55-2020). Moreover, only male subjects participated in the experiment to eliminate the gender factor as a variable possibly influencing the results. It is planned to repeat the experiment with a larger sample, including both male and female participants.

Climate chamber

The experiments took place between mid-September and October 2022 in a climate chamber (5 m [16.4 ft] wide, 6 m [19.7 ft] long, and 2.5 m [8.2 ft] high) at the laboratory of the Department of Environmental and Resource Engineering at Technical University of Denmark.

The chamber was developed to accurately control the thermal environment (Kjerulf-Jensen et al., 1975) and is located in an indoor lab with an HVAC system. The inside wall layer of the climate chamber is made of vinyl sheets separated from the solid outer walls by an air gap of 1.6 cm thick approximately.

This space allows mean radiant temperature to be always equal to air temperature, even during thermal transitions.

Participants

Thirteen subjects (seven university students aged 20–28 and six older adults aged 45-60) participated in the experimental sessions. All subjects were men, healthy, normotensive, and not undergoing any treatment that might alter the cardiovascular or thermoregulatory responses to the temperature changes. Before the experiment started, each participant signed the consent form to process personal data.

During each session, up to eight subjects attended the experiment, sitting in the chamber at separate workplaces with a desk and a chair. Each participant worked on a computer during the investigation. Each subject participated in the two sessions on two different days of the same week, chosen randomly to minimize biases caused by the order of exposure.

Measurements

Environmental and physiological parameters were recorded in the experiment. The environmental parameters included air temperature, globe temperature, and relative humidity.

These quantities were detected at 30-second intervals using two sensor stations positioned in the middle of the two long sides of the chamber. The sensor stations comprised HOBO sensors to measure air temperature and humidity. Moreover, we used grey bulb sensors (0.04 m diameter) to calculate the operative temperature according to UNI EN ISO 7726: 2002.

The sensors were positioned at a height of 0.6 meters to resemble the position of seated participants according to ASHRAE Standard 55. Moreover, Sessler's method of estimating skin blood flow (SkBF) was used to determine vasoconstriction thresholds (triggering core temperature) (Sessler et al., 1988; Sessler et al., 2003).

Skin temperature measurements were taken at 30-second intervals on the forearm ($T_{sk\ forearm}$) and index finger ($T_{sk\ finger}$) through iButton temperature loggers.

This allowed vasoconstriction/vasodilation to be characterized by the temperature difference calculated using the following equation (1):

$$T_{sk\text{-}diff} = T_{sk\ forearm} - T_{sk\ finger} \qquad (1)$$

The accuracies of the measuring instrumentation were 0.35 K (0.63 °F) (air and globe temperature), 2.5 % (relative humidity), and 0.1 °C (skin temperature).

Subjective questionnaires

While monitoring environmental and physiological parameters, participants were asked to complete their subjective thermal responses four times per session. The psychological responses involved the thermal comfort vote (TCV), thermal preference vote (TPV), and thermal acceptability vote (TAV). Figure 34 represents the thermal response scales developed by UNI EN ISO 10551:2019.

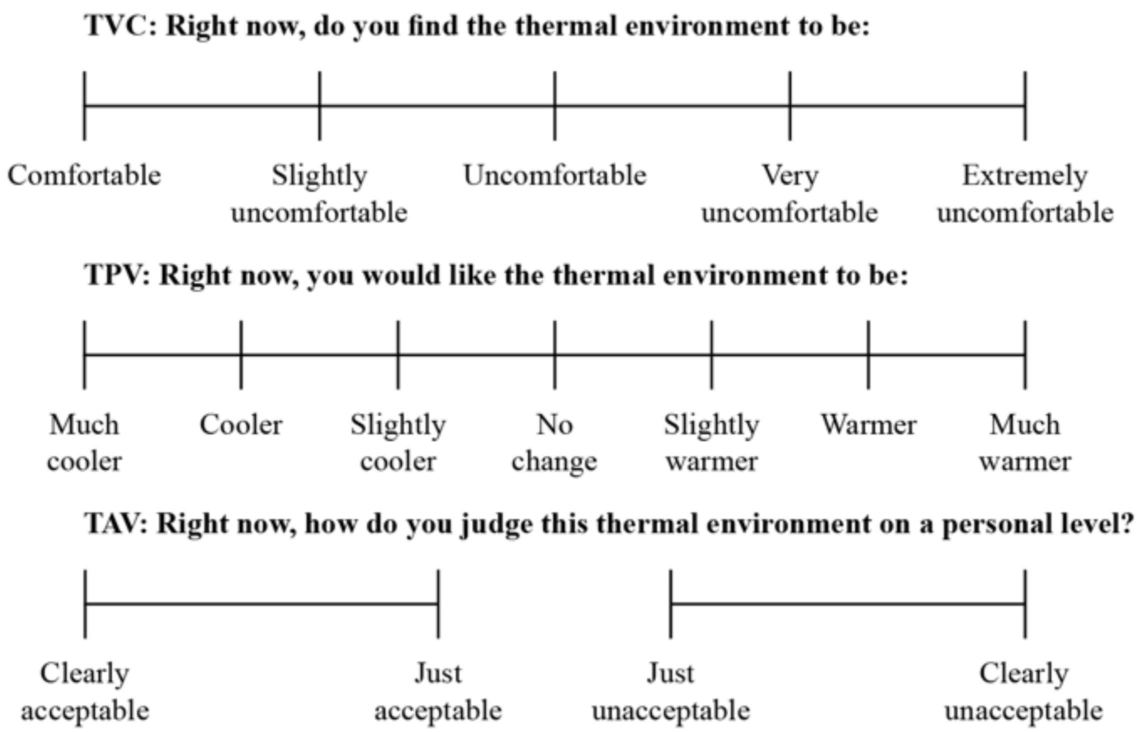

Figure 34 Scales for assessing thermal comfort, preference, and acceptability, according to UNI EN ISO 10551:2019.

4.3.2.2 *Experimental procedure*

Figure 35 represents the main steps of the warm ramp and cold ramp exposures used in the experiment.

In both sessions, subjects were initially exposed at 22 °C with 40 % humidity for one hour to allow their adaptation to the starting condition. Participants were allowed to modify their clothing to achieve thermal neutrality (i.e., feeling neither hot nor cold) after the acclimatization time.

This was allowed only during the first session, with subjects being asked to maintain the same chosen clothing during the following session.

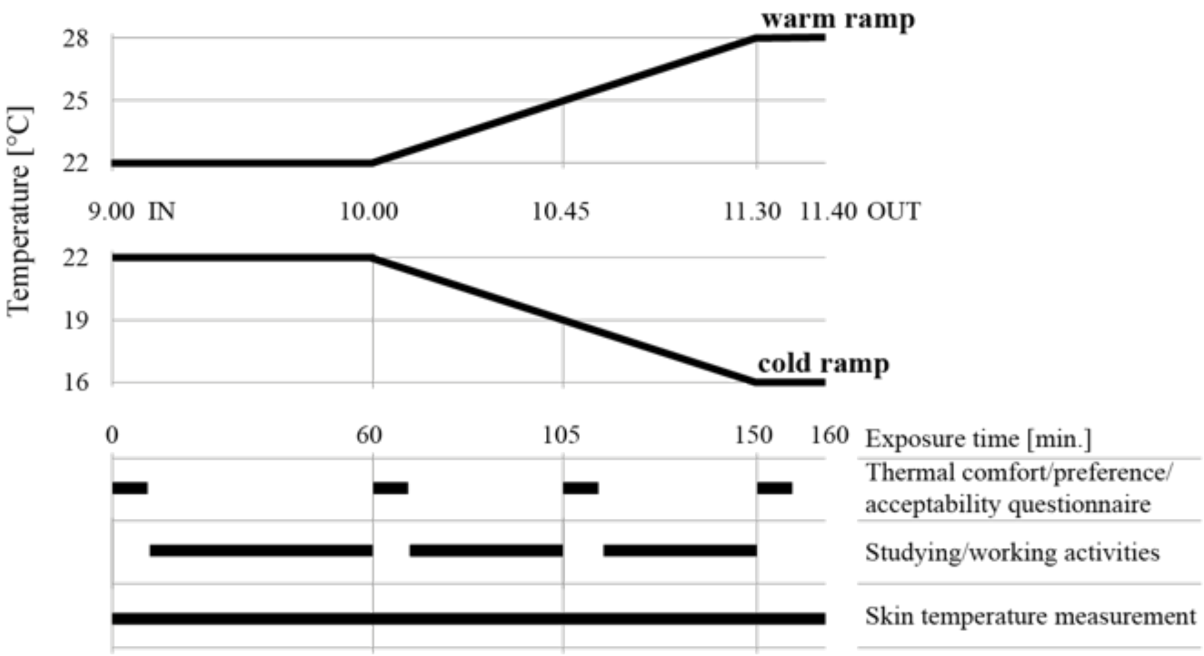

Figure 35 Experimental procedure.

Subjects could choose between three garments (long-sleeved T-shirt, light jumper, or thick jumper) that differed slightly in insulation (0.20-0.35 clo), according to UNI EN ISO 7730:2006, but not sleeve length. This permitted us to obtain comparable skin surface temperature results.

It is essential to specify that the initial clothing adjustment was not aimed at maintaining comfort during the entire ramp duration, as the purpose of the study was to evaluate psychological and physiological responses to discomfort conditions as a function of the subjects' age.

After the acclimatization period, participants underwent two temperature ramps at the rate of 3.5K/h from 22 °C to 28 °C and from 22 °C to 16 °C, respectively.

Both during the warm ramp and the cold ramp, participants were asked to fill in the same questionnaire four times: (1) as soon as they entered the climatic chamber; (2) after one hour, just before the ramp began; (3) halfway through the ramp; (4) at the end of the ramp before leaving the climatic chamber.

4.3.2.3 Results and discussion

Cold ramp

The trend in skin temperature difference characterizing vasoconstriction ($T_{sk\text{-}diff}$) of older workers and students during the cold ramp is represented in Figures 36 and 37, respectively.

The trend in the two graphs is similar, except for the two peaks in the workers' graph (Figure 36) when they enter the thermal chamber (22 °C) and reach 16 °C. These peaks and the resulting standard deviation highlight a higher variability in the physiological response of older workers' samples.

Moreover, the initial peak suggests that workers were uncomfortable entering the chamber because it was not meeting their neutrality condition. In both samples, vasoconstriction values were close to zero during the first adaptation hour, then rising again as the chamber temperature decreased.

In the case of students (Figure 37), the growth of $T_{sk\text{-}diff}$ values is due to the slowing down of metabolism aimed at maintaining the initial stationary comfort condition. The effect of this process is a decrease in the temperature at the extremities (fingers). In the case of older workers, the initial vasoconstriction peak has been compensated by the possibility of adjusting the clothing level.

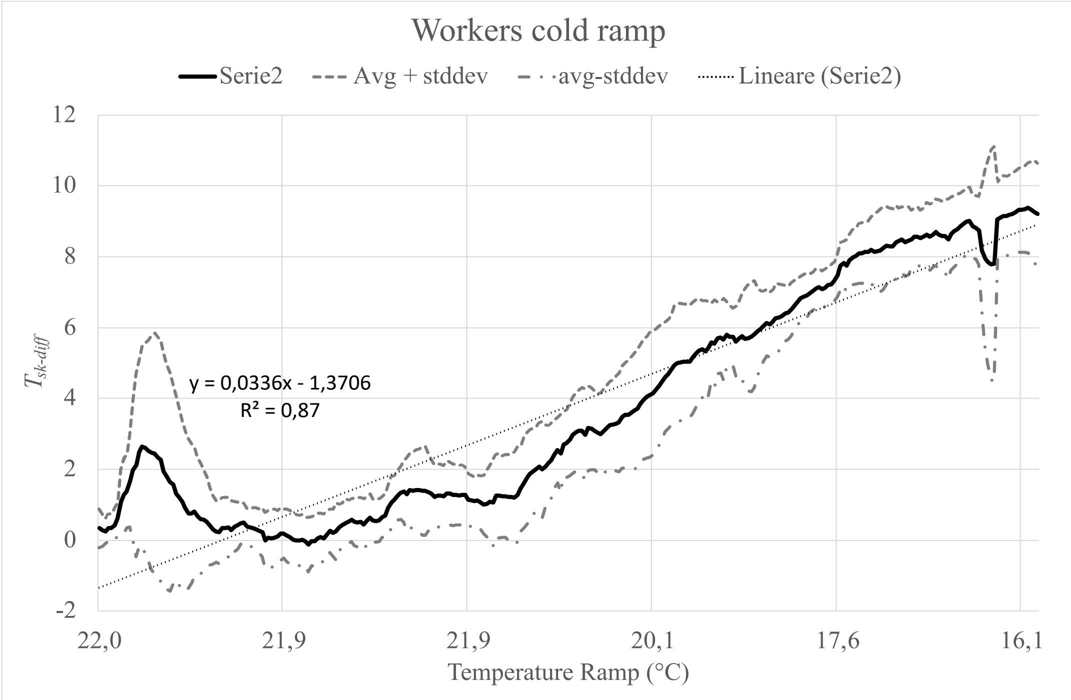

Figure 36 Trend in $T_{sk\text{-}diff}$ value for older workers during the cold ramp.

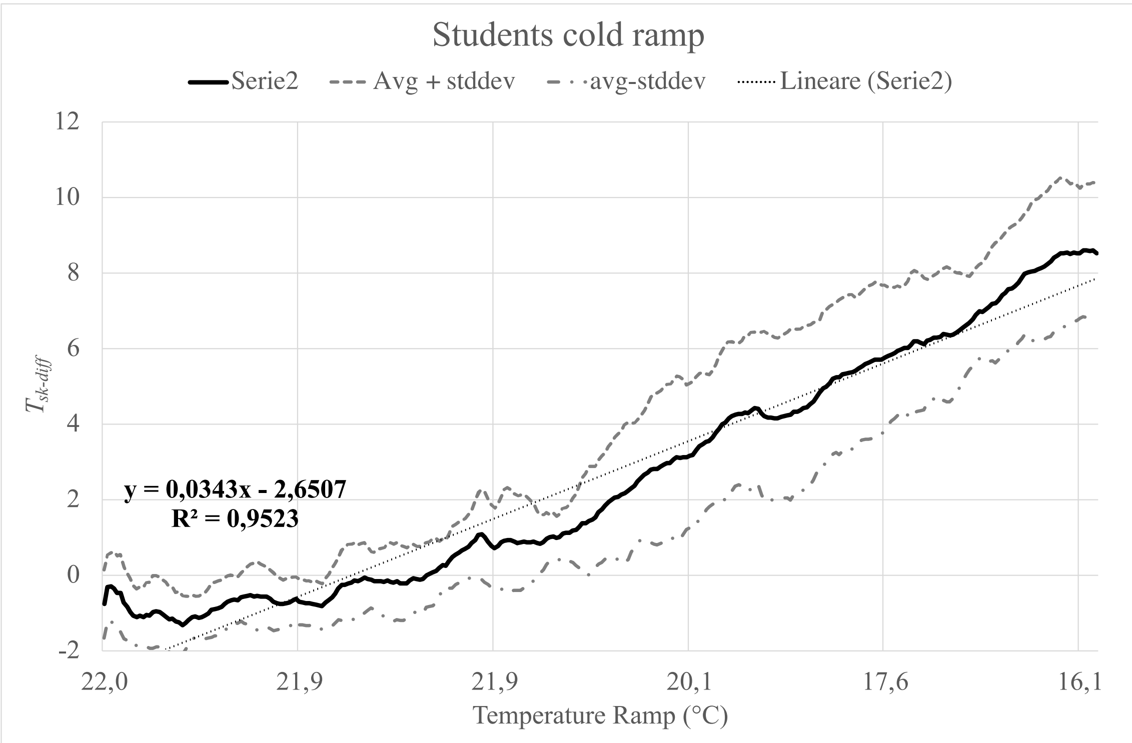

Figure 37 Trend in $T_{sk\text{-}diff}$ value for students during the cold ramp.

At 19 °C and 16 °C, students show a lower $T_{sk\text{-}diff}$ than workers. At 19°C, the value for students is 4, while for workers, it is close to 6. At 16°C, the value for students is 8.3 and 9 for workers.

Figure 38, which represents the TCV of workers and students during the cold ramp, shows contrasting results compared to the physiological response observed when analyzing vasoconstriction.

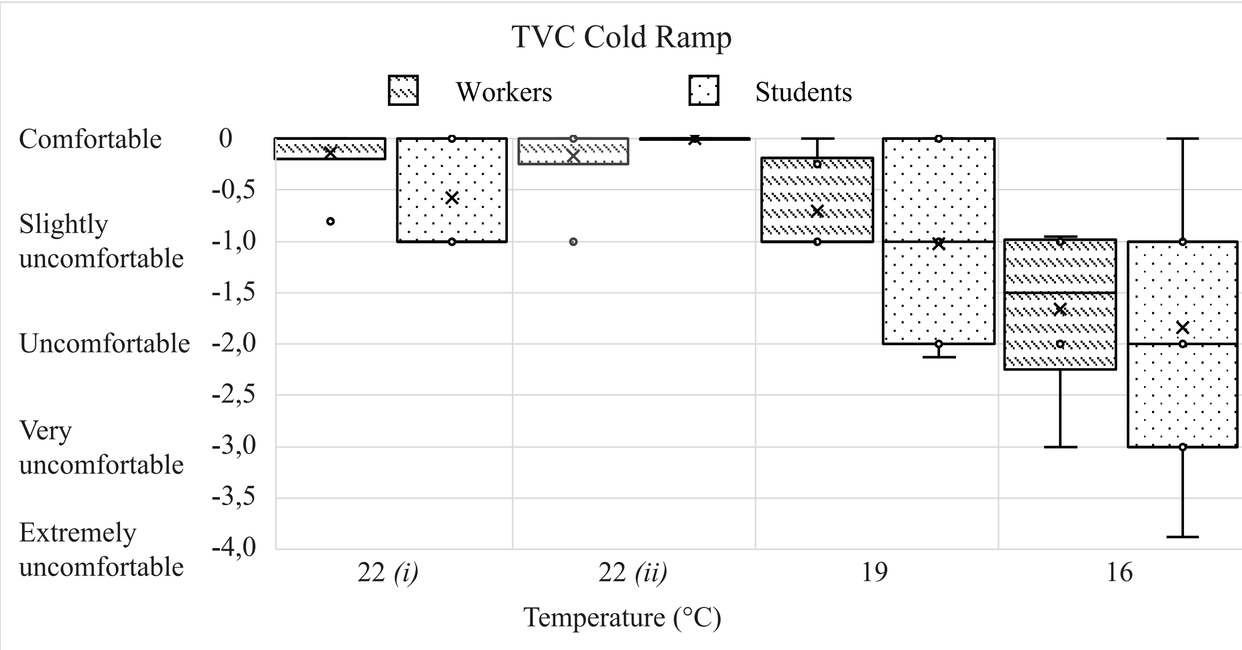

Figure 38 Comparison of students' and workers' thermal comfort votes (TCV) during the cold ramp. On the horizontal axis, *22 (i)* refers to the participants' thermal comfort votes recorded as soon as they enter the thermal chamber, while *22 (ii)* refers to the ratings recorded after one hour.

Despite their lower $T_{sk\text{-}diff}$ values, students expressed slightly lower comfort ratings at 19°C and 16°C than their worker counterparts. Results in Figures 39 and 40, comparing students' and workers' TPV and TAV, respectively, are coherent with the ones regarding TCV.

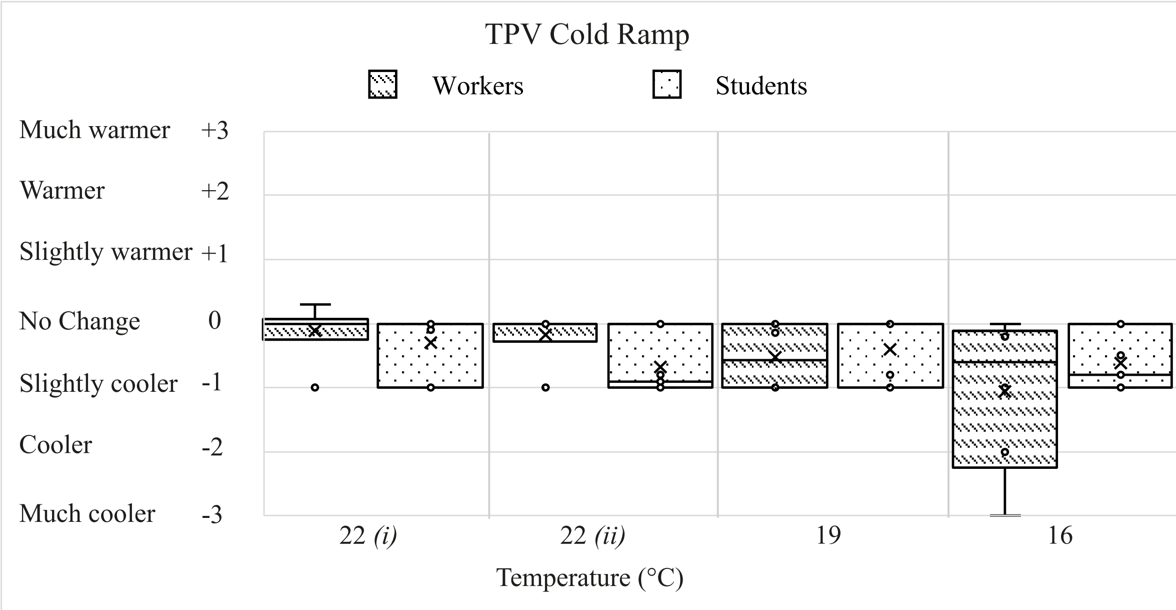

Figure 39 Comparison of students' and workers' thermal preference votes (TPV) during the cold ramp. On the horizontal axis, *22 (i)* refers to the participants' thermal preference votes recorded as soon as they enter the thermal chamber, while *22 (ii)* refers to the ratings recorded after one hour.

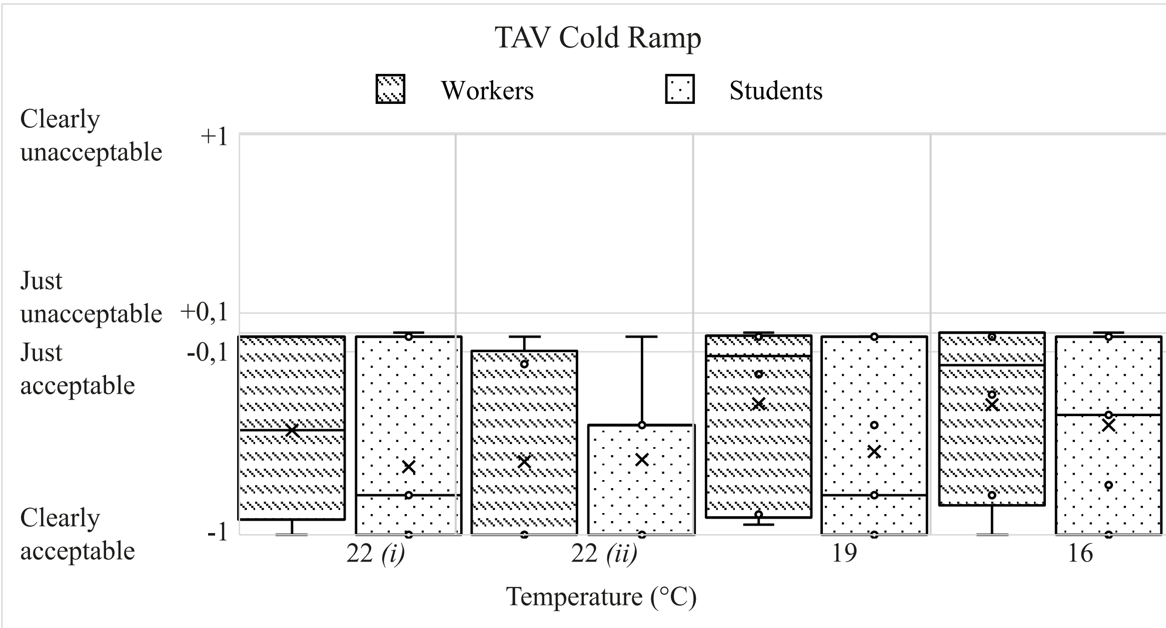

Figure 40 Comparison of students' and workers' thermal acceptability votes (TAV) during the cold ramp. On the horizontal axis, *22 (i)* refers to the participants' thermal acceptability votes recorded as soon as they enter the thermal chamber, while *22 (ii)* refers to the ratings recorded after one hour.

In particular, the two subject samples expressed the same preferences (figure 39) as the temperature decreased. Still, older workers show a lower variability in thermal acceptability at the lowest temperatures (19-16°C) (figure 40).

These results confirm the hypothesis that the thermoregulatory response decreases with consequent increases in vasoconstriction values and less awareness of thermal discomfort with advancing age.

Warm ramp

The trend in $T_{sk\text{-}diff}$ values of older workers and students during the warm ramp is represented in Figures 41 and 42, respectively. The trends in the two graphs are similar, except for the fact that the students show no signs of vasoconstriction by keeping the $T_{sk\text{-}diff}$ close to zero for the whole length of the ramp (Figure 42).

In contrast, the $T_{sk\text{-}diff}$ values of the older workers' graph (Figure 41) vary between 0 and 4, with a peak just after entering the thermal chamber and one after one hour, just before the start of the hot ramp.

This second peak shows how maintaining a stationary posture slows down the metabolism with a consequent decrease in the temperature at the extremities.

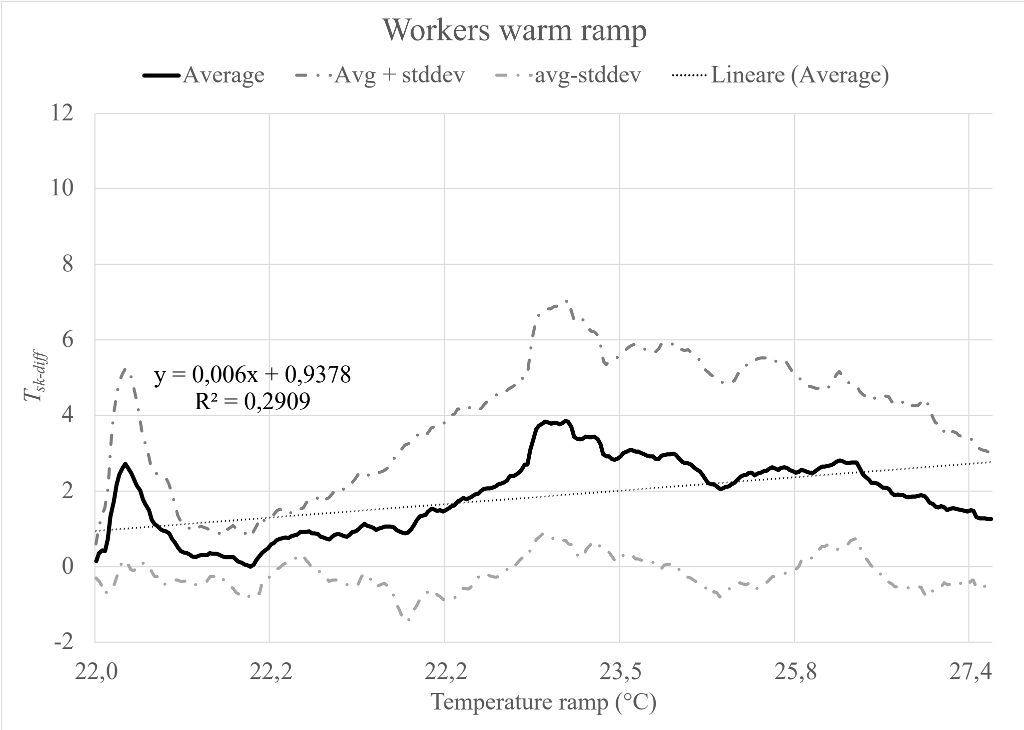

Figure 41 Trend in $T_{sk\text{-}diff}$ value for older workers during the warm ramp.

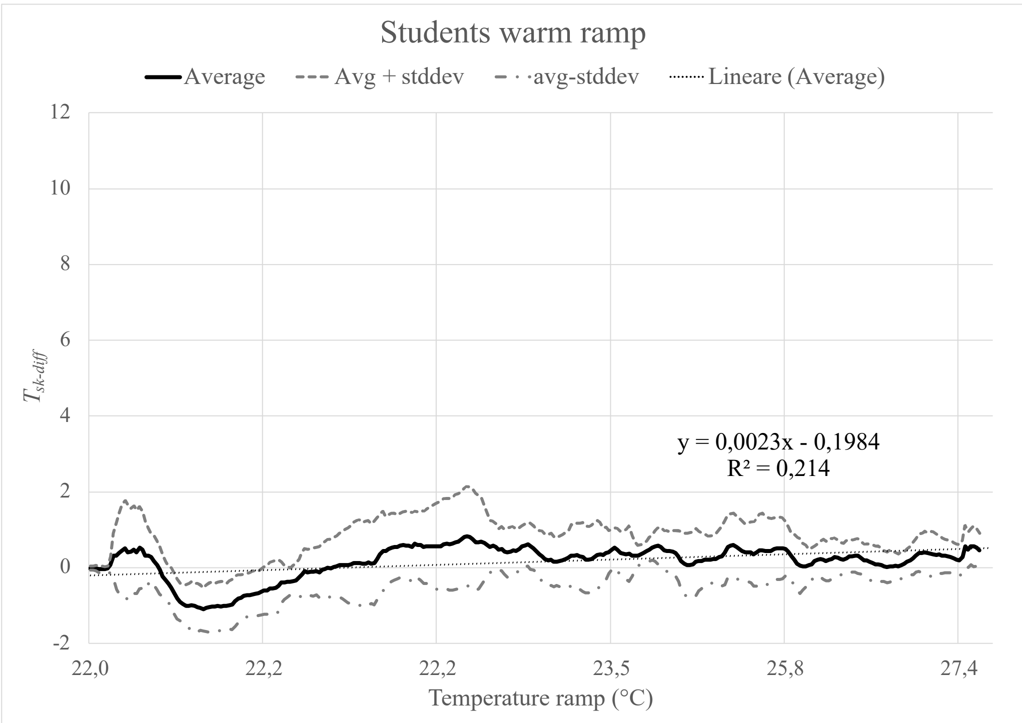

Figure 42 Trend in $T_{sk\text{-}diff}$ value for students during the warm ramp.

Moreover, Figure 41 shows a higher standard deviation in Tsk-diff in the older workers' group. A greater physiological response subjectivity than the students characterizes this sample.

Figure 43 shows the comparison between the TCV of students and that of workers. Even though the average votes were similar, the older workers' votes at 25 °C and 28 °C show a higher variability during the hot ramp, confirming the higher standard deviation analyzed in Figure 42.

This is in contrast with what happened during the cold ramp when a higher variability in the physiological response was not confirmed by the psychological (votes) given by workers.

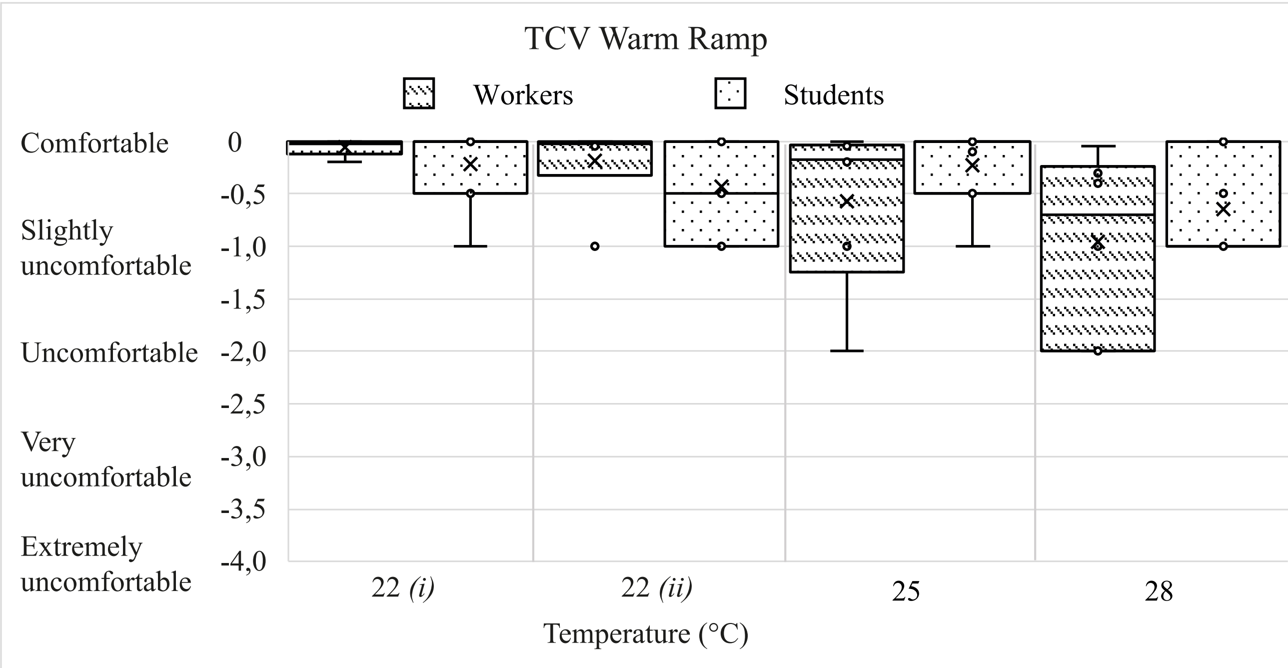

Figure 43 Comparison of students' and workers' thermal comfort votes (TCV) during the warm ramp. On the horizontal axis, *22 (i)* refers to the participants' thermal comfort votes recorded as soon as they enter the thermal chamber, while *22 (ii)* refers to the ratings recorded after one hour.

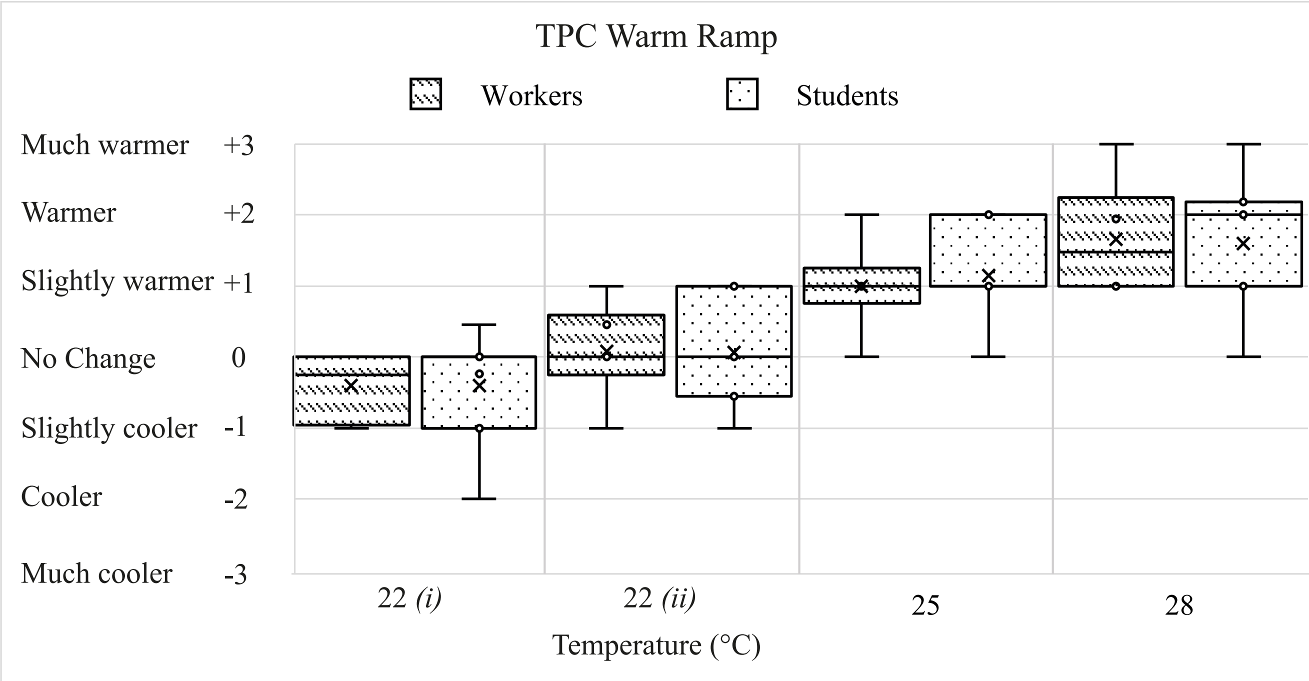

Figure 44 Comparison of students' and workers' thermal preference votes (TPV) during the warm ramp. On the horizontal axis, *22 (i)* refers to the participants' thermal preference votes recorded as soon as they enter the thermal chamber, while *22 (ii)* refers to the ratings recorded after one hour.

Figure 44 shows a similar trend: the TPV expressed by the workers at 28°C confirms the higher subjectivity in the sample analyzed. Workers showed less tolerance to the hot ramp than their younger counterparts.

Despite the differences in TVC and TPC, the workers and students who participated in the experiment expressed similar thermal acceptability for the hot ramp, as illustrated in Figure 45.

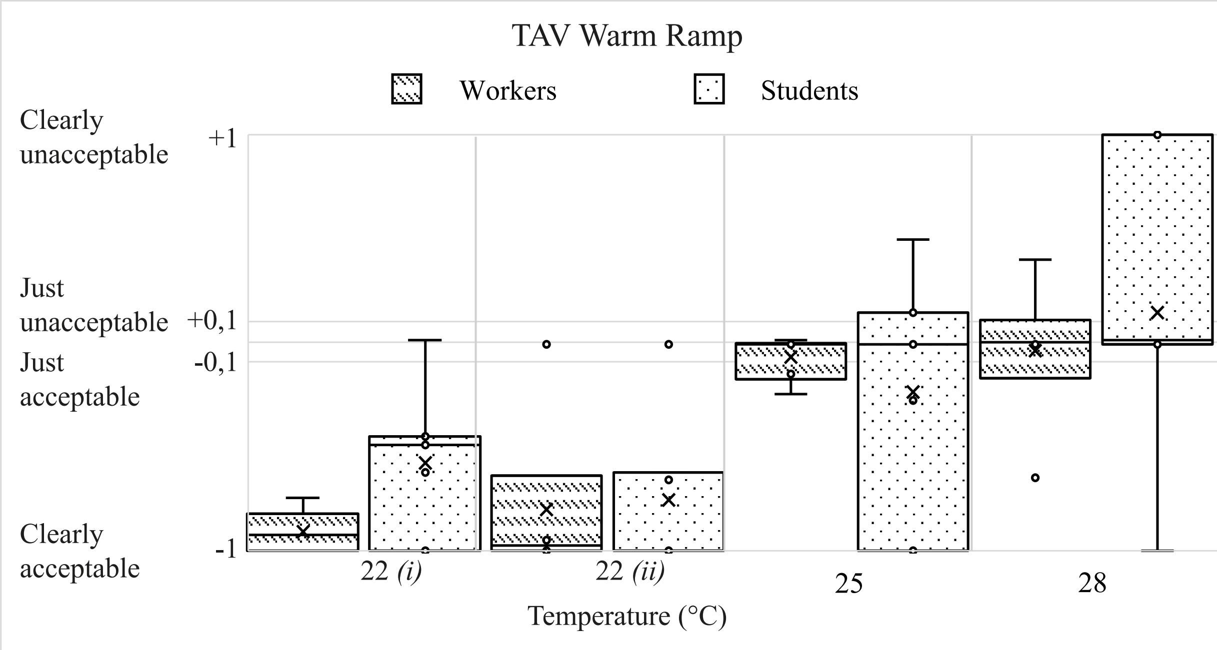

Figure 45 Comparison of students' and workers' thermal acceptability votes (TAV) during the warm ramp. On the horizontal axis, *22 (i)* refers to the participants' thermal acceptability votes recorded as soon as they enter the thermal chamber, while *22 (ii)* refers to the ratings recorded after one hour.

Even in the case of the warm ramp, the results suggest that with advancing age, discomfort conditions provoke a more subjective and variable physiological response. In contrast with what happened during the cold ramp, this is also reflected in TCV and TPV, but not in TAV, responses collected by questionnaires.

4.3.2.4 Concluding remarks

The new composition of the workforce necessitates reformulating the conditions of the work environment to prevent discomfort conditions from impacting the health of older workers and vice versa.

Fanger's model assumes that older workers are similar to their younger counterparts. However, although everyone ages differently, a distinguishing feature of the age factor is the progressive decline in health that might result in reduced tolerance to environmental stresses and different thermal preferences.

In this framework, this study aimed to assess subjects' thermal comfort, preference, acceptability, and acclimatization capacity, comparing the physiological and psychological response of older workers (45-65 years old) and university students exposed to moderate temperature ramps.

Comparing the vasoconstriction graphs, older workers show higher values in both ramps. Greater vasoconstriction reveals a faster and more significant cooling of the extremities.

However, this result contrasts the comfort, preference, and thermal acceptability graphs related to the cold ramp, which show a higher tolerance of thermal discomfort conditions by older workers (higher thermal comfort votes). This result suggests that older workers might suffer more from thermal discomfort from a physical point of view but are less aware of it.

This result is partially in contrast with what happened during the hot ramp: even though the psychological responses of the two groups were average, older workers showed higher variability in terms of thermal comfort and preference.

In contrast with what the PMV-PPD model suggests, the results highlight that elderly workers might have similar neutral temperatures with respect to young people. Still, under some discomfort conditions, different percentages of dissatisfied might be present. This experiment highlights that percentages of dissatisfied might be higher during exposure to a warm ramp.

This experimental study is based on a minimal data sample. It is only intended as a first age-based comparison analysis to preliminary research the validity of the current thermal comfort model for older workers. Future developments will include more in-depth evaluations and field investigations, extending the analysis sample, the reference period, and the monitored activities.

Furthermore, the experiment should be repeated with female subjects to generalize the results to the whole population and highlight potential differences between genders in temperature perception when ageing.

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5 CONCLUDING REMARKS

The main purpose of this thesis is to investigate the impact of the age factor in assessing worker comfort to develop new prevention and protection strategies to ensure older workers' safety, well-being, and productivity. As age increases, metabolism slows down. Therefore, tools and indices for analyzing microclimate and thermal comfort should consider the actual metabolic decline of workers instead of estimating it.

However, updating the indices and calculating metabolic expenditure represent complex tasks.

On the one hand, modifying the currently used comfort and stress indices requires consistent and systematic data collection to be integrated within the regulations. In addition, the precise calculation of metabolic expenditure requires adopting special tools that monitor workers in real-time and a system to analyze the collected data.

Based on these statements, the research presented in this dissertation elaborates on three research questions that narrow down the set of potential approaches to the problem of microclimate management to ensure the comfort and health of older workers by proposing a model that integrates the age factor into the comfort assessment and an experiment to test the influence of age on the response to thermal stress conditions.

Moreover, the research activity is developed according to the research framework in Figure 2, where the research questions are addressed by four main research levers, i.e., (1) acting on constraint analysis, (2) acting on the industrial environment, (3) acting on prevention and protection measures, and (4) acting on operators. The research levers are then explored according to research topics.

The outline of this dissertation is organized as follows.

After the first introductive chapter, the second chapter of this thesis draws the state-of-the-art of the main factors that characterize indoor environmental quality (IEQ) by detailing, per factor, its influence on human well-being and productivity. Moreover, the chapter deepens thermal comfort and microclimate risk, presenting its primary reference standards, the factors affecting it, and evaluation indices. Chapter 3 and Chapter 4 illustrate the research activity.

In particular, Chapter 3 addresses *RQ 2* by exploring the three research topics underpinning the strategic lever: acting on constraint analysis. The first research topic focuses on product, production, and energy-saving requirements that result in microclimate risk to operators by analyzing three types of warehouses and related hazards. The second discusses the microclimate strategies adopted to cope with exceptional events and their impact on workers' health. Finally, the third research topic is a literature review addressing the ageing of the workforce population and the effect of age in achieving thermal comfort.

Chapter 4 addresses *RQ 3* by exploring three strategic levers: acting on the industrial environment, acting on prevention and protection measures, and acting on operators, illustrated in subsections 4.1, 4.2, and 4.3, respectively. The first concerns the study and application of technical solutions and the redesign of the work environment to improve environmental conditions.

The second lever relates to preventive measures, such as information, education and training, and protective measures (i.e., technical, organizational, and personal protective devices) that industrial workers can adopt. Finally, the third research lever addresses the analysis of comfort needs and reactions to uncomfortable conditions of older workers (over 45).

Underpinned by the research questions, the explored research topics led to the development of practical and easy digital instruments, methods, and a model from which some general conclusions can be drawn. Figure 46 summarizes these research outcomes, highlighting the interdependencies between the different works.

For example, the comparison of environmental requirements for product and operator safety, proposed in Section 3.1.2, supports prevention and protection strategies for workers exposed to such conditions. In addition, this analysis and the environmental strategy offered during COVID-19 underpins the advancements in the search for technical solutions included in the "Banca delle Soluzioni" web portal. In response to RQ2, the analysis of general comfort requirements is complemented by an in-depth analysis of the impacts of IEQ factors on older workers, accessible in Section 3.3.

In-depth knowledge of the factors that limit the achievement of thermal comfort in industrial environments has enabled the development of useful tools to restore comfort in response to RQ3. Some are general and have operational value as tools to support industries.

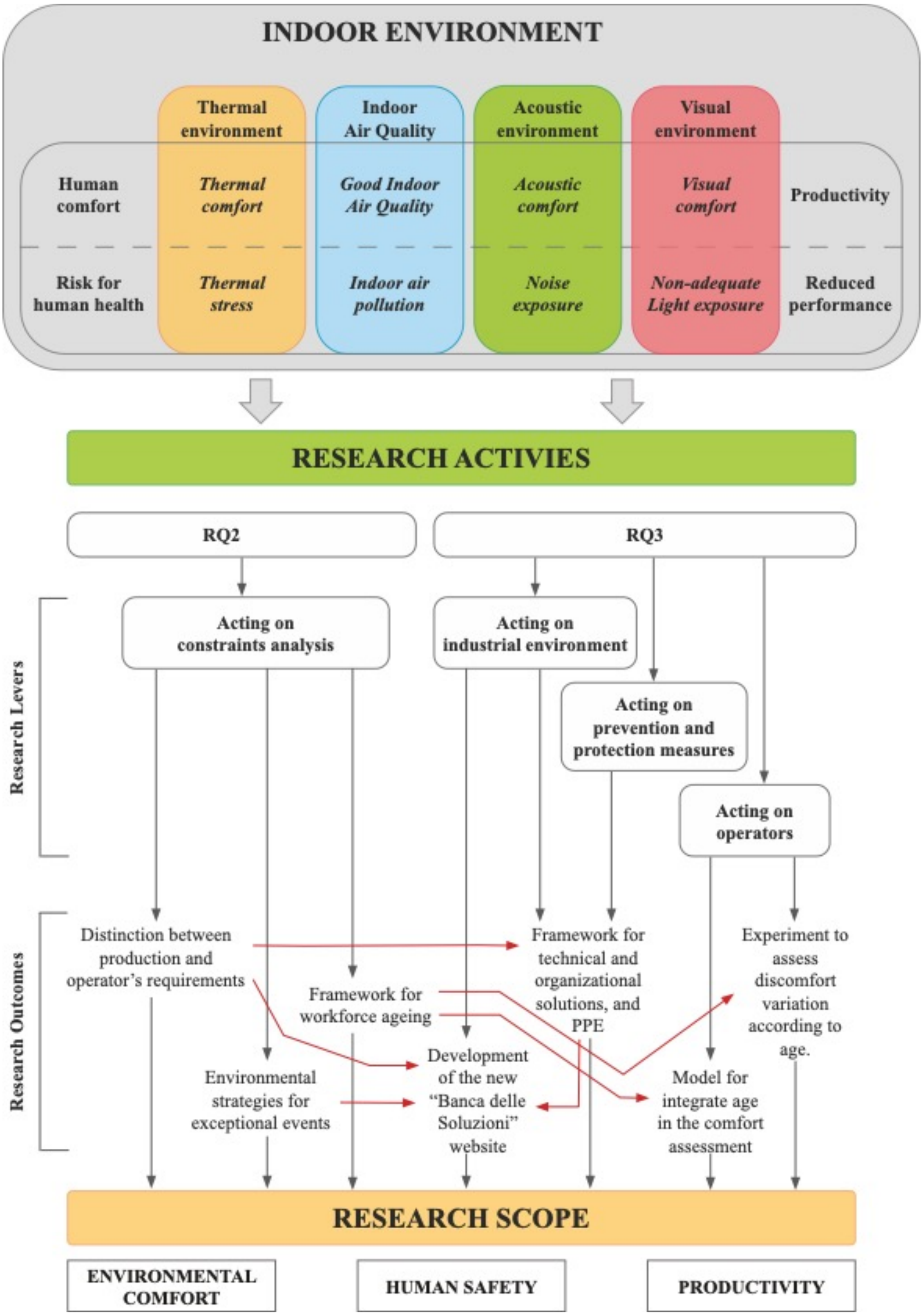

Figure 46 Framework of the main contributions presented in this dissertation.

In particular, the database of technical solutions within the "Banca delle Soluzioni" project is already a reference point for companies that need technological solutions to reduce ergonomic, microclimate, and confined environment risks. Conversely, the model for including the age factor in the thermal comfort index and the analysis of the physiological response of older workers to thermal discomfort conditions represent insights for new strategic approaches for industries to meet the ageing workforce challenges.

The following two subsections illustrate the research outcomes' theoretical, methodological, and practical contributions and the potential research developments.

5.1 Practical, theoretical, and methodological contribution

The initial literature review in the second chapter highlights the growing interest in factors that determine Indoor Environmental Quality (IEQ) due to the high permanence of workers at the workplace. The analysis also draws on the current literature landscape to identify the influence of each IEQ factor on worker health and productivity, providing scholars and practitioners with a snapshot of the state of the art.

Chapter 2 concludes by deepening thermal comfort and microclimate risk, highlighting how this risk is underestimated despite being among the most prevalent in the industry.

The analysis's most important contribution concerns understanding that well-being is the core aspect that links IEQ factors to worker productivity. The absence of environmental well-being, which can be declined in its components (i.e., thermal comfort, Indoor Air Quality, visual and acoustic comfort), as shown in Figure 5, compromises workers' health and productivity.

The analysis of risks associated with poor management of IEQ parameters will be further discussed and explored in subsequent chapters.

The research proposed in Chapter 3 shows the extreme complexity of managing indoor environmental quality (IEQ) factors in industrial environments by analyzing the factors limiting comfort achievement.

Section 3.1 delves into the conflict between operator comfort conditions and the preservation needs of products, production processes, and energy-saving requirements. The analysis shows that product storage needs determine the environmental conditions present in warehouses.

These environments are constrained, as defined in section 2.2, and do not allow operators to achieve comfort. This aspect can be generalized to many other industrial sectors, whether indoor (e.g., steel mills, ceramic industries, engineering) or outdoor (e.g., agriculture).

In such severe hot and cold environments, an accurate risk assessment must incorporate technical and organizational solutions and personal protective equipment (PPE) to protect workers' health and safety.

In addition, Section 3.2 highlights how the advent of COVID-19 has changed the recommendations for safety in industrial environments, resulting in new guidelines that, while limiting the spread of pathogens in environments, can also adversely affect environmental comfort. Such strategies, with proper precautions, are effective in maintaining good indoor air quality and can be extremely useful in day-to-day operations to cope with the transmission of influenza viruses or to ensure worker comfort. However, the mere opening of windows or the absence and lack of maintenance of filters inside workplaces can compromise workers' health. Therefore, the routine use and maintenance of systems and filters are necessary to prevent thermal discomfort, inadequate air humidity, and the introduction of pathogens from outside.

Finally, the chapter moves from the analysis of general comfort for workers in industry to individuals considered frail due to advanced age and disease onset.

The absence of thermal comfort models and indices dedicated to the ageing workforce, characterized by an impaired physiological capacity for thermoregulation, contrasts with the worldwide trend toward an ageing working population. Therefore, Section 3.3 aims to analyze the relationship between the work environment and the ageing of workers. The critical elements of this relationship are presented in Figure 25, which suggests the need to include the age of workers in comfort assessments.

Chapter 4 attempts to respond to the highlighted issues by exploring theoretical and practical solutions to restore thermal comfort to industrial operators.

Section 4.1 delves into the "Banca delle Soluzioni" project, created in 2014 in collaboration with the AUSL of Bologna, INAIL, the Labor Inspectorate, and the Fire Brigades, to highlight the importance of this digital tool in bringing companies closer to industrial safety solutions.

This project aims to represent an updated information document to guide companies in choosing automatic technical solutions capable of correcting work postures, improving the microclimate, and replacing the operator during risky activities in confined environments.

Then, the Chapter focuses on the logistics industry, presenting technical and organizational solutions and personal protective equipment to safeguard warehouse workers' health. The proposed solutions refer to the risks analyzed in Section 3.1.2.

Finally, Section 4.3 focuses on solutions to support the ageing workforce, presenting a model that integrates the age factor into the assessment of thermal comfort and an experiment that studies older workers' responses to thermal stress, constituting an innovative approach to occupational safety.

The analytical model in Section 4.3.1 addresses the prediction of thermal comfort as a function of workers' age, using the equation proposed by Harris-Benedict (1919) and revised by Mifflin and St Jeor (1990) for the calculation of Basal Metabolic Rate (BMR) within the calculation of metabolism (parameter M) of the Fanger model. This model was then applied to a multi-scenario analysis showing that increasing age corresponds to a decrease in basal metabolic rate (BMR) and a consequent decrease in M. The decrease in BMR values implies that, with increasing age, the feeling of thermal neutrality requires higher environmental temperatures. Thus, older workers suffer more than their younger counterparts in a cold or slightly cold environment. The main limitation of the model stems from the use of chronological age alone, which is unreliable. Regardless of the physiological changes that occur during the ageing process, everyone ages differently.

In addition, the multi-scenario analysis was simulated by holding the other individual parameters (height, weight, and clothing isolation) constant to test the change in the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) as a function of age only.

To overcome the two highlighted limitations, Section 4.3.2 presents an experimental study investigating differences in acclimatization capacity and thermal preference between university students and older workers. The study, conducted in a thermal chamber at the Technical University of Denmark, assesses subjects' thermal comfort, preference, acceptability, and acclimatization capacity, comparing the physiological and psychological response of older workers (45-65 years old) and university students exposed to moderate temperature ramps.

Data analysis shows that during the cold ramp, older workers exhibit greater vasoconstriction (i.e., faster and more significant cooling of the extremities) compared with students, which contrasts with the greater psychological tolerance to thermal discomfort.

This result suggests that older workers may suffer more thermal discomfort from a physical perspective but be less aware of it.

During hot ramp exposure, in contrast to what the PMV-PPD model and model results suggest, older workers demonstrated similar neutral temperatures as younger workers but higher dissatisfaction rates due to more significant variability in questionnaire responses.

Although the sample of subjects is tiny, the results of this study highlight the need to investigate further the age factor in the analysis of thermal comfort and discomfort to safeguard the well-being and, consequently, the productivity of industrial workers in the workforce ageing era.

5.2 Future developments

The results of this thesis show that there are still many challenges in the field of environmental comfort within industries. There are vast opportunities for further research on the presented topics and unexplored research paths.

Focusing on the research topics included in this thesis, the main challenges that need to be addressed by future research include the following.

First, the indoor environment quality factors outlined in Sections 2.1.1, 2.1.2, 2.1.3, and 2.1.4 should be investigated in the same detail devoted to thermal comfort.

In addition, the IEQ factors should be analyzed considering both single and combined impacts and then coupled with the other factors affecting comfort. These include the personal factors of the operators, considering not only their age in physiological terms but also their gender, presence of medical conditions, etc.

Finally, another challenge concerns the extension of the experimental study sample to derive a thermal comfort model that considers all the previously listed variables that can be tested in the field.

Focusing on topics not included in this thesis, future research should consider deepening Artificial Neural Networks (ANNs) to combine quantitative environmental factors and qualitative variables influencing operators' comfort and productivity responses. The normalization of these different variables will have a twofold advantage. The comparison will allow the hierarchy of impacts to be defined, which, in turn, will facilitate the redesign of processes, workstations, and tools according to safety and productivity criteria.

LIST OF APPENDED PAPERS

Caporale, A., Botti, L., Galizia, F.G., Mora, C., 2023. Working in warehouses with adverse microclimatic conditions: technical solutions and evaluation models. Submitted paper as a chapter for the book “Warehousing and material handling systems for the digital industry. The new challenges for the digital circular economy”. Springer

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