DISCUSSION PAPER

NEW TECHNOLOGIES AND PREVENTION OF OCCUPATIONAL RISKS RELATED TO CLIMATE CHANGE: THE CASE OF HEAT

Key takeaways

- Given the growing number of workers affected by climate change-related risks, it is increasingly urgent to move from ad hoc emergency responses to **systemic, structured and proactive strategies to manage climate change-related risks**.
- **New technologies can play an important role in preventing climate change related risks.**
- **Advanced digital wearables** now make it possible to collect individual body temperature data alongside environmental data, enabling personalised and highly effective OSH monitoring that was previously unattainable.
- **Smartphone applications** offer a real-time notification system to alert workers to risks and provide crucial practical guidance on breaks, hydration and safe work practices.
- **Ventilated garments** can substantially reduce heat exposure through various cooling mechanisms, particularly in work environments where the risk cannot be fully eliminated.
- While these technologies can mitigate heat-related risks in multiple ways, their effectiveness depends on **integration within comprehensive OSH risk prevention plans** that also consider organisational and operational factors.
- The **involvement of OSH institutions and specialists** is essential to assess, test and certify these technologies and digital tools, ensuring their quality and supporting the development of appropriate safety standards at national and international levels.
- **Workers and unions can play a key role** in implementing these tools effectively in the workplace, avoiding new forms of biometric surveillance and providing feedback to improve work organisation and safety practices.

Introduction

This paper examines organisational and technological strategies companies use to prevent and mitigate heat risk at work, one of the most serious occupational risks linked to climate change. It reviews existing heat prevention measures and explores the role of advanced digital and body-cooling technologies, highlighting challenges in their adoption and use in workplace occupational safety and health (OSH) prevention plans.

There is a clear consensus among scientists that climate change is driving an increase in the frequency of long-lasting heatwaves and extreme weather events. The average global temperature – which affects directly the frequency and severity of adverse weather events – went up by 1.1 °C between 2011 and 2020 with respect to the 19th century (IPCC, 2022). The warmest year to date was 2023, when the temperature was 1.48 °C higher than the pre-industrial level (EEA, 2024). Consequently, the proportion of the global population exposed to heatwaves increased by over 50% during the period 2010-2019 compared to the previous decade (2000-2009). In some regions, this proportion increased by more than 250%. Interestingly, there has been a rise not only in temperature during the summer months, but also in the number of days recording extremely high temperatures, especially in southern Europe (Ballester et al., 2023).[1] European countries are particularly exposed to these trends, given that the European warming rate is double the global average (EEA, 2024; IPCC, 2022; Van Daalen et al. 2022).

[1] For instance, a new record high temperature was set in Sicily: 48.8 ºC in 2021 (WMO, 2024).

Countries have experienced other extreme weather events, such as heavy rainfall, droughts, wildfires and floods, resulting in an increased risk of climate hazards, environmental damage and socio-economic impacts on the global population (Sutanto et al., 2020). In 2021, Europe incurred an estimated EUR 48 billion of losses due to economic, production and infrastructure damage linked to extreme events (Van Daalen et al., 2022). Such events also result in an increased mortality rate. According to the World Economic Forum, climate change will cause 14.5 million deaths worldwide by 2050, with an average value of 15:1 additional heat-related deaths per million inhabitants per decade (WEF, 2024). Certain socio-demographic groups among the population are more significantly affected due to vulnerabilities linked to age, physical health (Van Daalen et al., 2022) and occupation (Nunfam et al., 2018). Indeed, alongside the serious impacts on the environment, public health and well-being, climate change has considerable effects on the workforce (ILO, 2024).

A vast number of workers, such as outdoor workers employed in the construction and transport sector, face weather conditions and associated risks that the rest of the population can more easily avoid (Kiefer et al., 2016). Moreover, they usually have to perform physically demanding activities, which increase the severity of these risks. Most of these workers have economic and socio-demographic vulnerabilities that may be overlooked in public debates on health prevention. Being a precarious worker or being employed in a small firm without union representation can increase the likelihood of experiencing harsh working conditions, limited protection and reduced bargaining power (Narocki, 2021). Migrants are more likely to have informal job contracts and to work in places where standard occupational safety and health (OSH) practices might not be respected (Dodman et al., 2023). They may encounter significant language barriers that can hinder the effective implementation of the most appropriate practices (Schulte et al., 2023). Furthermore, female workers face specific risks depending on their age, their physical condition and hormone production (Desai and Zhang, 2021). Older workers, whose relative proportion in the workforce is increasing due to life expectancy trends and retirement reforms, are generally more sensitive to changes in the external environment. This is partly due to slower metabolism and weaker immune systems. Conversely, young workers may be more inclined to perform heavy tasks and to underestimate their level of resistance and well-being (Carnes, Staats & Willcox, 2014). Workers with specific health conditions (such as diabetes or respiratory diseases) will be impacted differently by these risks and may require specific measures.

In addition, the sectors most exposed to climate change are usually hit by negative shocks on infrastructure and business continuity. This is due to extreme and unexpected events that can impede the normal functioning of economic and productive activity, with negative effects on productivity and profitability. By the end of the current decade, it is estimated that over 2% of working hours will be lost globally because temperatures will be too high. Workers will not be able to maintain their usual work pace and will need to slow down (ILO, 2019).[2]

The increasing intensity and frequency of extreme weather events requires a comprehensive set of prevention and mitigation strategies that include regulation, sectoral standards and workplace guidelines. In recent years, national and local authorities in European countries have begun to partially adopt climate change plans. These typically follow tragic events like the flooding in the Spanish region of Valencia. However, in most cases, they do not explicitly include workplace measures. The scope and coverage of these plans is still quite limited when it comes to implementation, and the set of measures are quite varied across countries (ILO, 2024). Given the significant and direct exposure of workers to emerging and less well-known risks, it is urgent to adopt specific prevention measures at workplace level.

In this context, advanced digital and body cooling technologies, which are increasingly common in workplaces and can support a wide range of applications to prevent OSH risks (Gonzalez et al., 2024; Pesole and Cetrulo, 2023), could be an important complementary tool in the development and

[2] In their study, Casanueva et al. (2020) tried to quantify, through simulation models, the productivity losses in terms of working time reduction that could be observed if international standards and recommendations on heat risks are respected (mainly ISO 1989). According to their estimates, by the end of the 21st century, southern European countries will record a significant decline in working hours (around 15%) because of increasing environmental temperatures and sunny conditions during summer working days. This decline could reach as much as 50% in some areas of Spain, Italy and Greece. While these estimates are focused on summer days, similar issues might be experienced during other seasons of the year (Morris et al., 2021).

implementation of novel, effective measures and plans to prevent climate change-related risks. However, qualitative evidence on their actual implementation remains limited. The aim of this report is therefore to address this gap by shedding light on emerging organisational and technological strategies adopted by companies to prevent and mitigate heat risk, which is one of the most serious climate change-related risks. After a brief overview of the main consequences of climate change on labour from a safety and health perspective, this report describes the main strategies in place to mitigate exposure to heat at work. The empirical section discusses the potential use of advanced digital and body cooling technologies in this framework. It highlights some of the main challenges concerning their degree of diffusion and specific cases of implementation in health prevention plans at company level.

Climate change and occupational safety and health risks

Before the detailed analysis in the following sections, it is important to distinguish between the various types of OSH risks that can be most directly linked to climate change (climate change-related risks hereafter). As underlined by Schulte et al. (2023), a clear assessment of climate change-related risks was missing until Schulte and Chun (2009) provided the first literature review. They proposed a framework that distinguished seven climate hazards: 1) high ambient temperature, 2) air pollution, 3) ultraviolet (UV) exposure, 4) extreme weather, 5) vector-borne diseases, 6) industrial transition and 7) changes in the environment. Subsequent research expanded this framework to other related types of risks, such as the effect of climate change on mental health and the economic burden, and identified the most appropriate workplace prevention mechanisms (Schulte et al., 2016). There are similarities and differences among climate change-related risks with respect to their impact and the composition of the population that is exposed, as reported in Table 1.

The best known and most widespread climate change-related hazard is **extreme heat**. While heat exposure is usually linked to environmental temperature and humidity, heat stress also depends on the level of metabolic heat generation due to performing heavy physical work, wearing insulating clothing, air speed and solar radiation intensity (Spector et al., 2019). Heat stress induces a natural reaction in the human body to maintain thermal equilibrium. When this capacity is severely compromised, heat-related symptoms or illnesses can emerge, such as heatstroke or heat exhaustion (EU-OSHA, 2023a, 2023b). According to available estimates, this risk is more pronounced for workers employed in the agriculture, construction, transport, refuse collection, tourism and maintenance sectors, where it affects globally around 2.41 billion workers every year (ILO, 2024). The case of agricultural workers is striking (Lundgren et al., 2013; EU-OSHA, 2020). Estimates provided by Gubernot, Anderson and Hunting (2015) show that farm workers are 35 times more likely to die from heat-related causes than workers employed in other occupations. Park, Pankratz and Behrer (2021) studied the frequency of workplace-related injuries recorded in California between 2001 and 2018, distinguishing those that occurred on the hottest days. They identified an increase in injury claims of 6% to 9% when the temperature reached 32°C, and of 10% to 15% when the temperature reached 38°C, compared to days with lower temperatures. These studies also confirm that companies face additional costs to address an increasing number of injuries and fatalities. The construction sector has also recorded many cases of heat-related injuries. For example, US construction workers accounted for 36% of all occupational heat-related deaths between 1992 and 2016, despite representing only 6% of the country's workforce (Dong et al., 2019). Moreover, during heatwaves, construction workers are exposed to an even greater risk, because the physical exertion causes an additional increase in body temperature, which makes work a further source of vulnerability (Kjellstrom et al., 2016, 2022).

Several studies that use time series and cross-sectional analyses have confirmed a positive correlation between heat exposure and the likelihood of an injury (Binazzi et al., 2019; Morabito et al., 2006). According to available research, this correlation could be explained by various physical and cognitive paths. Heat exposure can have a great impact on muscle fatigue and dehydration, and on workers' cognitive performance, changing their safety behaviour and reducing their vigilance, awareness and dexterity in performing complex tasks (Spector et al., 2019). Overall, the growing incidence of heat risk over time can also determine major damage to infrastructure, provoke labour supply shortages and reduce labour productivity. According to ILO (2019), 2.2% of total working hours will be lost by 2030 due to high temperatures. This results in a productivity loss equivalent to 80 million full-time jobs and a reduction in global gross domestic output of USD 2.4 trillion.

Table 1 Brief overview of the main climate change-related OSH risks

Climate change-related hazards	Exposure context	OSH outcomes	Occupation/sector affected
Extreme heat	Prolonged exposure of workers to high temperatures while performing their tasks, personal protective equipment (PPE) use	Heatstroke, physical injuries, cardiovascular and other related diseases	Agriculture, construction, transport, refuse collection, tourism, and maintenance sectors, covering around 2.41 billion workers every year
UV radiation	Exposure of workers to sun radiation while performing their tasks	Sunburn, skin cancers, eye damage, etc.	Construction, agriculture and power utility workers covering around 1.6 billion workers
Air pollution	Exposure to environmental chemical particles, such as PM2.5, ozone, allergens, etc.	Respiratory and cardiovascular diseases, cancers, etc.	
Biological vectors	Exposure to parasites, viruses and bacteria that are transmitted by vectors (World Health Organization definition)	Infections such as malaria, Lyme disease and others	Outdoor workers. Lack of data on the affected population
Extreme weather events	Floods, strong winds, heavy rainfall, wildfires and cyclones	Physical injures with a varying degree of severity	Emergency workers, construction workers and outdoor workers

Source: EU-OSHA (2023a,b); ILO (2019, 2024); Schulte et al. (2023, 2009, 2016)

Another hazard closely related to extreme heat and prevalent among outdoor workers (e.g. in the construction, agriculture and power utility sectors) is **UV radiation**. Exposure to UV radiation can cause serious harm, ranging from sunburn to skin cancer and eye damage. It is estimated that 1.6 billion workers are exposed to this hazard (Pega et al., 2023). Outdoor workers exceed UV radiation limits within 10 minutes during the summer months if they are unprotected (ILO, 2024). Furthermore, the rising average temperature will lead to increased solar UV exposure, which will raise the probability of affected workers developing skin cancers (Van der Leun and De Gruijil, 2002). Around 18,960 work-related deaths from melanoma skin cancer are recorded every year, confirming the relevance of this climate change-related risk. A key challenge in preventing it is raising awareness among workers and employers. Several studies have shown that workers tend to underestimate its importance and very rarely wear sunscreen and adequate clothing, such as long-sleeved shirts and sun hats (Reeder, Gray & McCool, 2013; Reinau et al., 2013). Even when they are conscious of these risks, workers may not be able to adopt the best practices, partly because they are not directly involved in making relevant decisions (e.g. ensuring adequate provision of personal protective equipment (PPE) and shaded areas for work and rest). This general lack of attention is also reflected by the fact that many national legislations do not recognise skin cancer as an occupational disease and, even when they do, under-reporting remains high (John et al., 2021).

Health risks due to **air pollution** affect most of the population and are among extensively regulated issues at national and international levels. Although much attention has been paid to the impact of air quality on the well-being of the general population, there has been relatively little focus on workers' health (Schulte et al., 2023). The estimated size of the workforce that is most directly affected is equivalent to those exposed to UV radiation: around 1.6 billion outdoor workers (ILO, 2024). Outdoor workers are exposed massively to a variety of pollutants, including fine particulate matter (PM2.5), ozone and allergens (Schulte et al., 2023). Every year, around 860,000 work-related deaths are attributed to air pollution. A major challenge regarding this climate change-related risk is that it cannot be completely neutralised in the workplace. It can only be mitigated partially with measures such as PPE, air purifiers, task rotation or medical surveillance.

Outdoor workers, particularly farmers, construction workers and firefighters, are more likely to be exposed to **biological vectors**, and therefore to contract vector-borne diseases such as malaria or Lyme disease (Schulte et al., 2016). Data on the number of workers exposed to this hazard is still limited, although around 15,170 work-related deaths are attributed every year to vector-borne diseases (ILO, 2024). These estimates are probably an underestimation of the actual risk because of under-reporting and insufficient data. In this context, climate change is again extremely relevant, as it affects the natural ecosystem and changes seasonality, thereby favouring the distribution and spread of these illnesses. An extensive review of the literature on this topic has revealed a positive correlation between high temperatures and the expansion of vector-borne diseases due to higher survival rates (Levi, Kjellstrom & Baldasseroni, 2018). A similar effect is driven by increased frequency of rainfall, which raises humidity and favours the proliferation of mosquitoes and related viruses (e.g. West Nile virus).

Another climate change-related hazard concerns the increasing occurrence of **extreme weather events** such as floods, strong winds, heavy rainfall, wildfires and cyclones. A variety of workers are exposed to this hazard, especially emergency, construction and outdoor workers. Statistical data are still limited, but available figures provided by the World Meteorological Organization (WMO, 2021) report 2.06 million deaths due to climate and water-related hazard events. According to the International Disaster Database, between 1970 and 2019, climate-related hazards accounted for 50% of all recorded disasters, 45 % of reported deaths and 74 % of economic losses (ILO, 2024; WMO, 2021).

It is important to consider not only the massive scale of these disasters, but also their increasing frequency and intensity over time. Moreover, extreme events caused by climate change are usually interconnected, creating a vicious circle where one event can cause another. For instance, heatwaves can increase the risk of cyclones (Choi et al., 2024). Conversely, tropical cyclones, winter storms and torrential rains can cause climate migration and water-borne diseases. This trend will lead to more serious economic and social consequences that, together with damage to infrastructure and production facilities, can negatively affect employment levels, productivity and collective well-being. Some categories of workers, especially those at the forefront of emergencies and extreme weather events related to climate change, will experience the disruptive impact of these disasters first-hand.[3] This is already affecting workers' lives. For example, healthcare workers' anxiety and psychological pressure related to climate change risks has increased (Clayton, 2021). A growing body of evidence highlights that prolonged exposure to extreme weather events can significantly impact mental health, leading to increased stress, anxiety and post-traumatic stress disorder (Moilanen, Turunen & Teperi, 2025; Schulte et al., 2023).

Managers and workers are exposed to these hazards and they face the resulting economic, productive and social impacts (Habibi et al., 2021; Schulte et al., 2023). Companies can prevent occupational risks

[3] Firefighters are particularly exposed to these risks, such that climate change has been defined as a 'threat multiplier' for them, since it significantly increases the likelihood of natural disasters (Flanagan et al., 2011).

related to climate change by implementing new organisational practices, investing in infrastructure and providing training, particularly in sectors such as agriculture, energy, construction and transport, which are also heavily impacted by the transition to clean energy and environmental sustainability.

Nevertheless, despite the critical significance of these challenges, little attention is paid to assessing the incidence of climate change-related risks among workers and to raising awareness about the need to implement specific preventive measures.

In the following sections, we present the main strategies that are currently implemented to prevent heat-related risks in the workplace. The focus on extreme heat is motivated by its widespread occurrence and its interdependence with other climate change-related risks. First, we highlight the types of prevention and mitigation measures that are adopted in workplaces to tackle heat-related risks, as documented in the literature. We then discuss the potential role of digital and body cooling technologies in strengthening these measures. Finally, we present novel evidence on cases of the adoption of wearable technologies in heat-related prevention plans, discussing the most critical issues that emerge from these cases.

Extreme heat at work and main prevention measures

The emergence of heat-related risks in outdoor work is influenced by three macro factors: environmental temperature (air temperature, humidity, solar radiation and wind speed), metabolic heat production from physically demanding tasks, and thermal insulation associated with protective clothing. Alongside these external variables, several individual and socio-demographic factors affect the individual capacity to cope with heat. Age, for instance, is an indicator of effective thermoregulation (Carnes, Staats & Willcox, 2014).[4] Older workers are more likely to have additional comorbidities and take medical drugs that can affect their ability to cope with heat (Kjellstrom, Oppermann & Lee, 2022). From a gender perspective, which is usually neglected or only partially investigated (see Desai and Zhang, 2021, for a discussion), the menstrual cycle or pregnancy can impact female thermoregulation (Alele et al., 2020; Nagashima et al., 2002). Social norms can further increase the risks for female workers, as they may drink less when clean and private toilet facilities are lacking (Venugopal et al., 2016).

When body temperature rises above 38 °C and remains at this high level, physical and cognitive abilities are impaired. If body temperature rises further and reaches a threshold of 40.5 °C, the risk of organ and cognitive damage increases (IPCC, 2014). For this reason, attention is usually focused on estimating body temperature, as keeping it within a range around 37 °C is crucial for ensuring safety and health (EU-OSHA, 2023a, b). In fact, when body temperature rises, the body initiates cooling through sweating, which can lead to significant dehydration and, over time, increase the risk of chronic kidney problems (EU-OSHA, 2023b). Furthermore, workers are more likely to experience cognitive fog that reduces their attention threshold, with an increased likelihood of accidents due to fatigue, loss of concentration and unsafe use of work tools (EU-OSHA, 2023b; Morabito et al., 2006).[5] Dehydration caused by hyperthermia can further worsen cognitive performance and increase the risk of injury (Morris et al., 2020).

The extent of this phenomenon, its increasing recurrence, and its potential disruptive impacts on workers' safety and health, labour productivity and economic business activity, explain why employers, unions and institutions are showing strong interest in adopting preventive measures, and sometimes even anticipate national regulations. To prevent heat-related risks in the workplace, several measures can be adopted, from continuous hydration to work-rest cycles (see Table 2 for a brief overview).

[4] The potential increasing incidence of extreme cold risk is also an important factor. When core temperature drops below 35 °C the body goes into hypothermia, and cognitive and biological functions start to slow down, with a greater risk of heart attack and collapse (ILO, 2022).

[5] Morabito et al. (2006) assessed the likelihood of accidents and injuries in the presence of thermal stress. They examined cases of hospital admission for work-related accidents in the area of Florence during summer working days from 1998 to 2003. Through a quantile analysis, the authors found a significant difference in the number of observed work accidents when they compared the occurrence of accidents on the 2nd quartile with those that occurred in the 4th quartile in terms of environmental temperature. This confirmed the potential positive effects of warmer temperatures on the likelihood of work accidents.

According to the hierarchy of controls[6] framework, which ranks prevention measures from most to least effective, the selection of risk management measures must account for workplace realities and constraints, to ensure that any changes reduce, rather than amplify, overall risk. The framework prioritises the elimination of a hazard wherever feasible, followed by replacing it with a less hazardous alternative, implementing engineering controls, introducing administrative controls and, lastly, relying on PPE. However, with heat, the primary challenge is that total elimination and/or substitution is not possible, as rising temperatures stem from climate dynamics beyond the control of any single organisation. Employers must therefore rely on the remaining levels of the hierarchy: engineering controls, administrative controls and PPE.[7]

Table 2 Main heat-related risk prevention measures

Most common measures to prevent heat-related risks in the workplace	
1.	**Acclimatisation**
2.	Continuous **hydration,** provision of water and electrolytes
3. 4.	**Adequate work-rest cycle** (alternation of phases of work and exertion with phases of rest to reduce heat storage)
5.	**Self-pacing and autonomy** to adjust the work intensity and related metabolic heat
6.	**Allocation of tasks** considering the environmental temperature and the intensity of the task
7.	Provision of **adequate protective clothing**
8.	Availability of **shaded and ventilated rest areas**
9.	**Ventilation and air conditioning**
10.	Provision of **training courses** on heart illness and prevention strategies

Source: EU-OSHA 2023a, b; ILO, 2024; Ioannou et al., 2022; Morris et al., 2020

Engineering controls include several technological tools, such as air conditioning and fans (Cheveldayoff et al., 2023), and the construction of shaded and ventilated areas. **Administrative controls** correspond to work organisation practices, such as better scheduling of working time to account for temperature, increasing the frequency of breaks and allocating heavy tasks to the cooler hours of the day. **PPE** consists of clothing and specific devices designed to protect workers. Examples include hard hats, hearing protection and safety glasses. PPE is increasingly fitted with smart sensors (smart PPE) to enable better monitoring of the environment and the worker's personal condition. These tools are typically used alongside other prevention measures, depending on the specific working context. In most cases, it is difficult to assess the possibility of implementing these strategies at a larger scale because of conflicting factors. These include economic constraints with respect to the cost of an investment and its maintenance, organisational constraints, and specific production requirements concerning working time and task allocation. A positive social response from interested parties (industry managers, unions and workers) is also crucial, but difficult to achieve, as they might be impacted differently by each measure (Ioannou et al., 2021, 2022). Industry managers may be asked, for instance, to give workers more autonomy in taking breaks, thus weakening their degree of control. Unions will push for collective agreements and negotiations to reduce the risk of health-related surveillance (potentially enabled by smart PPE), while workers will be required to learn new rules and use new equipment (Morris et al., 2021).

[6] An overview of the hierarchy is available at: https://www.cdc.gov/niosh/topics/hierarchy/default.html
[7] For instance, most accidents that can be related to heat stress in the construction sector usually happen on the first day of a job, which confirms the importance of training and the adoption of proper acclimatisation practices (Acharya, Boggess & Zhang, 2018; Arbury et al., 2014).

As highlighted by EU-OSHA (2023a, 2023b), a crucial issue is ensuring the development of **participatory workplace risk assessments**, grounded in the direct consultation and involvement of workers, to effectively manage risks and identify the most effective prevention strategies. It is important to engage **workers** in implementation processes so that preventive measures can be adapted to each context to maximise their effectiveness. Several of the **strategies** listed in Table 2 will not follow a single, standardised model. Instead, they **will be shaped by companies' hierarchical structures, managerial practices and participatory routines** (Narocki, 2021; Notley, Flouris & Kenny, 2019). For instance, working in a micro or small company may increase workers' exposure to some hazards, as these companies frequently lack the structure of an OSH management system, have no trade union representation, and workers have very little bargaining power to shave OSH preventive measures introduced in the workplace. Informal workers and those employed on a piece-rate basis will be even more vulnerable to the risks of dehydration and overexertion, since the pressure to complete tasks quickly discourages them from taking necessary rest breaks (Narocki, 2021).

The practice of 'self-pacing'[8] can be used to illustrate the challenges of implementing a single strategy and the necessity of ensuring its social acceptance and legitimacy (Wang et al., 2018). Several field studies have shown that self-pacing is a very effective method for reducing heat stress, as it allows workers to decrease their work rate gradually and consistently, leading to stabilisation of heart rate. However, for self-pacing to be relevant, workers must be employed in sectors where this practice is allowed and must perform tasks that enable them to reduce their work intensity when necessary. This is not the case for emergency or maintenance workers, who are required to respond promptly to urgent or unexpected demands (Ioannou et al., 2022; Wright et al., 2013). Moreover, workers must feel entitled to self-pace and not be constrained by productivity incentives (Mairiaux and Malchaire, 1985), by surveillance or authoritarian supervisory practices, or by piece-rate payment schemes, all of which can discourage rest and inhibit the regulation of work intensity (Miller et al., 2011).

Other measures include prescribed rest and breaks in shaded or air-conditioned areas with easy access to water, constant hydration facilitated by providing easy and portable methods of carrying water, the provision of clean and adequate toilet facilities, the use of protective clothing, and the offer of training courses on heat stress and prevention strategies (Ioannou et al., 2022). Another important practice that can be used to mitigate heat stress is to allocate job tasks so that the most demanding ones (i.e. those characterised by higher metabolic expenditure) are performed during the cooler part of the day or are immediately followed by specific rest and work breaks (Ioannou et al. 2021, 2017). In this case as well, the production schedule and the work organisation model must allow for sufficient flexibility to enable the adoption of such complementary measures.

Given the strong interaction between socio-economic, health and organisational factors in shaping heat risk mitigation plans, an increasing number of experts are advocating for the adoption of a socio-economic approach to climate change-related risk prevention. This perspective aims to comprehensively link the individual dimension of the worker with the socio-relational one (frequency of interaction with other colleagues, spread of teamwork and job rotation, etc.), while also accounting for the role of employers and work organisation dynamics (Spector et al., 2019). Essentially, the idea is that **individual, relational and employer-level factors should be treated in a holistic way, while also accounting for community-level and institutional factors** (Spector et al., 2019), to complement the hierarchy of controls approach. The discussion of cases of implementation of digital wearables and cooling garments, presented in a further section, will show how this approach can be useful when companies adopt new technologies as tools of heat risk prevention.

[8] Self-pacing refers to a work organisation practice that enables workers to autonomously control and manage the intensity of their work. They adjust the pace of their activities and take breaks to prevent or mitigate physical and cognitive fatigue.

The role of new technologies in preventing heat-related risks in the workplace

Main applications: digital wearables, cooling garments and smartphone apps

One of the most prevalent preventive measures introduced by local, regional or national authorities is the establishment of specific environmental temperature thresholds[9] above which working is forbidden. Alternatively, regulations may require adjustments to working time schedule to avoid outdoor work during the hottest hours of the day. Thresholds can also be used to trigger specific preventive measures (e.g. proper worker acclimatisation) to allow safe work at temperatures that would be a high risk in other circumstances. Where implemented, these measures have proven to be an effective and simple tool for reducing the risk of heat-related occupational injuries and illnesses (EU-OSHA, 2023b; ILO, 2024). Thresholds are usually set under the assumption that workers are in good health, fit for the level of work intensity required by the tasks and wearing adequate clothing. However, this approach does not account for the individual characteristics of each worker and for the possibility that thermoregulatory mechanisms can lead to different perceptions of the ambient temperature, leading to varying levels of heat-related risks.

In fact, when strategies and practices are developed to prevent, control and mitigate heat-related risks in the workplace, various factors should be considered that influence their incidence. These factors include individual worker's characteristics that cannot be modified (e.g. sex, age, previous diseases and general health condition), intra-individual factors that can be modified because they are at least partially under individual control (e.g. sleep deprivation, water consumption/degree of hydration, degree of acclimatation) and work-related factors that are not under the direct control of the individual worker (e.g. duration of the work shift, number of breaks, days of rest, work pace, availability of shaded areas, PPE clothing insulation, metabolic activity due to task intensity). This variety of factors all contribute to the level of heat stress experienced, which suggests that the application of a single, general exposure threshold may underestimate the specific risk faced by the worker (Cheung, Lee & Oksa, 2016; Schulte et al., 2012; Wang et al., 2018). Moreover, temperature limits are sometimes set at the regional or local/city level, yet these values may differ significantly from the microclimatic conditions in each workplace – even when most activities are performed outdoors. Local environmental conditions can vary greatly and are strongly influenced by factors such as the presence of heat sources, airflow and ventilation patterns, and humidity levels, among others.

All these challenges highlight the usefulness of technological solutions that enable more effective real-time management of individual heat stress, as illustrated by the European HEAT SHIELD project (Morris et al., 2021). The adoption of technology to prevent heat-related risks is not new. In some cases, **automation** has replaced human labour, so that machines are used to execute physically demanding tasks that are characterised by high metabolic heat production and exposure to excessive environmental heat. The implementation of **air-cooling systems (**either 'traditional' or HVAC – heat, ventilation and air conditioning – systems) **has also provided a technological solution to heat**, although it is frequently considered controversial from an environmental perspective (Morris et al., 2020). Furthermore, **mobile and fixed sensors that measure wet bulb temperature** are important technological tools for monitoring heat in the workplace.

However, the most recent innovations are in the domain of wearable technologies, that show significant potential in the management of heat-related risks. These innovations include **digital wearable technologies** that collect data on the wearer's skin temperature and heart rate (Dolson et al., 2022; Notley, Flouris & Kenny, 2018); **personal cooling garments**, which are useful when heat-related risks are linked to the outdoor temperature and to the metabolic effort of the worker (Del Ferraro et al., 2024)**; and mobile applications that provide weather forecasts, instant notifications and personalised recommendations to workers** on best practices during heatwaves that can be considered another valuable complementary tool for protecting workers' health (Morris et al., 2020).

[9] The air temperature is measured together with the humidity, level of air flow and proximity to radiant heat sources.

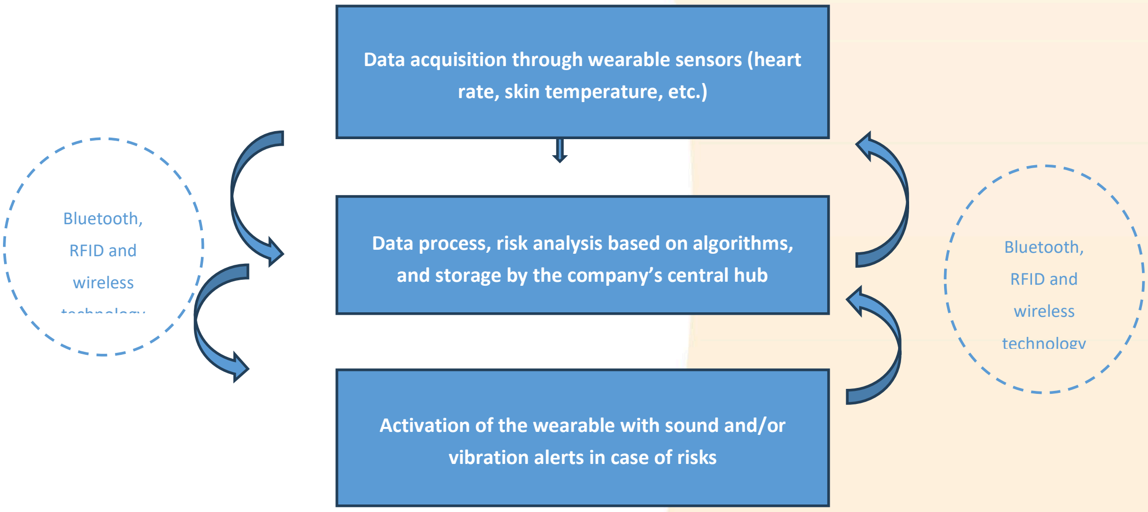
While still marginal, the wearable technology market has expanded steadily in recent years, also because of its increasing number of applications in the area of occupational safety and health. It includes tools for the prevention of ergonomic risks and musculoskeletal disorders, the identification of risks related to proximity to heavy machinery (i.e. smart hard hats and radio frequency identification - RFID - tags) and the prevention of heat-related risks (Patel et al., 2022).

One of the main advantages of **digital wearables** is that they enable skin temperature to be measured in a much less intrusive way than commonly used contact thermometer techniques. Another advantage is that they can measure both skin temperature and other biometrics, such as heart rate, exertion level, oxygen saturation and respiratory rate. When these data are combined and analysed using predictive algorithms, the technology provides an indicator that closely approximates the core temperature, which is challenging to measure directly except through invasive techniques such as ingestible telemetry pills (Buller et al., 2018). This algorithm-based measure is more reliable than skin temperature, which can vary significantly depending on environmental factors, clothing and sweating levels.

As illustrated in Figure 1, **digital wearables act as data-collecting devices that transmit the information to a central hub via Bluetooth, RFID or wireless technology**. The hub is typically equipped with a visual interface where data can be processed easily by company staff, such as supervisors or OSH professionals. A central dashboard usually displays all the information generated through the real-time monitoring of individual wearables, with disclosure levels that vary according to the system's technical design and the data protection measures in place (Saidi and Gauvin, 2023). At the same time, the central dashboard facilitates direct communication between workers and supervisors through a notification system that allows urgent messages to be sent promptly to the worker. These wearables, typically worn on the upper arm or wrist, provide workers with real-time feedback and alerts when their estimated core temperature exceeds a certain threshold (Patel et al., 2022). Notifications suggesting that the worker should take a break or reduce their work pace can be generated automatically by the system or issued manually by the supervisor. In addition, the large volume of collected data enables the use of predictive analytics to anticipate risks and improve the efficiency of the processes that are being monitored. Decisions on whether data should be stored or deleted rest with the company, in line with applicable privacy regulations.

Notably, the above description is a general model. In practice, the specific technological configuration adopted by a company will depend on many factors, including the available information and communication (ICT) infrastructure, workers' digital skills, the organisation's level of exposure to heat-related risks and the relative cost of the investment.

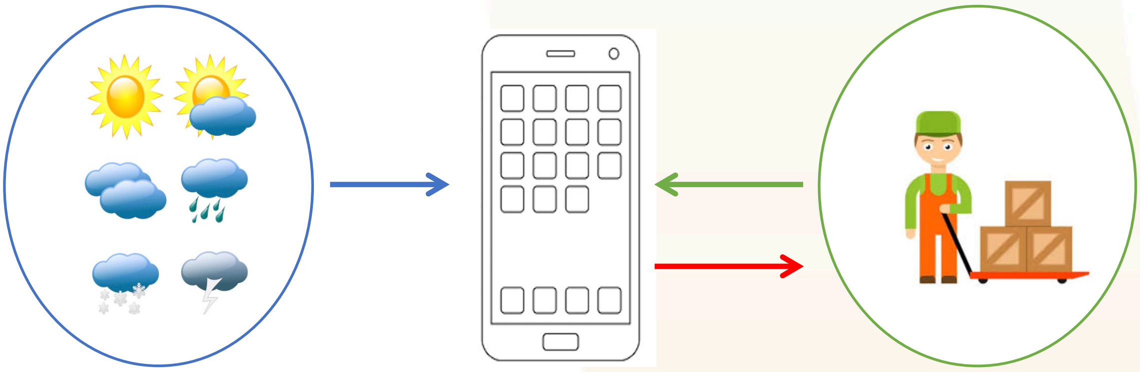
Figure 1 Main stages of digital wearables for heat prevention



Source: Compiled by author, based on Saidi and Gauvin, 2023

Smartphone applications rely on a similar architecture to digital wearables (see Figure 2), with the difference that individual real-time body temperature and heart rate data cannot be collected directly through sensors. Most applications on the market allow users to match real-time environmental data (provided by GPS phone functionalities) with personal information (age, weight, clothing, work intensity), entered by the worker usually at the beginning of the work shift. The level of risk is assessed through an algorithm that matches the two sources of data. This activates notifications and messages directly to the worker (for instance, drink water, take a break, go to a shaded area) if the threshold is exceeded. Moreover, workers usually have access to an alert/SOS button in case of necessity. Data collected via smartphone is transmitted to a central hub under the supervision of company staff.

Figure 2 Information flow of smart-phone applications for heat-related risk prevention measures



Source: Compiled by author

Personal cooling garments (PCGs) are another valuable tool for preventing heat-related risks, as they help remove heat from a worker's body, thereby reducing discomfort and improving overall well-being (Del Ferraro et al., 2021; 2022). These solutions should be considered essential mitigating strategies for a risk that cannot be completely eliminated, especially for outdoor workers. Indeed, in the context of more frequent and intense heatwaves, the field of ergonomics of thermal environments is expanding broadly to identify technological solutions for monitoring and reducing workers' exposure to heat (Falcone et al., 2021). As shown in Table 3, PCGs can be categorised by cooling mechanism, which may be based on air ventilation, liquid cooling systems or phase change materials.

Table 3 Main types of cooling garments and related mechanisms

Main types of cooling garment	Cooling mechanism
Air cooled garments (ACG)	Convective and evaporative cooling
Liquid cooling garments (LCQG)	Liquid cooling with a conductive cooling mechanism that relies on the circulation of the liquid
Phase change material garments (PCMG)	Conductive cooling that uses the heat stored in the phase change material
Hybrid cooling garments (HCG)	Combinations of two cooling systems
Air ventilation garments (AVC)	Air ventilation cooling obtained through fans embedded in the clothing

Source: Del Ferraro et al. (2021), compiled by author

Given the features of the PCGs outlined above, their degree of application and current deployment is highly heterogenous and still very limited. For instance, PCGs are less suited to very humid environments. Other important factors to consider are the duration and intensity of the cooling power in relation to the length of the work shift and the degree of interference with the work activity.

Among the solutions, air ventilation jackets are currently under trial for heat risk prevention in various workplace settings. These garments can be described as short cotton jackets equipped with small fans located at the sides of the lower back. One of the main advantages over other PCGs is that they do not require a power connection or connection to an external tool (such as a compressor or refrigerant supplier). Therefore, they guarantee total autonomy and freedom of movement for workers, but the duration of use is limited by the battery capacity. These features make this technology a promising tool for heat risk prevention, as reflected in the growing interest among researchers (Del Ferraro et al., 2021; Zhao et al., 2013). The choice of the most adequate cooling garment depends on the work setting.

Figure 3 An example of air ventilation jacket worn by an outdoor maintenance worker in Japan

Challenges and limitations of these new technologies

Despite some promising applications of these technologies, there are challenges to consider in their normative and operational dimensions. Currently, there is no clear institutional standard on their adoption. Companies invest in and test these solutions independently, according to their needs. However, relying mainly on commercial technological solutions for compliance with OSH obligations or the achievement of OSH goals can lead to unsatisfactory and controversial outcomes (Notley et al., 2018; Patel et al., 2022). Indeed, **these workplace technologies currently lack scientific field studies that can demonstrate their effectiveness and safety**. Nevertheless, a number of controlled studies in specific experimental settings or with extreme environmental conditions have been published, with possible measurement biases and limited scope for generalisation. The accuracy and durability of these technologies can vary significantly when they are implemented in industrial environments, due to the complexity of such settings and the potential exposure to other hazards that need to be considered. However, as revealed in the field study presented in detail in the next section, some collaborations between OSH institutions and companies are taking place, and confirm the advantages of involving institutional and professional actors to validate the efficacy of new tools.

An examination of the technical sheets of these tools shows that only a few of them have obtained certificates of conformity for medical use (Saidi and Gauvin, 2023). Furthermore, the number of algorithmic models for predicting and evaluating core temperature is high, since developers may be reluctant to develop common standards. Instead, they may try to demonstrate the efficacy of their own model. Without a common standard, it is very difficult for companies to understand which best practices and tools to adopt.

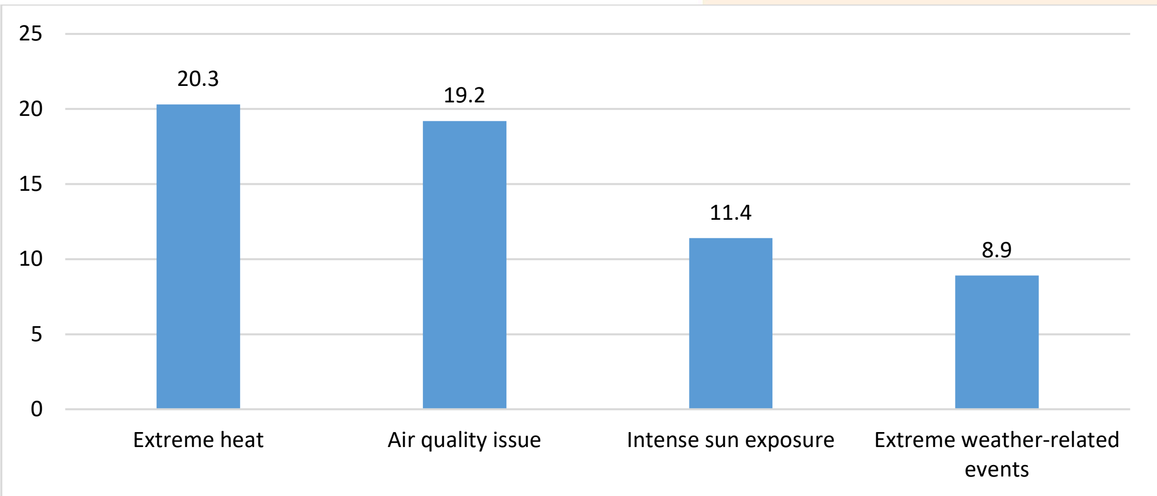
With respect to digital wearables, there is **growing uncertainty about which data are needed to ensure an effective prevention strategy**. Another issue is which criteria to use for data transmission and storage. Massive data collection can lead to pervasive individual biometric surveillance and to the Hawthorne effect, where users' behaviour changes because they know they are being observed. This can lead to improved performance or more diligence. Several empirical field studies have shown that workers may feel uncomfortable when their physiological parameters are under scrutiny (Ioannou et al., 2017; Kenny et al. 2012; Notley, Flouris & Kenny, 2018), particularly if they feel that this monitoring is being used to check their productivity and physical fitness. In these cases, workers may be less willing to accept the innovation if they perceive that the entire system is driven by algorithmic managerial control, rather than by OSH specialists. These challenges confirm the need for further qualitative analysis highlighting the interdependence between the technological, OSH and socio-economic characteristics of each workplace.

Adoption of wearable technology and climate change-related risks in the workplace: evidence from OSH Pulse 2025

To assess the potential role of wearables in preventing and mitigating climate change-related risks, it is important to gain a better understanding of the prevalence of the risks, and the extent to which these technologies are used and implemented in workplaces. As attention to climate change-related risks is relatively recent and wearable technologies are only adopted slowly in the workplace, statistical data that combine these two areas remain scarce. A notable exception is the OSH Pulse Survey. This is a periodic workers' survey conducted by EU-OSHA of approximately 28,000 workers across all Member States and Iceland, Norway and Switzerland. The survey collects information on occupational safety and health, including on climate change-related risks and the use of new technologies in the workplace.

Figure 4 shows the share of workers exposed to types of climate change-related hazards, as reported by workers interviewed in the OSH Pulse Survey 2025. Extreme heat is the most prevalent hazard, affecting 20.3% of workers, followed by air pollution (19.2%) and intense sun exposure (8.9%).

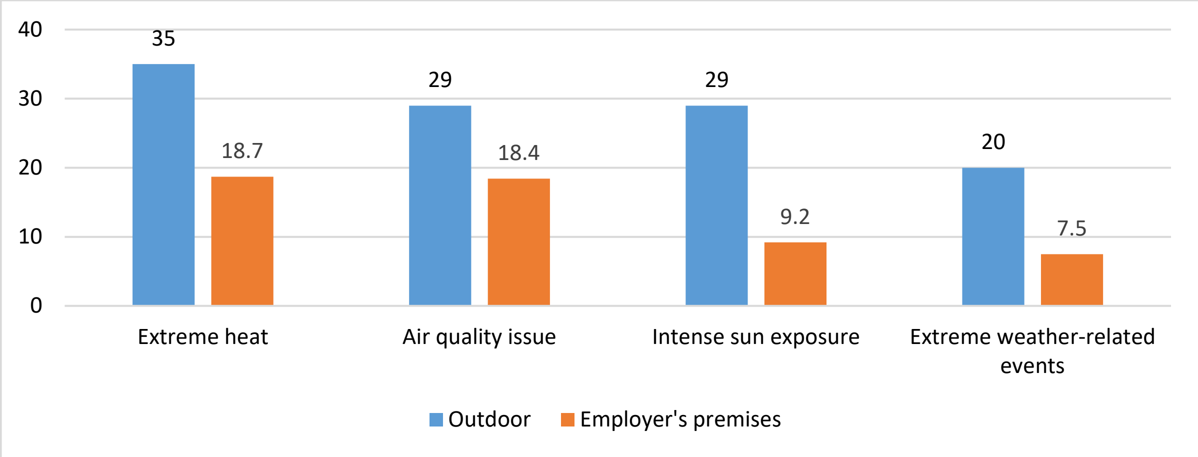
Figure 4 Prevalence of climate change-related OSH risks across EU workers (% of total workers)



Source: OSH Pulse Survey 2025

In some cases, workers will be simultaneously exposed to multiple climate change-related OSH risks, which requires the adoption of comprehensive prevention measures. For instance, outdoor workers have a significantly higher incidence of multiple risks than workers who are usually based at the employer's (indoor) premises (Figure 5).

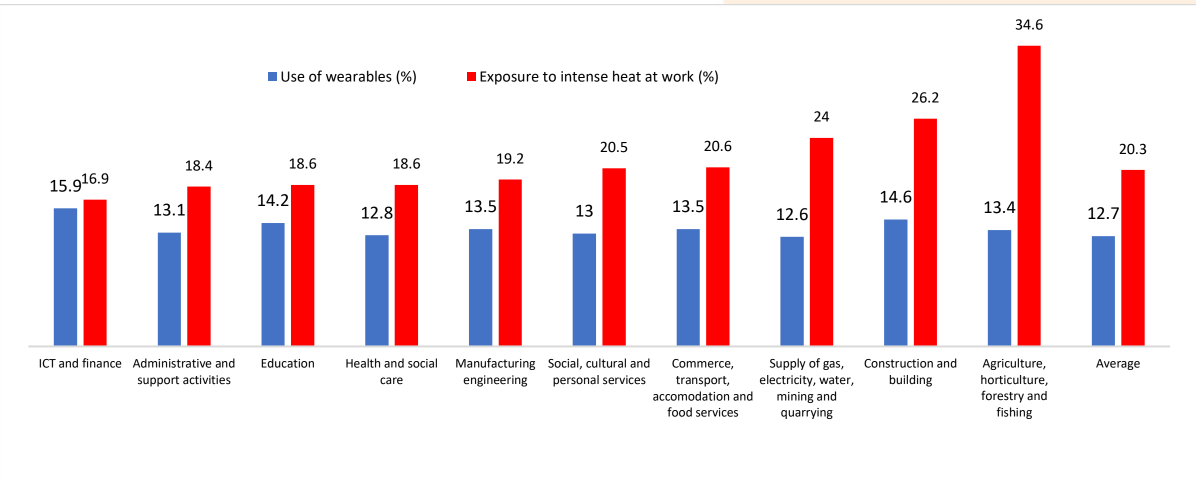
Figure 5 Exposure to climate change-related OSH risks by workers' location (% of total workers)



Source: OSH Pulse Survey 2025

To assess the potential role of wearables in climate-change prevention strategies, we first need to understand how widely they are currently used. In general, **the adoption of wearable technologies remains limited**. Around 13% of workers report using devices such as smart glasses, activity trackers or smart watches in their workplace. The low uptake of wearable devices, despite their potential utility in monitoring individual temperature and/or cooling body temperature, suggests that there is still limited scope for their application in climate change-related risk prevention plans. When the uptake of these digital technologies across sectors is analysed in combination with the exposure of users to extreme heat (Figure 6), it is likely that wearables are more commonly adopted in technologically advanced sectors such as ICT and education. However, these sectors face comparatively lower exposure to intense heat at work. In contrast, the agriculture and energy sectors, which are both at higher risk, have a lower adoption rate. The construction and building sector is an exception, as it has the second highest adoption rate of wearable devices, while also being the second most exposed sector. However, further research is required to see to what extent wearable technology deployed in high-risk sectors is actually used for heat prevention purposes.

Figure 6 Adoption of wearable technology and exposure to intense heat at work by sector (% of total workers)



Source: OSH Pulse Survey 2025

The evidence outlined above is documented in a recent publication by EU-OSHA that provides a comprehensive overview of the findings of OSH Pulse 2025. This includes information on the links between climate change and mental health; the relevance of national, demographic and sectoral differences in the implementation of digital technologies; and the exposure to climate change-related risks (EU-OSHA, 2025).

Implementation of new technologies for heat risk prevention in the workplace: evidence from field study analysis

To obtain more insights into how digital and body cooling technologies could contribute to the prevention of heat-related risks, we conducted 15 semi-structured interviews with US and European technology developers, industrial hygienists, OSH specialists and trade unionists at the Italian level.

The analysis focuses on three types of technological solution (see Table 4): 1) advanced wearables that collect and transmit real-time individual biometric data, 2) ventilated jackets and 3) smartphone apps that combine real-time environmental data with information about individual workers. These technologies vary in functionality and specific prevention purpose, ranging from personal monitoring and body-cooling solutions to the estimation of heat risk thresholds. For the first type of technologies (digital wearables), a more detailed analysis of implementation processes was possible due to the availability of the developer and two companies that started to use these tools around ten years ago. In contrast, the ventilated jacket examined in this study was still in a trial phase at the time of the interview. The design process for the smartphone app has been concluded for one company.

Table 4 Overview of the technologies implemented in the cases under study

Technology	Stage of implementation	Specific prevention purpose	Actors interviewed	Sectors
Wearables collecting individual biometric data	Highly advanced	Prevent the occurrence of heat-related accidents through real-time and remote monitoring of workers' personal physiological conditions	Two technology providers and two US adopters	Pharmaceuticals, cleaning of industrial and power plants
Ventilated jackets	Under trial	Mitigate heat strain and discomfort through cooling garments	One OSH specialist and two Italian companies	Transport and infrastructure sectors
Smart-phone apps combining environmental real-time data with individual information provided by the worker	Design concluded	Prevent the occurrence of heat-related accidents through automatic monitoring that combines real-time environmental data with individual (fixed) characteristics	One university expert, two technology providers	Agricultural sector

Source: compiled by author

The companies under study are from sectors including pharmaceuticals, the transport industry and specialised activities of cleaning industrial and power plants. The size of the companies is on average quite large, with hundreds of workers in different plants and cities.

The two US companies that are long-term adopters of digital wearables are active in sectors where heat stress is one of the main hazards inherent to both the activities performed (cleaning of closed and insulated buildings, treatment of chemical products in hot clean rooms) and the PPE that is required. The resulting heat stress seems to be further aggravated by increasing temperature trends at local level. Through interviews with the technology developer and the two companies, it was possible to analyse in detail the entire process of introduction and implementation of a technology. Moreover, interviews with unions and workers allowed to identify the main outcomes in terms of health and work organisation.

The two Italian companies under study are in the transport and infrastructure sector and are currently experimenting with the use of ventilated jackets. In recent years, these companies recorded a significant worsening of working conditions, due to the prevalence of outdoor activities and the rising environmental temperatures caused by climate change. In this context, the institutional and organisational challenges related to the implementation of new tools, such as ventilated garments aimed at reducing heat risk, emerged in interviews with both companies' managers and institutional OSH specialists directly involved in the trial project (see Table 5 in the Appendix for further details).

To sum up, this variety in terms of stages of adoption, implementation strategies, sectors covered and features of the job activities facilitated the identification of a range of challenges that may arise, from the preliminary design to the integration of technologies in a company's organisational and productive structure.

Drivers of adoption

The first clear and consistent finding concerns the main factors driving these companies to invest in new technologies to prevent and manage climate change-related risks. According to the interviewed technology developers, companies are increasingly concerned about the growing impact of climate change, prompting them to seek solutions that support prevention and management of the associated risks, and safeguard good working conditions. Interestingly, although this concern first emerged in companies where workers operate in extremely harsh environments – such as enclosed high-temperature spaces or roles like firefighting that require insulating PPE – it is now spreading across sectors and regions, with notably strong growth in demand from oil companies in the Middle East.

A driver that emerged implicitly in some interviews with respect to notification systems and risk alerts, which are found in digital wearables and smart phone applications, is the idea that deploying such tools in the workplace demonstrates a company's attention to compliance with OSH regulations.

> *So, this is a way to not only protect the worker, but also protect the company. Because the company has provided them with the solution, sending them notifications to remind them, asking them to click that they understand. But if the worker doesn't drink water, at that point that's kind of the worker's fault, right? Because we've done everything we can to remind them, to help them. But at the end of the day, they have to drink the water. [Developer_1]*

The digital wearable solution is presented by adopters as quite effective because it enables the measurement of something that was previously impossible to quantify and assess in real time: individual biometric condition. This should reduce information asymmetry and make broader OSH prevention measures more effective. These considerations are probably also linked to a lack of clear, compulsory plans for heat-related risk prevention, which leaves a company uncertain about the type of policies to adopt. At the same time, the simple adoption of these tools does not exonerate firms from their obligations on OSH management strategies.

Effects of the adoption of technological tools for preventing heat-related risks

Although these technologies have been implemented to reach specific OSH goals, the overall impact observed in the companies under study is much broader and requires the adoption of a comprehensive perspective, as underlined in the previous sections. The successful integration of these technological solutions in the production process has major consequences for work organisation, workers' competences and working time schedules.

Impacts on OSH

The main impact reported by the two US companies that are using digital wearable devices to monitor workers' body temperature is a **significant decline in the number of heat-related accidents and fatalities**. With the alert system, these companies can intervene before an incident occurs, due to risk thresholds that are often more precautionary than the temperature thresholds suggested by national or regional standards. For one of the two companies, the decision to implement wearable devices was prompted by a worker's fatal heatstroke. The company wanted to find a swift, effective solution for tracking workers' real-time health state, and to monitor accidental falls or a prolonged lack of physical movements that would suggest a sudden illness.

> *You can't judge somebody by looking at them physically and assess if they're going to be susceptible to heat-related illnesses. These devices could be customised to an individual. You knew exactly what was happening with that person at that point in time. That was really the game changer for us. We used to have five to six heat-related illnesses a year across the sites with somebody not feeling well, who had to go to rest or having to call emergency services. Since we implemented the wearable devices, we haven't had one heat-related illness. It's now been five years that we haven't had a heat-related event, since we implemented them. So, it's working. [Adopter_2]*

Impacts on work organisation and working time schedules

Once successfully integrated into work processes, these devices can not only impact workers' safety and health, but also contribute to further improvements in the production process. In one of the two companies, the analysis of workers' body temperature on summer days enabled industrial hygienists to **demonstrate to managers the impossibility of working during the hottest hours of the day and the need to rethink working hours,** by introducing early morning shifts. Objective data on heat-related risks, as provided by the wearables, helped to offset the lack of clear regulations on summer work shifts in the region concerned.

> *One of the things these devices have proved to our management is that it's really not smart to work at 2 pm in the afternoon when the sun is out. Because we had to take so many breaks (due to the alert system) when we work in the heat, we have shifted to what they call a 'tropical shift' in the summer. … The technologies show that you're not going be very efficient working in the hottest part of the day. [Adopter_1]*

Notably, in all cases under analysis, national and regional regulations, when present, mainly provide broad guidelines on heat-related risk prevention and management (see Table 2). This leaves companies with considerable discretion over the implementation of specific measures. When regulations are compulsory, they tend to be introduced too late, once a heat emergency is already underway. More generally, the lack of clear regulations on emerging climate change-related risks, as underlined in the introduction, leaves companies with significant autonomy that often leads to the adoption of incomplete OSH risk prevention plans. Only the most exposed, risk-aware companies are likely to develop well-structured measures and invest in wearable and body cooling technologies as objective tools to support heat-related risk prevention and management.

Improved perception of the occurrence of personal heat strain is also an important outcome driven by the adoption of these technologies. Many workers are reported to underestimate or tolerate for too long the discomfort caused by excessive heat. Consequently, the presence of a personal notification system that alerts workers in case of risk has raised their awareness of the intensity of their physical effort and relative well-being.

But you know, the most positive thing is that it has taught the workers to pace themselves better because they had no idea how hard they were working, when you know that saying: 'don't work harder, work smarter'. So now they go in, and they can pace themselves a little better. Sometimes when you go into the work area you have to climb up five flights of steps, because we don't have an elevator. So, once they get up there, they take a break before starting work. So, it has altered a little bit the behaviour patterns of our workers and they just don't go at it as hard in the summertime. They do pace themselves a little better. [Adopter_1]

Related to the more widespread introduction of self-pacing, companies that have adopted the digital wearable system reported increased reliance on job rotation schemes and teamwork. One of the main implications of adopting an alert system is that workers are allowed to interrupt their activity once a given temperature threshold is reached. To ensure these interruptions do not stop production workflows, the promotion of job rotation schemes, functional flexibility and teamwork become essential, as they allow workers to be temporarily reassigned from one task to another. Such an approach makes workers feel more confident in taking breaks without fearing negative consequences, since they can rely on the collaboration of other colleagues.

They share those real physical tasks a little bit more. Because they know if this guy receives an alert, then it's going affect our little crew. Because the crews are in groups from three to eight. If one guy has to come out, that does affect their work. And so they do share the physical task when it gets that way. [Adopter_1]

Effects on OSH specialists' competences and role

The implementation of a comprehensive monitoring system characterised by wearable devices and firm-level software processing of the collected data is changing and increasing the prominence of **OSH specialists' role in companies**. These specialists can now monitor the well-being of a larger number of workers in real time and are asked to promptly intervene when a risk is imminent. Therefore, people in this role should receive advanced training in digital skills and data analysis. At the same time, interaction between OSH specialists and supervisors in units where workers face the highest risks should be strengthened.

The OSH supervisor gets to learn about the workers, because he has to know who they are to make sure to assign the right armband to them. You learn about people, you learn the task and you learn a technology that is very user friendly. [Adopter_1]

Several interviewees underlined the need to empower the role of OSH supervisor, also through the use of technologies that allow data collection to better address climate change-related risks and more generally to develop a more efficient, individualised approach to health prevention.

We now talk about four Ps medicine: if you want to do precision, preventive, predictive and personalised medicine, you must consider the use of wearables. [Occ_Phys_1]

Challenges to an effective 'smart' prevention strategy for heat-related risk

Several challenges and obstacles could hinder the adoption or reduce the potential benefits of these technologies. These challenges are in technological, privacy-related, organisational and institutional areas, and require different types of intervention.

Challenges and obstacles to the use of digital wearables

In the **technological area**, users and providers have underlined the need to ensure: i) **maximum efficiency in terms of battery life**, connection power and transmission mechanisms (without relying on Wi-Fi, which may not be available in remote areas); ii) **ease of use and low cognitive load** (ensuring intuitive and simple human-machine interaction) and iii) **physical comfort** (with a preference for devices that are lightweight and quiet). In one of the cases, the company provided valuable inputs to the developer of digital wearables on how to improve user-friendliness. The suggestions were based on workers' direct feedback on the alert system. This confirms the importance of user-developer interaction in the field of innovation.

The feedback from the workers concerned the number of beeps because if you're familiar with their system, (there is) one beep, or two beeps or four beeps. And if you're working, it's like: 'Oh, did I feel that beep? Was that one, two?' So, now we just have the red alerts and that was directly due to feedback from the workers. [Adopter_1]

All actors recognise the importance of protecting **workers' privacy**, not only to comply with EU regulations, but also to ensure workers' acceptance and therefore efficient implementation of the tool. In one case under analysis, the trade union played a key role in ensuring, from the outset, that any form of monitoring of workers' locations was avoided. As a result, the company asked the technology provider to permanently deactivate the device's GPS option.

We don't use GPS at all. First, workers did not want that. And second, it uses the batteries up on the device. Our workers are always in pairs because of the kind of dangerous work we do, we never work alone. I can see the GPS is beneficial for workers who work alone … But not only did we turn the GPS function off, we asked the developer to disable it. So even if we try to turn it back on, it doesn't work. [Adopter_1]

Another technology provider made workers' privacy protection one of the key distinguishing features of its solution, activating the GPS localisation function only in case of emergency. Since the app is installed directly on the worker's phone, the presence of any tracking system could potentially lead to disputes between the company and the worker.

When it comes to location, we consider ourselves a privacy-first solution. And what that means is we are not sharing location or collecting location. The only time that someone's location is shared is if there is an emergency. So as an example, let's say that I'm a worker and I have a high heat risk, I pass out and I stop moving. I do have a feature called 'worker down'. And if I hold still for a period of time without moving, this will send off or trigger an alert that will go to all our emergency contacts to let them know that I have stopped moving, maybe I've passed out, I'm unconscious, I'm unable to respond. And so that is the only time that a location is really shared. Otherwise, there's no way to go into the system and say: 'Where is he right now?' [Provider_1]

More complex issues concern wearable devices and smart apps' alert systems. One of the main functions of these technologies is to send an alert to the worker when an estimated temperature threshold is reached. As explained, this alert prompts the worker to take a break, drink water, move to a shaded area and return to work only once the parameters have returned to normal levels. For such a system to be truly operational, workers should be granted a high degree of autonomy in managing the execution of their tasks, adjusting their work pace, and temporarily leaving their workplace to rest and recover. However, the actual possibility of exercising such **autonomy can be significantly limited by various constraints**: *operational* constraints, since some tasks cannot be interrupted in an emergency or because the worker is the only one who can perform them; *hierarchical* constraints, when the worker does not have the freedom to interrupt the activity without incurring negative consequences; *educational* constraints, if the worker is unable to understand the alert message; *remuneration* constraints when the work is paid on a piece-rate basis; and *socio-economic vulnerabilities*, as in the case of precarious workers who may fear losing their job if they complain. Some of these constraints can be resolved, for example through training and more frequent use of teamwork and job rotation. However, others would require a much more complex rethinking of the distribution of power and autonomy among the workforce, with the development of more horizontal and participatory workplaces.

Interestingly, the **financial cost** of the investment is rarely presented as a crucial barrier to the adoption of digital wearables. All the companies agreed that implementing effective risk prevention strategies that incorporate advanced technologies would be less costly than managing the consequences of workplace accidents, not to mention their human impact. Moreover, from the interviews with developers, the market price of these tools is decreasing due to technological advancements in the last ten years in the sector and the development of less complex, cheaper artifacts. These more recent market trends may be interesting for small and medium-sized enterprises that could have greater doubts about investing in these technologies because of their more limited scope and relatively higher costs.

Challenges and obstacles to the use of personal cooling garments

Up to this point, the focus has been on digital wearables whose implementation phase is quite advanced in both the companies under study. In contrast, this section provides some insights emerging from on-going trials of body cooling clothing, in this case, ventilated jackets. Organisational barriers and institutional constraints are considered.

In terms of organisational barriers, ventilated jackets are much less invasive from a privacy perspective, but they face considerable obstacles to their adoption. They require periodic maintenance and the allocation of a specific time for workers to put on and take off the garment within their work schedule.

In terms of institutional constraints, all stakeholders must be involved in developing implementation strategies. This requires formal channels of interaction, such as negotiations and collective bargaining, and the promotion of a network among companies and specialised institutions to discuss best practices. An additional institutional barrier related to labour market deregulation emerged during one interview with a large company operating on Italian territory. The interviewee highlighted the challenges of implementing the same OSH technological tool (ventilated jackets) in highly segmented workplaces with domestic outsourcing. In this case, it may be very difficult to ensure the widespread implementation of the same product across all interested companies. Competitive tendering prevents suppliers from mandating the use of a specific ventilated jacket, unless it is first certified as an official PPE by the competent authority. This restriction also holds if the efficacy of the tool has been validated through the involvement of national OSH experts in a number of trials.

> *We have many external companies and we know that PPE must be provided by the employee. We could stipulate that anyone working with us must be equipped with this technology, but as these are public contracts, we cannot even specify the brand and model of this technology. We would have to include the requirements that these devices must meet in the specifications, and then whoever wins the tender will have to purchase a device on the market that meets these pre-established performance requirements. This could be complex ... The issue then is also to verify that they have purchased something that meets these requirements, because then there is a cost and it must be recognised. [Adopter 3.A_IT]*

Looking ahead: the role of institutions and standards in advanced technologies

The market of digital wearable devices, ventilated jackets and, more generally, new technologies designed to prevent heat-related risk at work has grown steadily over the last decade. This growth has been driven by increasing demand from companies seeking concrete solutions to rising environmental temperatures and the prevention of work-related accidents. The supply of these tools is also increasing significantly, with new market entrants offering technologies at more competitive prices. Given these trends, there is a risk that poor-quality tools will spread through companies in the absence of a **robust validation system led by institutional experts and the establishment of clear standards regarding tool quality and functionality**. This concern was raised in multiple interviews with technology providers, companies and OSH specialists. Many of the interviewees underlined the need to develop validation protocols under the guidance of institutional bodies, to assess the effectiveness of the tools and the quality of the data collected. Reliance on strong, institutionalised validation mechanisms, rather than on market trends, was highlighted as a crucial requirement to choose the right tools and control the possibility of generating unexpected risks through their use.

In general, **more structured involvement of occupational physicians and OSH specialists** is needed to ensure the implementation of broader prevention plans in the workplace. In these plans, technology should not be the main solution, but rather one tool within a broader risk prevention and management strategy. The added value of adopting these tools is the opportunity to better monitor workers' individual well-being through the collection of their real-time data and the provision of cooling mechanisms. The enforcement of more tailored practices accounting for not only environmental conditions, but also individual specific factors can significantly reduce the gravity of heat-related risk. Moreover, systemic heat prevention plans are needed, where factors at individual level are combined with organisational settings that can differ significantly within the same industry.[10]

The adoption of such an integrated perspective essentially implies a change in the way climate change-related risks, and heat-related risks in particular, are dealt with by companies and institutions. As suggested by one interviewed trade union representative, a shift is needed from **an emergency approach, where preventive measures and regulations are introduced on a temporary and exceptional basis in response to worsening working conditions during the summer period, to a 'reality-based' approach**, where heatwaves are managed systematically, with a high degree of anticipation, in a structured and gradual manner over the year. For example, in the construction sector, which is one of the sectors that is most exposed to heat, this would mean rethinking the entire value chain and ensuring that heat prevention plans are implemented from the outset, namely when contracts for construction works are drafted. According to one trade unionist, a real leap forward in climate change-related risk prevention and management for workplaces would be to **adopt a work organisation model closely aligned with a heat risk prevention policy from the start of production cost planning.** Possible measures would include reducing working hours due to heat, scheduling days off, requiring companies to provide PPE and monitoring tools (once these have been validated robustly), building shaded rest areas, and offering training courses to all workers on climate change-related risks. In such a framework, the implementation of digital technologies would be the final step in a much broader, ambitious prevention plan.

[10] One trade unionist noted that in the transport sector workers are exposed to extremely different types of risk depending on their activity (from airport staff to railway and rope access workers). Consequently, localised intervention plans are required.

There are two key points. In the construction industry, we are aware that we are in a phase of adaptation: we should neither fight nor deny that climate change is happening. We need to understand how we can adapt. We need to take a two-pronged approach: on the one hand, we need to demand comprehensive legislation that addresses the issue and, on the other, we need to incorporate these factors right from the design stage of a project. We should be able to design from the beginning what health and safety conditions must be respected on a construction site, since these are non-negotiable costs. … If, during the design phase, I do take into account that there is climate change, that there is heat, then the water supply must be provided for, not just in emergency situations, shaded areas must be provided for. … The organisation of work must undergo changes that lead to slowdowns in production, because objectively it is not possible to work … In my opinion, this is the revolution: if we can get the work design to speak for itself. Why isn't this happening today? Because we treat it as an emergency. [Construction trade union]

Conclusions

The evidence and information collected through the desk research and semi-structured interviews conducted for this study has confirmed the relevance of the workplace as a crucial area of intervention to prevent and reduce the incidence of heat-related injury and illness. Despite the increasing prevalence of this risk among the working population, the adoption of prevention strategies at the company level still faces several issues, and is scattered, uneven and uncertain (Woetzel, Pinner & Samandari, 2020). First, the incidence and intensity of heat risk is determined by not only environmental factors such as air temperature, humidity level, solar radiation and wind speed, but also several organisational factors, such as work intensity and work-rest cycle, and safety requirements that could prescribe the wearing of insulating clothing. Additionally, several intra- and inter-individual factors influence heat risk, such as quality of sleep, gender, age and chronic disease. The numerous factors that affect individual thermoregulation capability should be properly accounted for in the development of a comprehensive OSH risk prevention plan, informed by hierarchy of control principles and a socio-relational approach.

In this context, the adoption of new technologies, including advanced digital technologies, can play an important role in identifying and preventing hazardous situations. The most relevant innovations in the field that have been recorded and reported by firms, OSH specialists and developers are **digital wearables and body cooling technologies**. Digital wearables include sensors that monitor and track an individual's body temperature, whereas body cooling technologies may take the form of cooling garments that can reduce body temperature through various cooling mechanisms. Additionally, smart phone applications that provide alerts and notifications have emerged as a new digital tool for heat risk prevention.

The possibility of tracking individual temperature, setting safety thresholds and sending alerts to workers to encourage them to take a break is an innovation that could significantly reduce the incidence of heat strain. This is confirmed by companies with longer experiences of adoption that recorded a decline in heat-related accidents. Effective implementation of these tools seems to entail a number of changes in work organisation, with the promotion of practices such as self-pacing, job rotation schemes and early morning shifts. It also affects the role of OSH managers in a company, as they can access a vast amount of real-time data, promote the development of more comprehensive prevention strategies and make suggestions on the allocation of tasks across time slots and work groups.

Cooling garments that decrease body temperature are another useful tool for mitigating exposure to heat and reducing the likelihood of developing heat strain and related illnesses. These tools could be particularly useful for those who are in hot environments for most of their working day. However, despite their potential contribution to heat risk prevention, these technological solutions are rarely adopted by companies. There are few studies on their use in workplaces in the literature, and clear regulations drawn up by national OSH organisations and governments are still lacking. Most provisions and guidelines issued by national institutions make only limited reference to digital and body cooling technologies. This inaction entails considerable risks, as it leaves more proactive firms to evaluate products without clear standards. In an expanding market, this can favour the adoption of tools that are presented as efficient, although they lack scientific and institutional validation, and can pose potential risks to workers' rights.

As confirmed by some interviewees, digital wearables can potentially allow pervasive monitoring of workers' biometric data and geo-positioning, which makes it easy to assess their labour productivity and level of exertion. However, evidence from two case studies has shown that the set of functionalities required by the technological solution is not fixed. Instead, there is scope for bargaining and negotiation to ensure workers' privacy rights and health protection. Excessive and exclusive reliance on technological solutions could marginalise the role of OSH specialists and institutions, who should instead play an active role in developing and validating these tools, particularly regarding how they function, their modes of application and how they can complement other organisational measures.

At the same time, meaningful progress must extend beyond the workplace, as consistently highlighted by all interviewed stakeholders. National governments are increasingly prioritising these issues, as evidenced by recent national action plans in countries such as Belgium, China, France, Spain and Japan (ILO, 2024) that identify climate change–related risk prevention as a key objective. However, comprehensive and clearly defined regulatory frameworks remain insufficient. A central challenge is the systematic integration of climate change-related occupational risks in workplace health and safety risk assessment and prevention measures. This process should begin with careful identification of the most vulnerable socio-economic groups and occupational categories, particularly workers facing heightened exposure and limited protection (Parsons et al., 2025). More broadly, climate change should not be treated solely as an environmental or developmental concern, but embedded within national development strategies and public health policies as a cross-cutting structural issue (Dasgupta and Robinson, 2023).[11] As highlighted by Dodman et al. (2023), climate change does not operate in isolation. Rather, it interacts with broader socio-political, environmental and economic dynamics that reinforce and compound one another, thereby intensifying risks for workers, especially those in informal employment.

According to interviews with union representatives, such measures should not be treated as temporary responses to emergencies, but grounded in a comprehensive assessment of recurring risks. In this context, new digital and body cooling technologies can offer valuable and innovative support, but only when implemented as part of a broader, coordinated strategy at local, regional and national levels. Drawing a parallel with the historical use of canaries in coal mines to detect toxic gases, Roelofs and Wegman (2014) described workers as the 'climate canaries' of the 21st century. Today, workers are often directly exposed to hazards that will increasingly affect the wider population, pointing at the urgency of these risks and underscoring the need for immediate action.

[11] This is the approach adopted by the ILO Global Strategy on Occupational Safety and Health 2024-2030, which stresses that all issues related to climate change need to be integrated into the global and national policy agenda.

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Appendix

Table 5 List of interviewees (role, technology, sector and country)

Category	Interview code	Role	Technology	Company/sector	Country
Technology developers and providers	Provider 1_US	Business development specialist	Smart phone app	Tech company	US
	Provider 2_UK	Business development manager	Wearable	Tech company	UK
	Provider 3_US	Co-founder and CEO	Wearable	Tech company	US
	Provider 4_IT	Product and marketing manager and sales representative	Environmental sensor and data logger	Tech company	Italy
Adopters	Adopter 1_US	Industrial hygienist	Wearable	Cleaning	US
	Adopter 2_US	Director global environment, health and safety	Wearable	Healthcare	US
	Adopter 3.A_IT	HSE excellence corporate safety manager	Ventilated jacket	Transport and infrastructure sector	Italy
	Adopter 3.B_IT	Health and safety coordinator	Ventilated jacket	Transport sector at regional level	Italy
	Failed Adopter 4_IT	Professor and technician	Smartphone app combined with environmental sensor	University with agriculture activities	Italy
Trade unionists	Union_1_IT	National secretary	-	Construction sector	Italy
	Union_2_IT	National secretary	-	Transport sector	Italy
OSH experts and professionals	Expert 1_IT	OSH researcher	Ventilated jacket	OSH national institution	Italy
	Expert 2_SP	OSH expert	-	Private OSH company	Spain
	Occ_Phys_1	Coordinator of occupational physicians	-	Transport sector	Italy