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Smart digital monitoring systems for occupational safety and health

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“Everything you lose is a step you take.”
Taylor Swift

Abstract

Every day, millions of workers all around the world, face risks and hazards in their workplace that frequently lead to injuries and, in the worst cases, even death. Occupational safety and health (OSH) is the discipline dedicated to the prevention of accidents in the workplace. While the industry sector continues to evolve, and the workforce continuously changes, the associated risks and hazards also increase and multiply. OSH aims to guarantee that the safety and health of all workers remain a high priority for organizations. Implementing an OSH management system – compliant with the guidelines of standard ISO 45001 – becomes of utmost importance not only to protect workers but also to avoid economic losses for the organization and, more in general, for society. In this context that continuously evolves, digitalization comes into play bringing changes and opportunities. Advancements in new technologies can be employed for OSH purposes. Examples of technologies used to improve workers' safety are wearable devices (e.g., exoskeletons), drones, IoT and wireless systems, as well as artificial intelligence (AI) algorithms. This thesis aims to provide a comprehensive overview of challenges and opportunities in implementing an OSH management system within an organization. Additionally, this work will describe some innovative digital OSH monitoring systems, and provide examples of organizations that successfully implement and produce these technologies.

Contents

Listing of figures

Listing of acronyms

A

ADAS Advanced Driver Assistance System

AI Artificial Intelligence

AR Augmented Reality

C

CXS Collision Avoidance/warning Systems

D

DARPA Defense Advanced Research Projects Agency

G

GDPR General Data Protection Regulation

GNSS Global Navigation Satellite System

I

ICT Information and Communication Technology

IIoT Industrial Internet of Things

IoT Internet of things

L

LiDAR Light Detection and Ranging

LTIR Lost Time Incident Rate

M

M2M Machine-to-Machine

ML Machine Learning

MMH Manual Material Handling

N

NFC Near Field Communication

O

OSH Occupational Safety and Health

P

PaaS Platform as a Service

PDCA Plan-Do-Check-Act

PPE smart Personal Protective Equipment

PSD Personal Safety Device

R

RADAR Radio Detection and Ranging

RIR Recordable Incident Rate

RPAS Remotely Piloted Aircraft System

S

SMEs Small and Medium-sized Enterprises

U

UAS Unmanned Aircraft System

UAV Unmanned aerial vehicles

UWB Pulsed or Ultra-Wideband

V

VR Virtual Reality

VSX Vehicle-to-Everything

W

WRMSDs Work-Related Musculoskeletal Disorders

WSNs Wireless Sensor Networks

WUSN Wireless Underground Sensor Network

1
Introduction

Occupational safety and health is the discipline which deals with the prevention of work-related injuries and diseases as well as the protection and promotion of the health of workers [1]. Its principal purpose is the improvement of the working conditions to guarantee the safety and health of employees. Recent advancements in new technologies can be used to reach this aim, leading to the concept of digital Occupational Safety and Health (OSH) monitoring systems. There is no common and agreed-upon definition of digital OSH monitoring systems at the EU level. Nonetheless, it is fundamental to identify a definition, mainly because it could be the first step to comprehend them and their constraints. Nevertheless, a definition of OSH monitoring systems can be proposed: *digital OSH monitoring systems use digital technology to collect and analyse data to identify and assess risks, prevent and/or minimise harm, and promote occupational safety and health.* (Source: Ecorys, 2022). It is a definition that provides a brief, but comprehensive scope of the uses and purpose of a digital OSH monitoring system, which is linked to the act of acquiring data regarding risks and workers' health in the workplace. The acquired data can be then exploited by firms to promote, inside of their organization, the use of OSH. In this way, digital OSH monitoring systems can be helpful in the continuous cycle of OSH's improvement [2]. The first standard to provide a framework for the effective management of OSH was the OHSAS (Occupational Health and Safety Assessment Series) 18001 which was one of the International Standards for Occupational Health and Safety Management Systems. It included all aspects of risk management and legal compliance, and it addressed occupational health and safety rather than any specific product safety matters. However, in March 2018 OHSAS 18001 was replaced by the new ISO 45001 [3]. ISO 45001 is an international standard that provides a framework for organizations to manage risks and improve OSH performance and it can be adopted by any organization without any limitation regarding its size, type and nature. ISO 45001 does not impose rigid criteria nor is prescriptive about the design and implementation of an OSH management system since each organization during the design of an OSH management system should take into account its own needs and design a system which is focused on solving these issues. For instance, a big organization will need to implement a more advanced system, while a small business could benefit from implementing a simpler one. Just like OHSAS 18001, ISO 45001 does not address issues such as product safety, property damage or environmental impacts, and an organization is not required to take account of these issues unless they present a risk to its workers. It is important to understand that it is not intended to be a legally binding document, but it is a voluntary management tool for organizations from SMEs upwards whose aim is to eliminate or minimise the risk of harm. Moreover, to design ISO 45001 a high-level structure has been employed, one similar to other ISO standards like ISO 9001 (Quality management system) and ISO 14001 (Environmental management system). This similarity regarding the structure of the norm allows for easier implementation of the ISO 45001 standard inside the organization's overall management process since its requirements are consistent with the other standards.

Thanks to digitalization new systems can be employed to improve the controls and policies implemented by the organizations to take care of the health and safety of workers. Various technologies can be used and each one of them can be customized to the specific needs of every industry sector. Some of these technologies are Artificial Intelligence (AI) and Machine Learning (ML); wearables, smart Personal Protective Equipment (PPE), exoskeletons; Virtual Reality (VR) and Augmented Reality (AR); widespread connectivity, the Internet of things (IoT), and big data applications. These different systems can be used for the prime objective to enhance risk assessment and management, as well as improve monitoring of workers' health and workplace environmental conditions in real-time. This constant surveillance can help organizations identify emerging risks, detect unsafe behaviours, and intervene promptly in case of hazardous situations. Notably, also the training and education of workers can be improved through the use of technologies such as VR and AR. Lastly, all these systems can collect, analyze, and interpret data, through which organizations can identify patterns and areas for improvement, enabling them to make informed decisions and optimize their safety protocols.

The structure of this thesis and the topics discussed will be organized as follows. In chapter 2, a comprehensive view regarding the adoption of digital OSH monitoring systems will be carried out, considering the advantages and disadvantages of implementing these systems in an organization. Moreover, a brief description of the guidelines to follow to be considered compliant with ISO 45001 is provided (2.5). In chapter 3, various technologies that can help in achieving OSH are described, including wearables (3.2), Industrial Internet of Things (IIoT) innovations (3.3), particularly the ones used in underground coal mines, drones (3.4), and Collision Avoidance/warning Systems (CXS) (3.5) based both on Radio Detection and Ranging (RADAR) and Bluetooth. Lastly, in chapter 4 some examples will be provided of organizations that implement these systems (4.1), specifically Enel and Amazon, and startups that create and sell these systems (4.2), Verve Motion and VOS systems.

In this thesis, the topic of OSH is discussed due to the crucial importance of granting safety to all workers. As the industry evolves and technology advances, many new occupational hazards emerge. It is a topic that transcends mere academic curiosity or regulatory compliance since it expresses a moral imperative. Every worker has the right to a safe and healthy working environment, however, every day millions of workers face a multitude of risks, some of them leading to their deaths. Moreover, investing in OSH is linked to economic productivity. Accidents and illnesses caused by poor working conditions raise financial costs not only for employers but also for society at large. In light of these considerations, this thesis is a general overview of the matter and many other research and studies must be made to make advancements in the sector, in order to make positive changes and promote a safe and healthy workplace for everyone.

2

Digital occupational safety and health systems and ISO 45001

2.1 Digital OSH monitoring systems and trends in their uptaking

Digital systems and technologies have had an advancement which was the fastest compared to every other innovation in history [4]. In particular, these technologies comprise technologies such as AI and ML; wearables, PPE, exoskeletons; VR and AR; widespread connectivity, the IoT, and big data applications. Due to their widespread these new technologies and digital systems have entered, and consequently transformed, the EU workplace for both workers and employers. The management and improvement of the safety and health of workers is being deeply influenced by these technologies, as well as the nature, location and organisation of work.

Digital OSH monitoring systems are becoming prevalent in occupational settings (for example data shows that 40 % of human resources (HR) offices employ AI in the selection process for suitable candidates [5]). Their widespread in this sector is due to the fact that occupational health and the well-being of working people are considered crucial prerequisites for productivity and are of utmost importance for all socio-economic and sustainable development [6]. However, despite their widespread and growing relevance, the available European data reveals that their uptaking is slow and limited. Data gathered by ESENER-3 (Third European Survey of Enterprises on New and Emerging Risks) shows that the development and uptake of digital OSH monitoring systems is more pronounced in industries where there are higher levels of OSH risks or where the tasks performed are easy to monitor. The available information allows to highlight some relevant trends. First of all, a decisive factor in the implementation of digital technologies in the work environment is the establishment size [7]. In Figure 2.1 we can see that the 95 % of large European

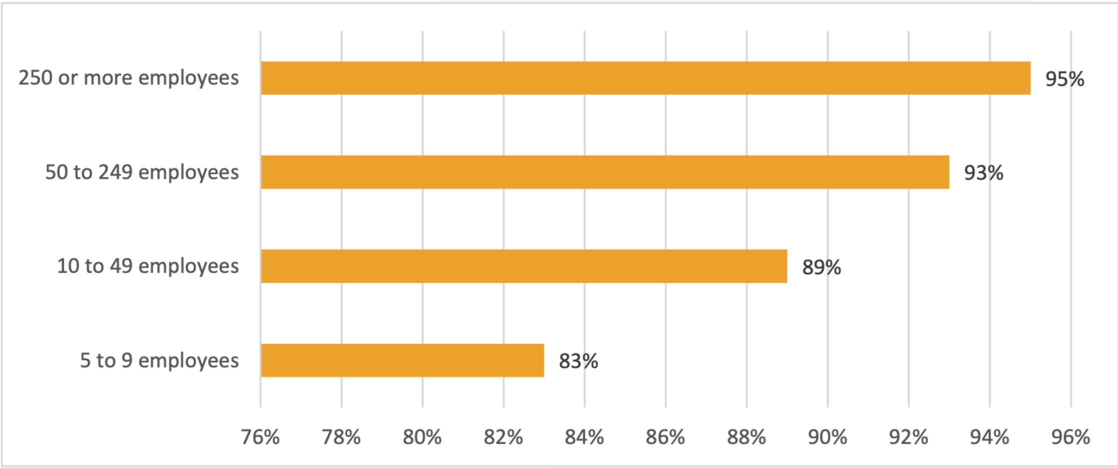

Figure 2.1: Usage percentage of digital technologies in European establishment compared to their size [7]

firms (250 or more employees) use digital technologies, compared to small European firms (5 to 9 employees) which have use of 83 %. This difference is probably due to the large firm's capability to invest in research, development and innovation, while a smaller firm may focus more on achieving financial stability. Not only that, but bigger establishments may also have more human resources to implement the new technology and the time and resources to deeply research and understand their organization's needs. Secondly, not all types of digital tools that enable the use of new OSH monitoring systems are equally adopted. For instance, according to ESENER-3 results only 5 % of establishments employ wearable devices, while a more consisting 77 % adopt more traditional technologies like laptops and smartphones. Moreover, data also highlight a tendency to use these technologies not to monitor OSH, but rather to control workers' performances as well as their content and pace of work. Lastly, the data underline that different industries are adopting the digital transition to different extents [8].

Overall, even if research conducted up to this point shows that the adoption of digital OSH monitoring systems is still in its early stages, factors like the growing importance of OSH and the opportunities given by the continuous development of new technologies, lead to a likelihood of a future increased implementation.

2.2 The role of digital OSH monitoring systems

Digital OSH monitoring systems can offer a multitude of new opportunities in the workplace. Among these, OSH improvements could lead, first of all, to an enhancement of worker safety and health with fewer incidents and injuries. Data shows that in 2016 EU member states reported 2.4 million non-fatal accidents and 3,182 fatal accidents at work. Moreover, in 2013 7.9 % of the European workforce suffered from occupational health issues (Eurostat, 2018a, 2018c). These occupational injuries, diseases and deaths produce higher costs for individuals, employers, and society. Costs that comprise direct costs, concerning medical expenses for workers, and indirect costs, that include loss of productivity and output losses [9]. Additionally, firms have to account also for the legal expenses that they will have to undertake during the trials to assess their responsibility in the unfolding of the accidents as well and if found guilty they will have to pay compensation for damage. Furthermore, a hidden cost in all this is the potential reputation cost that could damage the firm's value and credibility.

To prevent and manage all these various aspects digital OSH monitoring systems can undertake two distinct approaches: a proactive approach and a reactive approach. Both are crucial since if used and considered as one, they can lead to significant improvements in the OSH context, thanks to the data collected and analysed. [10]

2.2.1 Proactive approach: harm prevention

Proactive approaches aim to detect potential dangers before accidents occur, therefore trying to prevent them. OSH monitoring systems can help by collecting data that can be then analyzed and the results used to adjust each parameter to each organisation's exigencies. They also ensure routine checks and maintenance. There are multiple opportunities through which the innovation brought by OSH monitoring systems can be exploited. An example could be the measurement of the exposure to potentially damaging elements. In sectors like mining or chemical plants, it is of the utmost importance to detect harmful environmental conditions such as radiation leaks, chemicals and biological agents, and toxic dust in under-ventilated environments. Moreover, OSH monitoring systems can be employed to preemptively identify hazardous workers behaviours or poor individual health and well-being thanks to the use of wearables, which can detect early signs of physical, muscle, and mental fatigue, stress, low alertness and reaction times. Lastly, these technologies can be used to assess risks remotely as well as implement digital and dynamic inspections. [10]

2.2.2 Reactive approach: minimising the consequence of harm

Reactive approaches focus on minimising accident's effects after they have already happened. They consist of a fast intervention and the collection of useful data to quickly address the consequences of the harm, as well as store the resulting data for future reference. OSH monitoring systems can help in signalling and localising emergencies thanks to GPS tracking making it possible to swiftly locate and bring to safety workers involved in accidents. An example could be construction workers trapped in places hard to reach. Safety in these kinds of situations, where the accident happens in an isolated working environment, could even be addressed through the implementation of innovative wearable solutions, as well as Wireless Sensor Networks (WSNs) (which allow Bluetooth and WiFi stations to promptly locate the worker) and Unmanned aerial vehicles (UAV). Moreover, these technologies come into play when a rapid response to emergencies is necessary. Through wearables and AR, information (which can comprise text, video, images, and audio) can be delivered rapidly and accessed easily. Furthermore, digital OSH monitoring systems can provide support in accident investigations by providing data about where the accident occurred, who was involved in it, and the victims, what happened before (the actions and conditions that led to it), during, and immediately after (the rescue operations employed). These data can also be subsequently used to understand how to improve rescue operations in terms of response time and action taken. Finally, digital OSH monitoring systems can allow quick and accurate reporting. [10]

2.3 Drivers and barriers to their use

The drivers and barriers to the adoption of digital OSH monitoring systems can be summarized across three main themes: technological advancement, legislation and standardisation, and societal and organisational factors [8].

To begin with, in the last decade, improvements in digital technology have been extremely fast and recent advancements, particularly in IoT and WSNs [1], have enabled monitoring for various application scenarios, the fittest of which OSH. However, even though it opened up many possibilities, some factors could still hinder the widespread of these technologies. First of all, the time and monetary resources that these monitoring systems need are not sustainable for every firm, especially smaller ones, which may lack the long-term stability and financial resources to invest in this sector. Moreover, the testing phase and the certification of these systems must be conducted as a whole, and this could bring complexities due to environmental factors which can not be always measured precisely.

Moving on to the second point, crafting an efficient and relevant legislation for OSH is a challenging task for European policymakers. The current legislation does not specifically address the implications of technical change in OSH monitoring, which renders this a grey area in terms of policy [8]. The difficulty is heightened by the different conceptions of risk that each European country may have, as well as issues concerning privacy (2.3.1). Moreover, standardisation, which is fundamental for granting interoperability between technologies produced by different manufacturers and promoting innovation and competition [11], could hinder the adoption of these technologies, and since OSH concerns safety and health, having a well-defined, controlled, and secure system is of the utmost importance. The issue with standards is that in some cases there are little to no standards available, while in others a proliferation occurs, leading, in both situations, to a potential barrier to their adoption. Lastly, standardisation can also create problems when it is left to private parties leading to both the gatekeeping of crucial technologies, and the raising of questions about the quality of the standardisation process.

Societal factors (which can include economic, health, and societal changes) deeply influence the drivers as well as barriers of digital OSH monitoring. Hence, the focus here is not on the technology itself, but instead on how these technologies are integrated into systems, each with different needs and requirements. A recent driving force in the adoption of monitoring systems, was undoubtedly the COVID-19 pandemic since companies were required to mitigate the risk of exposure to biological agents by implementing safe processes and behaviours. Moreover, this health emergency also led to an increase in telework (in 2021 there was a double of employees teleworking then in 2019 [12]), which created new OSH hazards associated with home workstations and its ergonomic, like musculoskeletal disorders [13]. All this is aggravated by the difficulty for employers to effectively control the conditions in which teleworking is conducted. Lastly, another societal factor that influences the uptake of monitoring systems is the perceptions of companies about why these technologies have to be implemented. OSH monitoring systems could be adopted to fulfil legal obligations, improve their production or just as a response to market pressures. Therefore, their main purpose may not always be the safety and health of workers.

2.3.1 Privacy issues emerging from the use of digital OSH monitoring systems

Digital OSH monitoring systems involve a lot of data that is being monitored and subsequently analysed. However, in the rush to exploit these advanced smart technologies, often the privacy of workers is sacrificed. Private information of employees, that could be sensitive, include name and/or staff number, facial feature, real-time location and travel history. And even if privacy protection has been at the centre of many discussions in these last years, it is still often traded away for the "greater good", which in this case consists of security, safety, and efficiency [14]. Therefore, the risk consists of a threat to workers' privacy where these "intrusive" technologies could be used to control work, performances, team dynamics as well as sensitive characteristics, rather than used for their intended purpose, which is safety. Employers may be reluctant to the employment of digital monitoring systems due to their potential hidden purpose, which translates into employee surveillance. Trade unions are concerned that this will expose the workforce to productivity pressures, with detrimental effects on health and well-being [8].

The legislation better suited to deal with this is the General Data Protection Regulation (GDPR) 2016/679/EU even if in it worker's privacy is not particularly protected. Recital 4 of GDPR states that the employees' right to the protection of personal data «*must be considered in relation to its function in society and be balanced against other fundamental rights, in accordance with the principle of proportionality*». Therefore, employees' right to privacy is not safeguarded in a way in which it could prevail over companies' interests to improve their business [15]. However, attention should be drawn to Opinion 2/2017 on data processing at work adopted on 8 June 2017. In it, the European Commission focuses on the risks brought by new technologies in balancing between the legitimate interests of employers and the reasonable privacy expectations of employees, emphasizing that a new assessment is required. Anyway, this lack of protection across the European Union could be and should be mitigated by each member state through national rules.

2.4 Optimising the uptake of new OSH monitoring systems

The implementation of digital OSH monitoring systems could bring an improvement in the workplace, but there are still issues that make its implementation slow and limited. To boost their adoption in companies and firms some measures could be taken to optimise their uptake.

First of all, it is of the utmost importance to encourage effective and open communication inside the workplace regarding the main benefits and drawbacks of these systems, in order to clear every doubt or/and hesitancy among workers. Moreover, an inclusive process should be adopted. During the planning, design, delivery and use of the new OSH monitoring systems, establishing trust is of the utmost importance, and it can be achieved by giving the possibility for employer and employee representatives to express their concerns during all phases of implementation. This is important, even in the possibility of including in the workplace workers with physical disabilities (e.g., occupational exoskeletons used to reduce the physical load on workers can also be employed to assist people with motor impairment [16]).

Another important challenge to face in order to implement the adoption of OSH monitoring systems is standardization. Since standardization is constantly increasing in the Information and Communication Technology (ICT) this can lead to issues that can potentially act as a barrier in the implementation of these monitoring systems (2.3). To this aim, the European Union has been urged to develop new standards specific to the EU digital single market [17]. Moreover, the EU is pushed to supply suitable support to Small and Medium-sized Enterprises (SMEs) to help them in the adoption of these technologies, through the creation of networks to share investments (that undertaken alone would be too burdensome). That is important to ensure that not only larger and more profitable firms are a part of this revolution, but also smaller ones are included and are given the possibility to improve their businesses as well as their work environment [8].

2.5 ISO 45001 Occupational health and safety management systems - Requirements with guidance for use

It is paramount for an organization to implement measures to make sure that the safety and health of its workers are protected. The adoption of an OSH management system is the first step to ensure safe and healthy workplaces and prevent work-related injuries. The main purpose of a OSH management system is to eliminate hazards and minimize risks for the safety and health of workers, by taking preventive (2.2.1) and protective measures (2.2.2). Implementing an OSH management system which is compliant with ISO 45001 allows an organization to manage their OSH risks and improve the overall OSH performance. Moreover, the management system that this standard provides, can help assist an organization to fulfill eventual legal requirements or other requirements, which may be asked of them. However, it is important to keep in mind that the adoption of this standard in itself will not guarantee the total prevention of work-related injuries and the poor health of workers, since it will be each organization's responsibility to review and monitor the OSH management system and adapt it to their specific needs and challenges. Nonetheless, there are some factors that could enhance its effectiveness and its ability to achieve the health and security of all the interested parties. Some of these are the commitment of the top management to leading and promoting a culture in the organization that supports the expected achievements of the OSH management system, the consultation and participation of workers in the design of the system, the implementation of effective process(es) for identifying the hazards, and the actual integration of these monitoring systems in the organization's business processes, as well as the continuous and meticulous performance evaluation and monitoring of the OSH system.

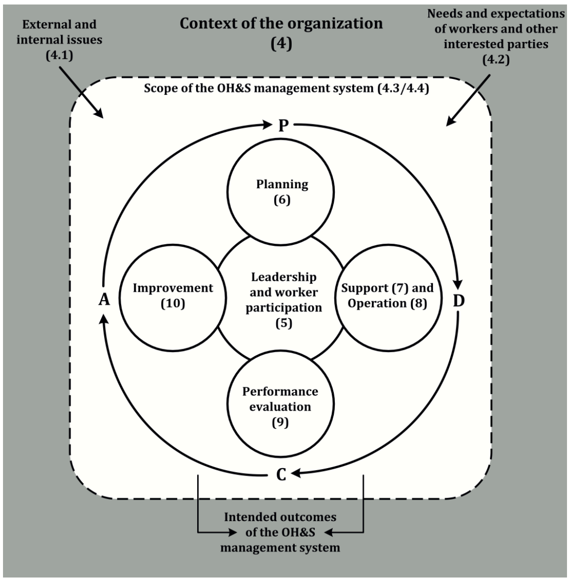

Figure 2.2: How the ISO 45001 incorporates the PDCA into the OSH monitoring system framework. The numbers in brackets refer to the clause numbers in the ISO 45001 standard document [18]

The resources needed, the level of detail, and the documented information required to ensure that an organization's OSH management system will be successful depend on various factors such as the organization's context (e.g. the number of workers, the size of the establishments, the geographical location and the culture along with additional legal requirements each organization could have), the scope of the organization's OSH management system, and finally the nature of the organization's activities and the related OSH risks.

In ISO 45001 the development of the OSH management system adopts the concept of Plan-Do-Check-Act (PDCA) (2.2). It is a four-step problem-solving iterative process to achieve continual improvement in business processes. The first step, "Plan", consists of determining and assessing OSH risks and opportunities and establishing OSH objectives and processes that will help deliver the desired results. Secondly, step "Do" consists of actually implementing the processes as planned in the previous phase. Then, in the third step, "Check", the implemented processes must be monitored and measured considering the previously defined OSH policy, and report the results. Finally, the last step, "Act", consists of taking actions to continually improve the OSH performance.

Organizations that adhere to this standard, and wish to demonstrate conformity to it, can do so by making a self-declaration, seeking confirmation by interested parties or by a party which is external to the organization, or seeking certification by an external organization.

2.5.1 Scope of ISO 45001

The guidelines inside ISO 45001 can be implemented by any organization that wants to establish and successively maintain an OSH management system. This standard can be helpful for any organization regardless of its size, type and activities since in designing an OSH management system it takes into consideration the context in which the organization operates and what the workers and other interested parties expect from the organization itself.

Moreover, this standard does not state specific criteria that must be implemented nor it is prescriptive about the design of the management system. It is just a combination of guidelines to assist organizations in the development of a proper OSH management system to protect the health and safety of workers, as well as their wellness. It does not prescribe anything about product safety, proprietary damage or environmental impact, it just focuses on the elimination of risk for workers. The requirements listed in the ISO 45001 can be used all or just a part, however, if an organization want to claim compliance with the standard it must implement all of them.

Meanings of terms used in ISO 45001

When talking about ISO 45001 and the development of an OSH management system, some terms are being used with a specific meaning to them in this peculiar context. The receiver of this standard is the organization, which here is interpreted as a person or group of people that has its functions with responsibilities, authorities, and relationships to achieve its objectives. Their purpose is to develop and implement an OSH management system used to achieve the OSH policy, which is a plan to prevent work-related injuries and hill health to workers and to provide safe and healthy workplaces. In the policy, the organization sets some specific OSH objectives to achieve specific results consistent with the OSH policy itself. The design of this management system is carried out to protect the worker, intended as the person performing work or work-related activities that are under the control of the organization, and all the interested parties, which are the people or organizations that can affect or be affected by a decision or activity of the organization. Both of them are required to participate and therefore have an involvement in decision making, and they must be consulted before making a decision. All of this relates to the workplace, which is the place under the control of the organization where a person needs to be or to go for work purposes. The OSH management system wants to protect the workers and all interested parties from OSH risks, which are defined as the combination of the likelihood of occurrence of a work-related hazardous event and the severity of injury and ill health that that event can cause.

2.5.2 Understanding the organization, its context and the role of all the interested parties involved

Establishing, implementing and maintaining an OSH management system is of the utmost importance, and to do that an organization, as the first thing, must understand its context and any external and internal issues that are relevant to its final goal, and how they would affect the ability to achieve the intended purpose. Internal and external issues can be positive or negative and include all those conditions, characteristics, and circumstances that can influence the OSH monitoring system. External issues comprehend any social, cultural, financial, political, legal and technological issue, and the competition in the organization's relevant market (including the introduction of new competitors, new technologies and new laws). Moreover, other external factors that could impact the OSH monitoring system consist of key drivers or trends which are relevant to the organization's industry or sector, as well as the relationships with external interested parties. Regarding the internal issues, instead, it comes into play policies, objectives and strategies to achieve organizational structures, and governance of the organization. Additionally, the capabilities (intended like resources, knowledge and competence of the human capital) and the products, materials, tools, software and information systems in the organization. Lastly, the relationship with workers, comprehending also the culture of the organization. Moreover, it is important that the organization preemptively determine and understand the relevant needs and expectations of workers and other interested parties (e.g., legal authorities, workers' representatives ...). Some of these are mandatory, since they may have been incorporated into regulations, or the organization could voluntarily agree to adopt some, which are specific to their establishment. Considering all that, the organization must determine the scope of the OSH management system, bearing in mind external and internal issues, and eventual additional requirements. The must be a "*factual and representative statement*" of the organization's operations included in the OSH management system, developed in a way to avoid misinterpretation from the interested parties.

During the adoption of a OSH management system, the top management of the organization plays a crucial role. The people that make up the top management have specific responsibilities and accountability for the prevention of work-related injuries, and for ensuring that the OSH policy is effectively implemented in the organization's processes and that it is compatible with the strategic direction of the organization. Additionally, they have to make sure that enough resources are available to pursue OSH objectives. The most important thing the top management is responsible for, is the promotion of a culture that supports the identification and elimination of health and safety hazards. The culture should be characterized (even though not limited to) by the active participation of workers, cooperation and communication founded on mutual trust. The top management is the one that outlines the principles in the OSH policy, which is needed to give a sense of direction as well as to set up a framework to follow. In the development of the OSH management system, every person involved in it must have a clear understanding of their role, and responsibilities. The responsibility to check the conformity to the requirement of the ISO and the reporting of the performance can be assigned to others, however, the responsibility for the functioning of the OSH management system is still of the management. During all these phases, the top management has to prioritize and continuously maintain a process for consultation and participation of workers, in order to allow them to contribute to the decision-making process. Feedback on the OSH management system and potentially hazardous situations need to be encouraged, whilst making sure that those who report are protected from reprisals, such as the threat of dismissal.

2.5.3 Planning an OSH management system

During the design and development of the OSH management system, the organization must identify the potential hazards and risks. It is not a single event, but it is an ongoing process, which has to dynamically and continually determine risks, trying to anticipate potential dangers. The processes used to identify hazards must take into account how the work is organized (workload, work hours ...), routine and non-routine activities, past relevant incidents and potential emergencies. Additionally, it must be considered the design of the work areas and the machinery and equipment employed, as well as the situations that could have an impact on the organization that are occurring in the vicinity of the workplace, both under the control of the organization or not. Notably, the design of a OSH management system must take into account the various people that come into contact with the workplace, both those who are employed in the organization and those that due to vicinity to the workplace could be affected by dangerous situations. An organization can use different methods to assess the potential risks. Still, they can not depend on the size of the organization, but on the hazards that the organization can be subject to. Nonetheless, the planned actions should involve the identification of risks and opportunities and possible legal requirements, and the preparation of action to respond to emergency situations. When planning on how to achieve the intended outcome, is mandatory that the organization determine what should be done, the resources required, who will be responsible, and how the results will be evaluated. These OSH objectives have to be consistent, measurable, and communicated and updated regularly.

Other important considerations that the organization must account for, in the developing of the OSH management system, are the competence of workers, whether their knowledge and skills are appropriate for identifying hazards or taking action to minimize the risks, plus their awareness to the OSH risks that they are exposed to, and their ability to remove themselves from situations that could endanger their lives. Moreover, is crucial to implement a communication system through which the organization can communicate information relevant to the OSH management system to both workers (internal communication) and all interested parties (external communication).

In the end, operational planning and control of processes must be made. This can consist of the establishment of criteria for the processes, for instance, the use of specific procedures, and in accordance the implementation of a control system which can comprise preventive maintenance and inspection programmes. It is required to also pay attention to the adaptation of work to workers, through the redefinition of how the work is organized and which processes are used, as well as the implementation of ergonomic approaches in the designing of workplaces and equipment. The organization must also establish a procedure through which to manage possible and future changes in products and services or legal requirements since changes could potentially introduce new risks. In alignment with this, the organization also need to elaborate an action plan to deal with potential emergencies through the formulation of a planned response and training for those who could be involved. Another important process, to which the organization must pay attention, is the procurement process to eliminate the risk of introducing workplace equipment and materials that could present a risk, and delineate guidelines to make sure that all is delivered and assembled according to their specifications. To this aim, the organization have to be sure that the requirements of its own OSH policy are met by contractors (i.e. external providers) and their workers. This can be achieved through the stipulation of contracts which clearly define the responsibilities of all the parties involved.

2.5.4 Evaluating the performance of a OSH management system

When the OSH management system is fully operational is of the utmost importance that it is continuously monitored and controlled, to ensure that the system is working, and is suitable for achieving the previously established objectives for the safety and health of workers. Therefore, the organization must determine what needs to be monitored, the frequency with which the monitoring will be carried out, as well as the methods and criteria to evaluate the performance. Examples of what could be monitored are the health of workers and the work environment, work-related incidents, injuries and ill health, and the effectiveness of operational control and emergency exercises. Instead, the frequency and timing of evaluations can vary depending on the importance of the requirement, the organization's past performance, and changes in legal requirements. Additionally, the organization must conduct internal audits at planned intervals to verify that the OSH management system complies with the organization's own requirements and the requirements of ISO 45001 and that it is effectively implemented and maintained. The extent of the audit has to be based on the complexity and maturity level of the OSH management system of the organization. The impartiality of the audit can be achieved by separating the auditor's roles from their normal assigned duties, or the organization can use external people. In addition to these checks, even the top management is responsible for monitoring, at planned intervals, to ensure the continuing stability, adequacy and effectiveness of the OSH management system, and to identify any need for changes. The relevant results need then to be communicated to workers.

The organization must always search for opportunities for improvements. For instance, when an incident or a nonconformity occurs the organization must, apart from reacting promptly and successfully dealing with the consequences, evaluate the need for corrective actions to try and eliminate the root causes of the incident to prevent it from happening again. This root analysis consists of exploring all the possible factors associated with the accident by asking what happened, how it happened, and why it happened. The focus of this examination is prevention. Finally, ISO 45001 prescribes that the organization have to continuously improve the effectiveness and suitability of the OSH management system by enhancing OSH performances, promoting a culture focused on safeguarding the safety and health of workers and encouraging the participation of workers in the continual improvement of the OSH management system. Improvement may consist of the adoption of new technologies or good practices, as well as the adoption of suggestions and recommendations from interested parties. Moreover, advancement could be signalled by new knowledge and understanding of occupational health and safety-related issues, new or improved materials, and changes in workers' capabilities or competence.

3

Technologies for digital occupational safety and health monitoring

3.1 How new technologies are shaping the workplace

The development of digital technologies like AI, robots, the IoT and big data, wearables, and mobile devices offer the potential for important changes in the workplace, regarding the location, who is working and when, and how work is organized and managed. Digital technologies provide essential services to all sectors of our economy and society, which leads to new challenges and concerns regarding OSH and its management.

Some applications of these new technologies brought by the increasing digitalization of the workplace are, for instance, collaborative and smart robots (also called cobots), specifically designed to interact and work together with the human worker in the shared workspace. Most of these cobots are provided with self-optimising algorithms, which allow them to learn from their human colleagues. Moreover, with the increasing use of AI, most of them will also be able to perform various cognitive tasks autonomously, making them useful in many sectors, such as hospitality, agriculture, industry, transport and services. Robotics allow also for the removal of workers from hazardous situations and the enhancement of the quality of work since repetitive tasks are handed to fast, accurate and tireless machines. AI plays an important role in the monitoring of workers, and not only their productivity but also their location, their vital signs or stress indicators, which are fundamental to establishing an OSH system which is effective and attentive to workers' needs. Another implementation of these new technologies in the workplace is exoskeletons, which are external supportive structures worn by workers to help them carry out manual tasks, alleviating physical strain and enhancing productivity. They could also be used in assisting workers with musculoskeletal disorders allowing them to work. Likewise, PPE, specialized clothing worn by workers to protect themselves, can be of great help in the real-time monitoring of hazards and the prompt detection of harmful exposures. The data that they collect can be used later on by organizations to help in the prediction of potential OSH problems. VR and AR are other applications of technology for OSH, offering the advantage of removing workers from hazardous environments while allowing them to perform the task, without the need to be physically present in those environments. They can be also helpful in supporting maintenance tasks and providing immersive training in a safe space [19].

In this chapter, I will analyze more in-depth some applications of digital OSH monitoring systems: wearables devices, IIoT, drones, and collision avoidance and warning systems.

3.2 Wearable devices used for occupational safety and health

Wearables are electronic components or computers that are designed to be worn directly on the human body, and they can take various forms, such as accessories, jewellery, and elements of clothing. Their application and implementation can be found in almost every industry, from agriculture to construction, mining, production, and healthcare, as well as the use that every one of us can make of them in our everyday lives. Wearable devices provide continuous monitoring of the person wearing them and the environment around them, without the need for the constant intervention of a professional. The information that the wearable sensor acquires is in real-time, which is essential for time-critical situations and emergencies. Moreover, the obtained data is often sent to a server or another device (e.g. a smartphone application), which allows for remote monitoring and analysis [20]. In the context of workplace safety wearables can be employed for safe lifting, ergonomics, hazard identification, fatigue management, work postures, and rest breaks.

3.2.1 Occupational exoskeletons

Manual Material Handling (MMH) is the process of regularly moving and handling objects by carrying, holding, lifting, pulling, pushing, and stooping and workers across various industries can perform it. This activity is one of the main causes for Work-Related Musculoskeletal Disorders (WRMSDs), which are impairments of bodily structures such as muscles, joints, tendons, ligaments, nerves, and cartilage (e.g. Carpal Tunnel Syndrome, Tendonitis). WRMSDs are the most common work-related health problems in the European Union since they concern workers in all sectors and occupations (3.1). Not only do they have adverse effects on the worker, but they also lead to higher costs to enterprises and society, since when workers are affected by these disorders, in the worst cases, they cannot work anymore and they must retire [21]. Thanks to the progress of technology, many heavy tasks have been mechanically automated, however, some of these cannot be replaced by automation [22].

In this context, exoskeletons may offer many possibilities to improve working conditions and help prevent WRMSDS. Exoskeletons can be defined as personal assistance systems that mechanically affect the body, and can be classified as active or passive systems. There are many possible applications of exoskeletons, but in recent years there's been an increasing interest in employing

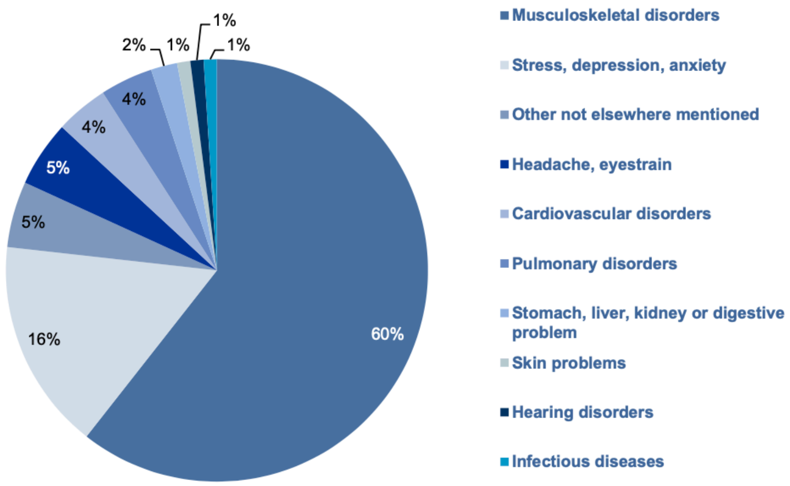

Figure 3.1: Percentage of workers reporting a work-related health problem, by type of problem [21].

exoskeletons to reduce the physical load on workers [16]. Used in this way exoskeletons are referred to as occupational exoskeletons, which can be classified into three groups: lower, upper and full-body exoskeletons. Back-support exoskeletons are the most widespread and are built around the concept of forces applied in the sagittal plane (which divides the body into left and right), between the user's torso and thighs, to assist with extension of the back and/or hip joints. They are designed to reduce the activity required of the para-spinal muscles [23].

An exoskeleton generates assistive forces using either passive or active (or powered) components. Passive exoskeletons employ springs or other mechanical elements and do not introduce additional energy from external sources. They rely on the energy generated by the user's movements, storing it and releasing it to assist in movements and reduce the effort required by the worker. Existing passive back-support exoskeletons employ different types of elastic elements, for instance, coil springs, rotational springs and integrated gas springs (3.2).

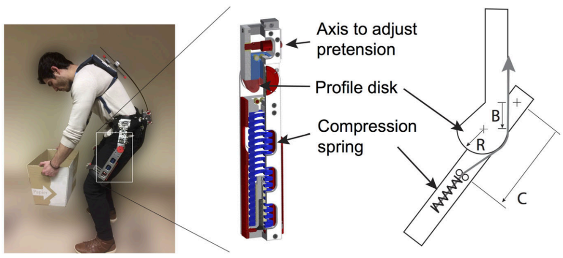

Figure 3.2: Picture of the spring-based, passive actuator on the SPEXOR prototype [23].

Also, elastic bands and flexible beams can be integrated into these wearables. It is important to note, that all these details must be decided at the design stage, with little possibility for a later-on adjustment or change.

Active exoskeletons, on the other hand, incorporate actuators and have the ability to introduce additional energy from external sources (3.3).

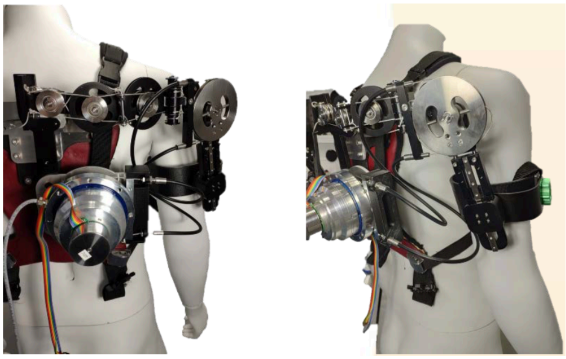

Figure 3.3: Example of occupational upper active exoskeleton [16].

The actuator's actions are controlled by a computer program based on sensor information, and for this reason, they are considered more versatile than passive exoskeletons (even though the latter are most frequently adopted). Most active exoskeletons use electric motors, but in some also pneumatic actuation is employed. Electric motors are used in combination with reduction gears to achieve the necessary forces. Another possible approach is to use electromagnetic clutches which are capable of decoupling the actuator from the exoskeleton when no assistance in motion is necessary. This allows for a reduction of energy consumption leading to the concept of quasi-passive or semi-active devices where the coupling/decoupling could be modulated automatically during operation. Finally, some active exoskeletons are powered by onboard batteries, which makes them more free to move. However, it must be kept in mind that batteries contribute to the total mass of the device, which can not be too heavy to avoid discomfort for the user. Summing up, passive exoskeletons are more appropriate for use in tasks that demand light to moderate assistance, while active exoskeletons are most suitable for demanding and dynamic tasks since are more versatile and are suited to provide stronger assistance.

The forces used in exoskeletons may be applied to the user in different ways. The direction of the assistive forces in back-supporting exoskeletons can be either parallel or perpendicular to the body segments. However, a force parallel to the spine could contribute to internal spine loading, which is a compression from within on the intervertebral discs, whereas a perpendicular force does not present this drawback. Exoskeletons can be soft or rigid. The former ones do not have a rigid structure and they consist of devices which are garments worn on body parts adjacent to the joint that is assisted (e.g., for a knee exosuit the garments will have to be worn on the thigh and the shank). The movement that provides assistance is created by the tension created by a cable or a strap pulling the two body segments covered by the garments together, generating a parallel force. These forces are usually situated rather close to the user's body, making it possible to wear the exoskeleton underneath clothes. On the other hand, rigid exoskeletons are built with rigid structures that run in parallel with the body and apply perpendicular forces to them (3.4). Exoskeletons can also combine soft and rigid components, and in these structures,

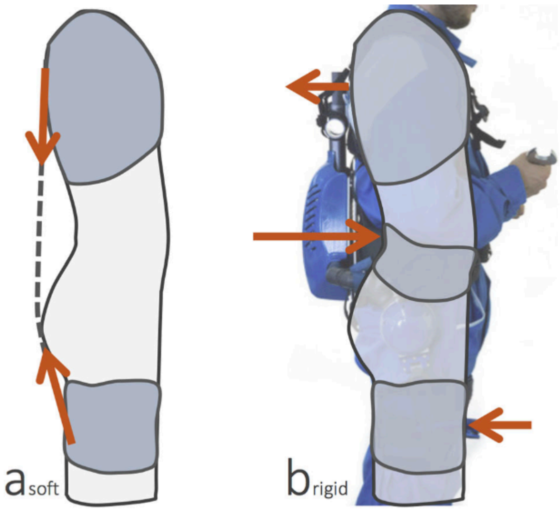

Figure 3.4: (a) An illustration of the principle of a soft exoskeleton; red arrows indicate the forces applied on the user, parallel to the trunk and thighs. (b) An example of a rigid exoskeleton: red arrows indicate forces applied on the user, perpendicular to the trunk and thighs.

despite the absence of a completely rigid structure, the intervertebral compression force is reduced (which is the main problem of soft structures). An important issue regarding rigid exoskeletons is the coupling of the articulated structure with the human joints, trying to make them kinematic compatible. The misalignment of the human and the artificial joints could create undesirable forces that could potentially disrupt the user's comfort. To avoid that two main approaches have been proposed. The first approach consists of aligning the exoskeleton's joint with the corresponding anatomical joints. However, a challenge arises since even though initially aligned, migration of the exoskeleton over time can lead to undesired interaction forces. Meanwhile, the second approach consists of allowing a certain amount of misalignment between the exoskeleton and the users, but at the same time incorporating additional kinematic structures (such as joints, sliders, and elastic elements). These additional elements ensure that there is minimal or no relative movement at the points where the exoskeleton interacts with the user's body.

The assistive action provided by the active exoskeleton can be modulated by control strategies, which allow the translation of user intent into specific patterns of assistance, thereby ensuring that the exoskeleton provides optimal support to the user. On the contrary, passive exoskeletons have no means of autonomously adapting to user intent while it is working. The concept of "*following user intent*", which is the ability of the user to move freely and as intended while experiencing assistive forces with appropriate timing and extent, is still an open challenge, particularly acquiring meaningful information about the user's intent. To gain information about the user intent, some form of sensor information is necessary. However, relying only on physical sensors can have limitations in occupational settings since they could impede movement or cause discomfort. To address this challenge two approaches are used. The first one is indirect control which relies on the measurements obtained from the exoskeleton device itself or from the environment in which it operates (e.g., joint motions or interaction forces). The second approach, called direct control involves capturing volitional information directly from the user (e.g., biosignals such as electromyography). Each approach has its advantages and limitations. One thing to always keep in mind while designing these solutions is the fact that the more integrated sensors are into exoskeletons, the better their use will be in application scenarios. Whatever the level and function of a control strategy the user needs to perceive the overall behavior of the device as smooth, responsive, and intuitive.

To conclude, the adoption of an exoskeleton will ultimately depend on user acceptance, which is determined by whether the worker feels hindered during work while wearing the exoskeleton.

3.3 Industrial Internet of Things used for occupational safety and health

IoT involves ubiquitous internet connectivity, which converts everyday objects into interconnected devices. The main idea behind it is to use a vast number of smart objects which are capable of sensing their environment, transmitting and processing data, and then responding accordingly. As a subset of IoT, IIoT, covers the domain of Machine-to-Machine (M2M) and industrial communication. It connects industrial assets, such as machines and control systems, to information systems and business processes. Consequently, a huge amount of data is collected, which is useful for implementing data-driven analytics to enhance industrial operations. IIoT influences the entire industrial value chain and it is crucial for implementing smart manufacturing strategies. IIoT applications encompass legacy monitoring applications, which refer to traditional or existing methods of monitoring systems and processes (e.g., process monitoring in production plants) as well as innovative approaches for self-organizing systems (e.g., autonomic industrial plants requiring minimal human intervention) [24]. IIoT innovations have led to solutions like smart sensors and devices that are capable of continuously monitoring workplace surroundings and infrastructure. These devices include hazardous material sensors that assess the levels of toxic gases, and equipment monitoring devices that capture various machine parameters that indicate the equipment's condition. This kind of monitoring is essential in vast and potentially dangerous workplaces, like a factory or a mine, where usually monitoring is a challenge. This workplace safety trend provides real-time data that allows safety engineers and managers to rapidly identify any issues that might lead to a potential hazard.

3.3.1 Wireless sensor network for environmental monitoring in underground coal mines

The production, productivity and safety of underground coal mines are deeply dependent on the environmental conditions of the mines. Coal mining operations are inherently associated with the generation of various poisonous and inflammable gases (e.g., hydrogen sulfide, carbon dioxide, methane, etc.). Moreover, coal and ignition firedamp (mixture of methane gas and air) could spontaneously combust, leading to mine fires and explosions. It must also be noted, that near-surface coal is getting rapidly exhausted, and to extract more coal, the underground mining activities are moving towards the deeper horizons of the earth. This will lead to worse environmental conditions in mines since the deeper you go the ventilation gets worse and an even larger amount of heat, humidity and poisonous and explosive gases are produced. Additionally, to meet the increasing demand for coal production a high level of mechanization is adopted, which only further deteriorates the environmental condition of mines. For this reason, continuous monitoring is crucial to ensure safe and healthy working environments for the miners. To this aim, data loggers, which is an instrument that monitors and records changes in conditions over time, are employed. However, they do not provide high spatial and temporal resolution, since they work offline. Therefore, online monitoring was adopted, even though initially these systems used wired communication, which suffered from many shortcomings (e.g., damaging of communication cables, inconvenient system maintenance, etc.). For this reason, systems that employ online monitoring of underground coal mines using WSNs are being adopted. As a result, Wireless Underground Sensor Network (WUSN) has emerged as a fundamental technology for continuous monitoring of workplace environments in underground coal mines. It can be realized by deploying sensor nodes in appropriate locations of mines to collect environmental data and to detect the occurrence of possible hazards like fires, explosions and roof failures in mines (3.5) [25].

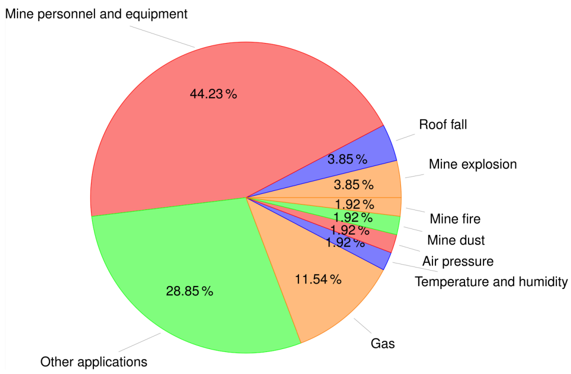

Figure 3.5: Percentage of WSN techniques explored in underground mines [25].

Gas monitoring

The underground coal mine environment is characterized by higher levels of impurities compared to normal atmospheric air. Despite this, it still contains sufficient oxygen to support human survival and allow combustion processes. Some of the impurities found in mines were: non-toxic but explosive gasses, toxic gasses, and acutely poisonous gases. Understanding and managing these impurities is critical for ensuring the safety and health of mine personnel working in underground coal mines. Several studies have explored different techniques and systems for gas monitoring in underground coal mines. Some systems use ZigBee sensor nodes applied to coal faces (i.e. the exposed area of a coal deposit where coal is actively being extracted) which collect data regarding gas levels, and other environmental conditions relevant to mining operations. Due to the unique characteristics of coal faces, a specific topology for the wireless sensor network is adopted. This approach combines the advantages of ZigBee technology with a specialized WSN topology and route selection algorithm to create an efficient monitoring system for underground mines [26]. Another implementation uses the WSN and ambient intelligence technology to build an integrated mine network (3.6). It aims to facilitate the monitoring of toxic gases within restricted areas by using a set of well-defined nodes. This framework is structured as a reactive system, meaning it responds dynamically to changes in its environment or inputs. The system is divided into three major nodes, each with specific functions. The first node is the sensor publisher node, responsible for collecting gas data from different regions of the monitored environment. Gas calibration nodes, on the other hand, adjust sensor readings by calibrating them, providing more precise and reliable measurements. Finally, the ambient intelligence node analyzes the data to identify patterns or anomalies that could indicate the presence of toxic gases, and provide support in the decision-making process of safety officers [27].

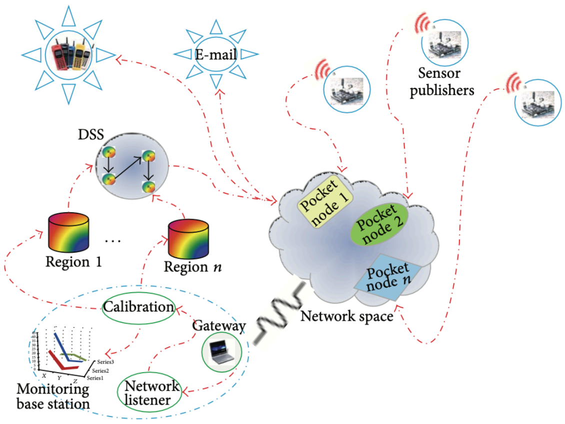

Figure 3.6: Gas monitoring framework using WSN and ambient intelligence technology [27].

3.4 Drones used for occupational safety and health in the construction industry

While sensors can provide valuable data and alerts, they may not always capture all the potential hazards. Visual inspection allows for a more comprehensive assessment ensuring that assets are operating within safety codes and standards. To this aim, small drones can be employed. A small drone can be defined as a Remotely Piloted Aircraft System (RPAS) or Unmanned Aircraft System (UAS) with a maximum weight of 25 kg (including batteries, or fuel). The weight limit is important since in this way they can be operated in many countries without the need for a flight permit from the aviation authorities [28]. They can be used for various purposes, especially in the construction industry. One of the first implementations that these systems may have is monitoring. The drones can be integrated with visible/IR cameras and other sensor payloads, to execute autonomous inspections in complex and dangerous environments. This allows for remote inspections of assets and infrastructure without exposing the employees to potentially hazardous environments. Moreover, a UAS could be an ideal safety inspection assistant, providing a safety manager with real-time access to videos or images around the job site. It could also be integrated with voice communication capabilities to allow safety operators to speak with workers and warn them about unseen hazards they may be exposed to [29].

Another use for drones in the context of OSH is gas sensing, thanks to gas detectors specifically designed to be incorporated into drone applications. The drones could be flown in hazardous premises to sense the quality of air and send a warning if the zone is too dangerous to be in, without needing a physical person to go and check. To this aim, low-cost chemical sensors (3.7), which are miniaturized devices providing real-time outputs reflecting the concentration of gasses and volatile organic compounds that came in contact with the sensor, can be employed. Their minimal size, low weight, and low power requirements make them easily integrated with drones. Among the various low-cost gas-sensing technologies, the most popular ones for drone applications are amperometric gas sensors (AGS), metal oxide semiconductors (MOX), and photoionization detectors (PIDs).

Figure 3.7: Examples of low-cost chemical sensors. (From left to right) MOX sensor (Model: Figaro TGS 8100); AGS sensor (Model: Alphasense CO-AF); PID (Model: RAE Systems PID 10.6 eV) [28].

The quality of the measurement acquired by a board chemical instrument depends on where they are placed on the drone and the type of drone used. If a rotary-wing drone is used, often employed since it is optimal even for thigh spaces, it is crucial to consider the airflow generated by the rotor blades (called downwash). The downwash can disrupt the airflow around sensors which are mounted on the one, affecting the accuracy of measurements. One method involves extending a boom from the drone's frame and placing the sensor at a distance from the rotors. However, booms are aerodynamically inefficient and could lead to instability of the drone, displacing its centre of gravity. Another approach is to use a pumped system with an inlet placed away from the drone's main body. This system involves keeping air away from the drone's body, using a pump, to ensure that the air sampled by the sensors is unperturbed. But, with time it can lead to contamination of future measurements due to adsorption processes on the inner walls of the tubing. For simplicity, many research prototypes mount the payload in a central position below or above the drone's fuselage (3.8). Drones equipped with chemical sensors can also be used in the early detection of fires.

Other scenarios where drones could be applicable include locating unconscious workers, or

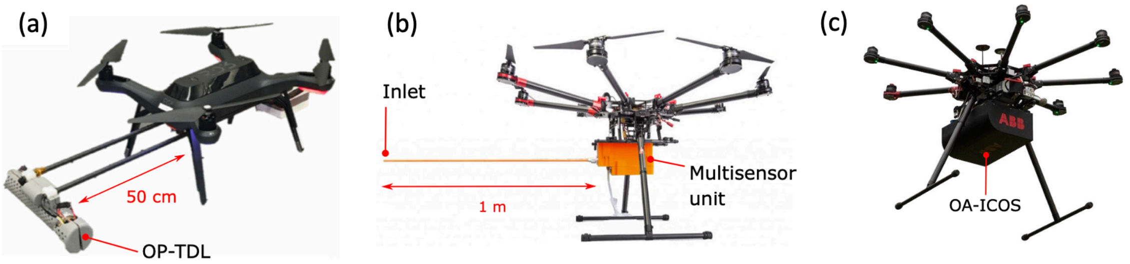

Figure 3.8: Integration of chemical instrumentation into RW drones. (a) an example of a protruding boom. (b) and example of pumped systems with horizontal/vertical inlets. (c) an example of bottom mount

workers trapped after an earthquake or an explosion. In these situations, rescue teams usually utilize trained dogs to search for victims, and these resources could be implemented with drones with cameras. Such drones would expand the possibilities for emergency crews, who could fly the drone throughout indoor spaces, overcoming obstacles and making the search smoother and quicker [28].

3.5 Collision avoidance and warning systems for occupational safety and health

In the mining sector, accidents involving powered haulage are one of the first safety concerns, since they account for most of the fatalities each year. Powered haulage encompasses a wide range of equipment used in mining operations, including rail cars, conveyor belts, belt feeders, service trucks, and haulage trucks. However, mobile equipment such as service trucks, haul trucks, and front-end loaders are the prevalent ones in incidents [30]. CXS technologies could be used to prevent and reduce the risk of powered haulage collisions at mine sites. Data shows that 21 incidents, from 2003 to 2018, resulting in 23 fatalities could have been prevented by CXS technology [31]. CXSs are technological systems employed to detect objects, warn operators, and/or automatically take action to prevent and mitigate collision accidents involving mobile equipment. In mining operations, CXSs are usually installed on powered haulage equipment, like haul trucks, which operations carry a significant risk of collision with vehicles or people who are in the same environment. Most commercially available CXS are designed to focus on detecting objects surrounding the vehicle, particularly in blind spots, to alert both the vehicle operator and other workers potentially at risk. Some of these systems operate independently, relying only on data from sensors integrated into the vehicle, while others establish communication channels between the host vehicle and other connected devices, vehicles, and infrastructure. Systems that communicate with other devices are commonly referred to as Vehicle-to-Everything (VSX) systems. These systems may incorporate different technologies in the same device. Some technologies that could be used are RADAR or Light Detection and Ranging (LiDAR) sensors. Other CXSs employ electromagnetic or radio frequency tags, which utilize received signal strength between a transmitter and a receiver (mounted on different vehicles or worn by people) to determine the distance between the two. CXSs are primarily designed to address situations where there is a loss of awareness regarding potential hazards which could lead to harmful interactions between vehicles, personnel, and the surrounding environment. However, it's crucial to recognize that technology alone cannot entirely eliminate the risk of collisions [32].

3.5.1 Radar-based collision avoidance/warning systems

One technology that can help in warning the equipment operator that there is an obstacle nearby, preventing collision, is radar. The most common accidents involving collisions with mining or construction equipment involve pedestrian workers or smaller passenger vehicles. A radar system should be able to detect these two entities [33]. Typically, in radar systems, the radio signal travels outward and is reflected off of objects that are within their path. A portion of this reflected energy returns to the radar's receive antenna. By analyzing the characteristics of the returned signals, such as their amplitude, frequency, or time delay, the radar system can detect the presence and location of objects in its vicinity. Radar typically operates in the microwave region of the electromagnetic spectrum—measured in hertz (cycles per second), at frequencies extending from about 400 megahertz (MHz) to 40 gigahertz (GHz). To detect people or vehicles, usually, two types of radar are employed: Doppler Radar and Pulsed or Ultra-Wideband (UWB) radar. The first one detects the relative motion of objects and it relies on the Doppler effect which is the change in the frequency of a wave in relation to an observer who is moving relative to the source of the wave. It is a radar which is effective for detecting moving objects. On the other hand, UWB radar, detects objects by measuring the time it takes for the pulses of radio waves it sends, to travel to the object and back. By measuring the time of flight the distance from the object can be estimated. The detention range of these types of systems can vary, going from less than a meter to over 30 meters. The wideness of this range is dependent on various aspects, such as the power of the radar system, the frequency used, the characteristics of the environment, and the size and material of the detected objects. In areas where wider detection is needed, multiple antennas may be employed to provide full coverage. By strategically placing multiple antennas, the radar system can ensure comprehensive monitoring of the surrounding environment [34].

An example of a radar system is the Preview Heavy Duty Radar, developed for off-highway earth-moving machinery. This system used pulsed radar and time-of-flight signal measurements to sense the presence of an object and its distance. Inside the machine, a display is mounted that provides both audible and visible warnings. It alerts the driver through a series of LED lights that light up in succession, and the warning sound changes frequency the closer you get to the object or the worker. This system utilizes multiple antennas networked to a single alarm display, which was placed near the operator's seat, allowing for better monitoring of the blind spots at the front and rear of the equipment. Moreover, a camera system is installed to provide also a visual check of the front and rear blind areas. The camera automatically switches between front and rear depending on if the vehicle is moving forward or if it is in reverse gear. Finally, for the installation of the antennas, two are mounted on the truck's rear axle and two on the front bumper. Furthermore, the rear antennas were angled towards each other to cover a wider area [34].

3.5.2 Bluethooth-based collision avoidance/warning systems

To avoid collisions between heavy machinery and workers who are moving in the same space Bluetooth devices can be used. These devices, through a signal, could warn the driver of the heavy machinery also through visuals and haptic signals. In the work of Garcia-Carrillo et al. [35] an ad-hoc collision avoidance system, using Bluetooth is developed. It is a proposal that aims to provide information about their surroundings and nearby workers to drivers of machines which operate in warehouses and similar indoor locations, where there is movement of different machinery and workers on foot. Bluetooth was chosen because of its reliability and affordability. The design aims to have an affordable and scalable deployment and to be a standalone solution, without the need for a support infrastructure. Moreover, it also takes into consideration the peculiar driving experience, which requires an extreme level of focus and accuracy from the driver. For this reason, it provides a simple yet meaningful feedback system and aims to a reduction of the cognitive load of the driver. This proposal comprises four elements: 1) the beacon emitters, 2) the detectors, 3)the Advanced Driver Assistance System (ADAS) engine, and 4) the Informational element of the feedback system (i.e., LED strip and haptic feedback system) (3.9).

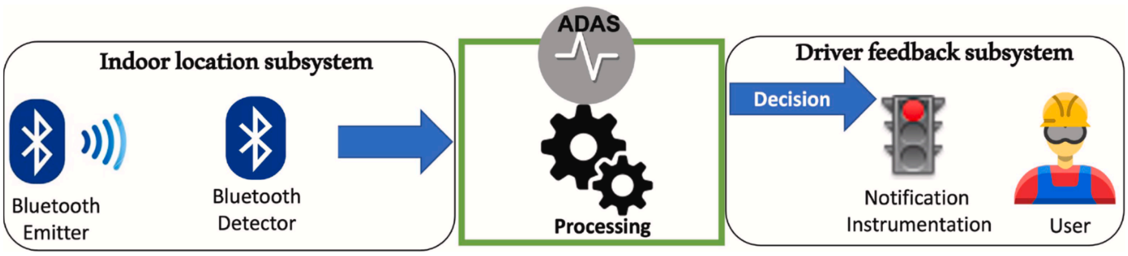

Figure 3.9: Ad-hoc location system architecture

Here is how it works. Each worker carries an emitter Bluetooth device that sends regular beacon messages. This device can be placed, for instance, on the hard hat. The Bluetooth detector systems installed on the heavy machinery (e.g., a forklift) receive these beacons. Every machine will have two detectors, one on each side. This information is gathered by a ADAS, which estimates the distance of the workers and emits an LED light. This light, coming from an LED strip, comes in two colours: amber and red (3.10). The amber-colored strip will be used when the worker is predicted to be close to the vehicle, and therefore the drivers should slow down and make sure the area is free before proceeding. The red-colored strip comes into play when the workers are too close and moving further could be dangerous, prompting the driver to stop. Moreover, a haptic feedback system is implemented and coupled with the red LED lights. When the situation could be hazardous the seatbelt will vibrate to improve the reaction time of drivers as re-enforcement. In this system, the accuracy of the location of each worker is not high, but it concentrates on issuing a warning about a nearby worker, rather than pinpointing its exact location. Additionally, it is a scalable approach, since we can add a Bluetooth receiver to each machine and make wear a Bluetooth emitter for each worker, so when a worker is near two machines both will receive a warning.

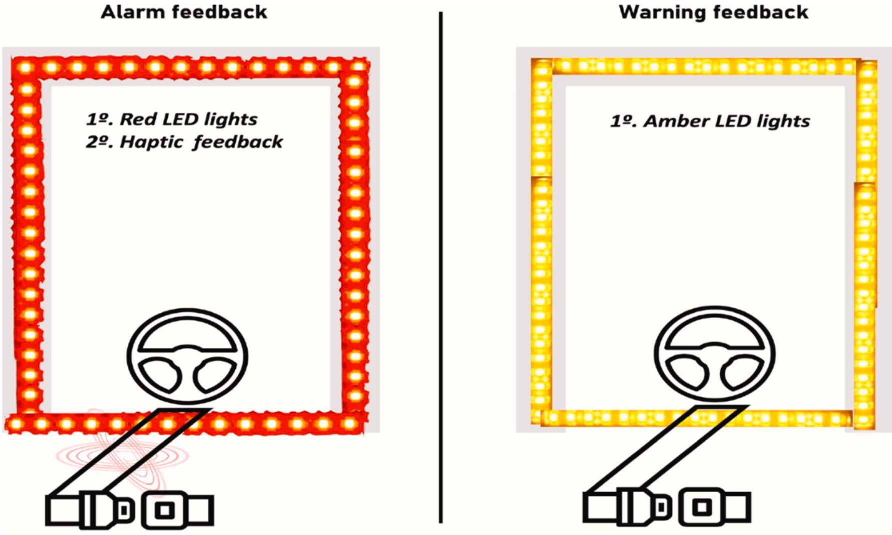

Figure 3.10: LED strips and haptic feedback system used to warn the driver.

4

Examples of organizations that adopt and produce digital monitoring systems for occupational safety and health

4.1 Organizations adopting digital monitoring systems for occupational safety and health

With the growing interest in OSH and the increasing digitalization in the workplace, many organizations have started to implement digital OSH monitoring systems. In this section, two organizations and their related digital systems to promote OSH will be explored. The first one is Enel, which is an Italian multinational energy company. It operates in the electricity generation and distribution, natural gas, and renewable energy sectors. The second organization is Amazon, a multinational technology company based in Seattle, Washington, USA. It started as an online marketplace for books but later expanded into other product categories.

4.1.1 Enel

Enel is committed to developing and promoting a safety culture in the organization to guarantee a safe workplace for every worker. The company follows and adopts various policies, among which the "Stop Work Policy" prescribes to company employees and personnel of contractor companies to intervene promptly and stop immediately their work if there are some signs it could endanger their own safety. Moreover, Enel has defined a "Health and Safety Policy", that requires every Group Business Line to have its own Health and Safety Management System in compliance with international standard ISO 45001. This Management System, beyond many other goals it sets, includes the adoption of technological tools, to support the assessment of the risk and its resulting mitigation. By following these policies, Enel was able to reduce the Total Recordable Injury Frequency Rate (TRIFR) which decreased by 21.3 % compared to 2021, with approximately 2.2 injury events for every million hours worked, as shown in the "Sustainability Report 2022" [36].

A variety of projects have been implemented by Enel, concerning digital OSH monitoring systems.

FIBA by Builti

Builti is an Italian startup and a Platform as a Service (PaaS) provider that effectively measures structural and infrastructural risk, tailored to each organization. This allows asset managers to make immediate decisions taking the best course of action given the situation. Builti's FIBA service solution provides knowledge of a building's risks without tearing it down, helping reduce carbon emissions. Moreover, risk assessment using FIBA reduces the time and cost of period assessments up to 80 % compared to traditional methods. Enel first used FIBA in 2019 to evaluate their buildings' seismic vulnerability. In 2022, a wider assessment started on various bridges that Enel manages. These infrastructures were built on average 70 years ago with the engineering criteria of the time, but they are used today by heavier vehicles. FIBA allow to assess the risk and the compliance to today's rules in order to then direct resources where needed [37].

Exoskeletons by Skelex

Skelex is a Dutch startup, which designs upper-body exoskeletons to protect industrial workers and enhance their capabilities. They aim to design solutions to empower humans in their working environment through the use of technology, and at the same time reduce work-related injuries. The inspiration was taken from the medical field where these kinds of tools are implemented to assist people who have lost the ability to move. Even though here the basic concept is the same, the purpose is completely different, since Skelex works with more of a mechanical and engineering approach. The Skelex exoskeletons are powered by FlexFrame Technology that supports biological movement of the shoulder joint and transfers weight to the lower body. This allows the structure to store and release energy intelligently to compensate for gravity and ensure the comfort of the user. They now offer four different models: Skelex 360-XFR, Skelex 360-Welding, Skelex Edge, and Skelex Neck Support [19]. They all have a simple structure that adapts to the user's body shape, allowing the worker to perform flexible movements of the entire body. These systems can be used in a variety of industries, from agriculture to defence. In particular, Skelex and Enel developed a project, in 2019, to test this technology with operators that work on maintaining the electricity grid, to deal with several risks concerning safety, such as heights and difficult positions that the worker adopts all while carrying heavy tools and materials [38] (4.1).

Safety jacket by D-Air Lab

D-Air Lab is an Italian startup, part of the Dainese group, that works on protecting the human body from risky scenarios. Originally, this project was developed for sports, such as motorcycling,

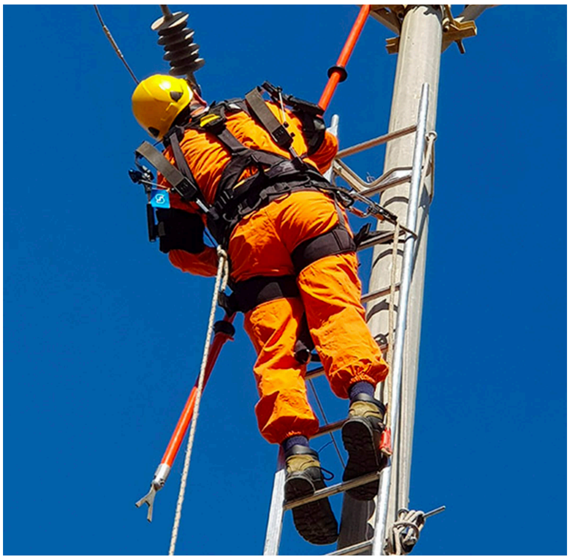

Figure 4.1: Skelex and Enel project to support workers in maintaining the electricity grid [38].

skiing and mountain biking. But, in 2016 the first prototype to protect workers who operate at heights, in collaboration with Enel, was designed. The safety jacket, called WorkAir (4.2), can be viewed as an airbag for the human body. It was developed specifically for operative personnel working in thermal power plants. By using this jacket, operators are ensured maximum protection in the event of a fall from a height of less than 2 meters when a harness is not required. It also protects for the effects of the pendulum impact when operators are working higher up and the use of a harness is mandatory [39]. WorkAir effectively protects the back and chest along with its vital organs. WorkAir, from the moment of recognizing the incident, inflates the bag in just 40 milliseconds. This system works thanks to its activation algorithm, which constantly analyzes data from the sensors of the built-in inertial platform to detect when the predicted accident conditions occur and send the activation signal [40].

Figure 4.2: WorkAir, a safety jacket to prevent injuries to workers working at heights [40].

4.1.2 Amazon

Amazon, with over 1.1 million workers across six continents, is particularly concerned about the safety and health of its employees. In these years many improvements in this area have been made. Their Recordable Incident Rate (RIR), which are all the work-related injuries requiring more than a basic first-aid treatment, has improved the 30 % over the past four years, with the progress of 8 % every year. Another impressive result is their Lost Time Incident Rate (LTIR), which are all the work-related injuries that require to take some time away from work to recover, has improved of the 60 % over the past four years, with a rise of 16 % in each year. Moreover, in 2024 alone, Amazon has allocated over $750 million to invest in programs, resources, training and technologies to enhance their safety efforts [41].

Amazon is particularly rigorous in auditing and inspecting its working sites to make sure that resources and protocols are effectively working and applied correctly. It is also important to determine the types of injuries. One of the most common ones is WRMSDs, which makes about 57 % of injuries at Amazon. To help prevent that the organization has invested in robotics that makes operations safer by reducing employee workload, and now 750000 robots are working in Amazon's facilities. One example is Proteus (4.3), which is an autonomous mobile robot, that helps move heavy objects and carts, and it is able to move and work together with human workers. Amazon is now pairing up Proteus with Cardinal, which is a robotic arm that can quickly select a single package, read its label, and autonomously sort it. By working together, Cardinal will load packages destined to the same zip codes into specific carts, that Proteus will then drive to delivery trucks. Both these innovations help reduce repetitive tasks reducing the risk to cause WRMSDs. Another robot which is being implemented is Sparrow, which is Amazon's latest robotic handling system. It picks and sorts customers' orders, taking on highly repetitive tasks. The latest innovation in Amazon consists of a new approach to inventory management and it is called Containerized Storage. It consists in using robots to deliver products to employees in a more ergonomically and friendly manner [42].

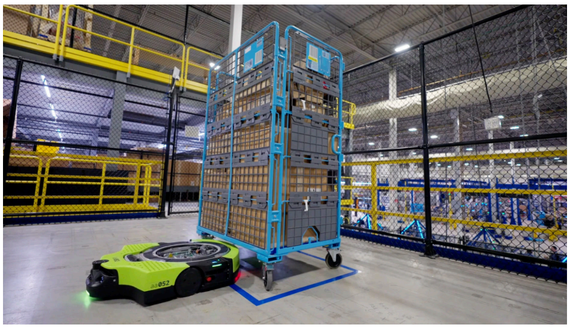

Figure 4.3: Amazon's robots Proteus [43].

4.2 Organizations producing digital monitoring systems for occupational safety and health

With the interest and the growing debate in the implementation of digital OSH monitoring systems by organizations, many startups have started to emerge. These startups design, produce and then sell their digital OSH monitoring systems to organizations that wish to implement an OSH policy. Many of them also provide specifically designed systems and solutions suited to each organisation's needs. The kind of solutions that they propose encompass various technologies from the most implemented ones like wearables to other solutions like AI, drones, robots, or immersive technologies. Two examples of startups providing these kinds of systems are described in the following sections.

4.2.1 Verve Motion

Verve Motion is an American startup born in Cambridge, Massachusetts. This project started in 2012 when they were awarded an initial Defense Advanced Research Projects Agency (DARPA) contract to develop exosuit technology. In the following years, the first successful tests were carried out till March 2020 when Verve Motion was officially launched. In May 2020 their SafeLift solution saw its first commercial deployment, indicating its successful development and market readiness. Their purpose is to power the human workplace through the use of people-centric robotics [44].

The solution that they designed is the SafeLift Exosuit, which is a soft and light exosuit to wear like a backpack. It is developed to take off of the worker's back 40 % of the weight he is lifting. The exosuit provides up to 240 N (newtons) of lift assistance force. Moreover, it allows users to move freely thanks to the breathable and flexible design which weighs only 6lbs (equivalent to approximately 2.72 kilograms). Additionally, the level of assistance is customizable to each user's need and task, ensuring in this way optimal support and comfort. It is a solution that requires minimal training and setup since it takes under 30 seconds to wear. The exosuit comes in different sizes, from XS to XXL and each suit regardless of the size has 8 points of adjustment which allow to customize the suit to allow for the right fit for each body. Additionally, the suit is equipped with 100Wh (Watt-hours) of battery life which allows it to sustain operations performed by the worker throughout the work shift and beyond. It must also be noted that the design of the exosuit is suitable for various types of environments, whether it is a confined warehouse space or an electric pallet jack. This allows users to perform their tasks with ease and without being hindered by physical constraints. This product is ready to be deployed also with dedicated locker storage, charging stations, and support kiosks to provide assistance to users. An important feature of this exosuit is the data collection which is securely transmitted via the Verve Logic cloud platform (4.4). On this platform, various metrics can be measured in real-time, such as number of lifts, how many hours the exosuit has been used, and the amount of weight that was offloaded. Moreover, it can automatically detect risky movements like excessive bending and twisting. This data which is collected during work hours is then useful to improve individual as well as group performances thanks to data-driven reports [45].

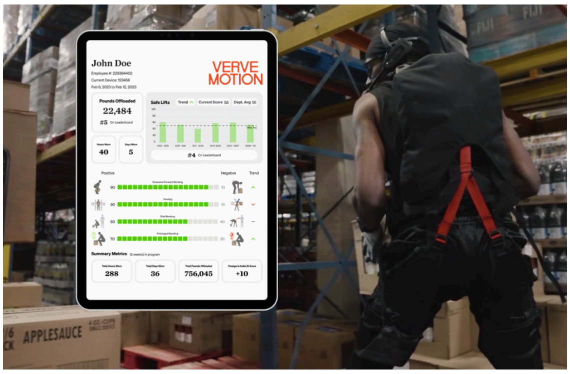

Figure 4.4: SafeLift exosuit by Verve Motion, with the related Verve Logic cloud platform[45].

4.2.2 VOS Systems

VOS Systems is a startup with its headquarters in Gainesville, Florida, and it was founded in 2020. Its platform CoRe (which stands for connected resources) enables the real-time flow of data from employees, equipment, tools, and assets to the analytics engine. To collect this data the platform uses 5G-enabled sensors. Moreover, the CoRe analytics platform is user-friendly and generates insight and data-driven results which can be analyzed and employed to ensure that safety protocols are met, maximize return on investment (ROI), and avoid economic and human losses due to unplanned failures. CoRe's IoT management platform is the first of its kind to provide complete project oversight in real-time in one convenient dashboard. Data is utilized to enhance safety, predict and plan future projects, lower project costs and much more. Industries that benefit from this system and have already successfully implemented CoRe are renewable energy, construction, oil and gas, and mining [46].

The CoRe platform is composed of various tools. First of all, a Personal Safety Device (PSD) is used (4.5), which is a sensor that each worker must carry during their work shift. It implements fall detection and movement detection. Apart from these key features it also provides location positioning of the worker through a combination of a Global Navigation Satellite System (GNSS) receiver, location beacons, and Wi-Fi, which ensures that the worker can be tracked even if underground. Moreover, it is interchangeable between employees since it employs a Near Field Communication (NFC) technology embedded in each worker's ID, to personalize the device as needed. All this could raise privacy concerns regarding the confidential data gathered for each worker. However, the system is specifically designed to protect the privacy of each user, since CoRe does not report data outside shift hours or outside the workplace. Moreover, the PSD is inactive unless it has been paired with a NFC ID card and the system already works by itself without any need for integration with personal phones. Another useful feature of PSD is that it is equipped with a temperature alarm if the user is in areas where the temperature could be dangerous, even though this alarm can be disabled by the user. An SOS button is also implemented, to be pressed by the worker in emergencies, where the PSD connects to the cloud server and sends the alarm together with the current position. This allows employees who work alone to feel safe knowing

Figure 4.5: Personal Safety Device for each worker by VOS Systems CoRe platform [47].

whenever they are if an emergency were to happen, reinforcement will be on their way. The PSD is also equipped with a piezo buzzer that can be triggered by the CoRe platform to alert the worker or a group of workers of potential danger. Additionally, this system is designed to provide a very high efficiency in terms of power consumption, with a battery life of 10 days, with a recharge time of 90 minutes using a micro-USB. Another piece of hardware which is being used is the CoRe equipment tracker for the organization's physical assets. It is equipped with 24/7 cellular connectivity to the Internet, highly accurate GPS location, speed and direction of travel, with precise geofence zones. It also records location and movement history. Regarding power consumption, it offers 36 to 96 hours of autonomy, even though it could be brought up to 12 months in custom applications [47].

5
Conclusion

Protecting the safety and health of each worker is a theme often discussed, particularly in recent times, due to its fundamental importance. Having the possibility to work while being safe is not a privilege, but a human right that should be respected in every working environment, ranging from low-risk office environments to high-hazard sectors like mining. Therefore, it is crucial to view OSH not only as a legal and regulatory imperative but also as a moral obligation to ensure the well-being of workers in all industries and sectors. Moreover, while investing in OSH introduces substantial initial costs for the implementation of safety measures, in the long term it actually reduces the overall expense and costs associated with poor management of working conditions. This thesis comprehensively explores the intersection of technology and OSH. The progress brought by digitalization reveals itself as an optimal tool for the advancement of systems to protect workers in their daily tasks. This convergence between OSH and technology is already a reality in many organizations including established companies like *Enel* and *Amazon*, as well as innovative startups such as *Verve Motion* and *VOS systems*.

Nevertheless, implementing an OSH management system is not always straightforward. While there are numerous advantages, organizations must contend with an equal number of obstacles and challenges. Organizations should not only provide a reactive approach to accidents, but they should also aim at having a proactive approach to managing potential hazards. Fostering a culture of safety is indispensable for organizations committed to investing in OSH since the effectiveness of these systems depends on the widespread acceptance among all workers, who initially may be reluctant to implement these new systems and protocols. To help manage these complexities, the standard ISO 45001 (the successor of OHSAS 18001) provides invaluable help. Providing only guidelines, without any legal implication or obligation, ISO 45001 allows for great flexibility, which allows each organization to create a OSH management system regardless of its size and type. This underlines the importance of tailoring OSH management systems to individual needs.

The advent of digital technologies ranging from AI and IoT to wearables and drones, has brought in a new era of OSH monitoring in the workplace. These technologies present unprecedented opportunities for enhancing workplace safety, efficiency, and productivity. Wearable devices provide real-time monitoring of workers' vital signs and environmental conditions, while exoskeletons alleviate physical strain and prevent WRMSDs. On the other hand, IIoT enables continuous monitoring of workplace environments, particularly in hazardous industries like mining, using WSNs. A practical application of WSNs consists of monitoring the gas present in mines to alert workers if the parameters are too dangerous to continue working there. Other applications are drones equipped with sensors and cameras enabling remote inspection of assets and infrastructure, as well as real-time monitoring of environmental conditions. Additionally, CXS, such as radar-based and Bluetooth-based systems, enhance safety in sectors like mining and construction by detecting and preventing collisions between vehicles and workers, through the use of alerting sounds and warning lights. However, it is essential to understand that while these technologies offer important benefits, they cannot eliminate entirely workplace hazards, and their successful adoption depends on factors such as user acceptance and effective integration into existing OSH management systems.

To conclude, this thesis provides a comprehensive overview of digital OSH monitoring systems, recognizing that many other advancements must be made in this field. As industries evolve and new hazards emerge, we must continue to innovate and advance our approaches to ensure workplace safety. The aspiration is to see widespread adoption of these digital OSH monitoring systems across multiple organizations, through which establishing more safety-centered workplaces worldwide. Undoubtedly, further research and developments on this topic are necessary. The landscape of workplace safety is dynamic and with constantly evolving technologies ongoing adaptation and innovation are crucial. However, even though there is a need for enhancement and refinement, the current state of digital OSH monitoring systems is already promising, making it a perfect starting point for creating workplaces where every employee can feel safe to work.

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