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New and Emerging Hazards for Health and Safety within Digitalized Manufacturing Systems

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Abstract: The Fourth Industrial Revolution is radically reshaping the procedures and the manufacturing environments through the digitalization process. The digitalization process can change according to the context and to specific solutions, and it is able to modify manufacturing systems and production areas. All the employees are directly affected by the transformation of the working environment, manufacturing tools, and working conditions and by the increasing need for new competencies. In this context, it is crucial to identify new and emerging hazards concerning the health and safety of the employees to ensure a conscious and safe digital transformation for everyone involved. In this regard, the paper presents the state of the research and defines seven areas of interest for a safe and harmless digital transformation for the employees, drawing attention to the hazards in the different technological areas. The state of the research unveils the absence of detailed analysis to identify specific hazards of 4.0 technologies. Therefore, every specific 4.0 technologies is analyzed by an extensive review to provide a comprehensive matrix of new and emerging hazards for health and safety within digitalized manufacturing systems. The results can help manufacturing organizations to perform robust risk assessments for worker when introducing specific 4.0 technologies.

Keywords: health and safety; Industry 4.0; digital transformation; smart factory; workers; risk management

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1. Introduction

Over the last decades, the notion of sustainability has come to be of indisputable social relevance [1], also in manufacturing [2]. Here, the fourth Industrial revolution (I4.0) basic concept is the integration of advanced technologies into the working environment and operations. Therefore, the human factor inside the workplace needs to achieve sustainability in four main categories: behavioral (e.g., skill and motivation), physical (e.g., ergonomics and training experience), mental (e.g., fatigue and cognition) and psychosocial (e.g., interaction, emotion and perception) [3]. Thus, the health and safety of workers strongly belong to the sustainability research field and contributes to the world sustainability. According to the report by the American management consulting firm McKinsey [4], new digital technologies are changing the entire industrial landscape, including the manufacturing sector. In particular, the report introduces a new form of human-machine interaction, delineated within the four lines of development. The ever-increasing implementation of technologies in the workplace involves paradigms that can strongly interact both with humans and technology. In these contexts, workers are more and more often playing the role of 'human in the loop', which is defined in literature as a form of cooperative control between machines and human beings, where the latter holds the principal decision-making power. The implementation of technological innovation is advantageous for companies, as it ensures significant benefits, e.g. in terms of technology, costs, management, etc., and it allows to enhance employees' safety. However, technological innovations require an update of the analysis of risks to the workers. For instance, new injury risks should be taken into account, as well as new potential causes of diseases, or new hazards caused by new activities or procedures [5]. Therefore, technological innovation poses new challenges for companies, and it requires a revision of well-established practices and activities. As stated in the investigation 'EY Digital Manufacturing Maturity Index 2019', companies are more and more often struggling to find employees with the necessary competencies to face the Industry 4.0 paradigm. The new and constantly evolving competencies do not apply to employees at all qualification levels [6]. Moreover, digitalization and the use of new technologies pose new and emerging hazards for employees. Namely, changes affecting the workplace, the operating procedure, and the physical components engender new hazards concerning occupational safety and health (OSH). Therefore, workers should be fully aware of the ongoing changes to feel involved and not replaced [7] and to feel safeguarded in a context where safety becomes technology-centered. Against this background, and following the strategies identified by the European Commission, the European Agency for Safety and Health at Work (EU-OSHA) incorporated the impact of ICT (Information and Communications Technologies) in the list of research priorities concerning occupational safety and health. In this way, the EU-OSHA stressed the need for an integrated and proactive approach for the identification of emerging hazards related to the changing workplace. In particular, the above-mentioned approach should ensure the definition of appropriate prevention measures in connection with new applications [8]. Furthermore, EU-OSHA clarifies that the OSH hazards associated with digitalization include increased ergonomic risks, mainly deriving from the different operating procedures. For instance, with the increasing establishment of remote work, employees are required to perform most of their tasks outside of the business workplace. Moreover, additional risks emerge concerning new human-machine interfaces and the growing number of interconnected objects or individuals. As a consequence, organizations and companies face new challenges. On the one hand, companies need to take into account the crucial role played by safety in new technology implementation [9]. On the other hand, due to the rapid digitalization process, it is crucial to promptly develop protocols and safety standards to incorporate them in the work environment [10]. Indeed, one of the main issues involves the implementation of technical standards, i.e., ISO (International Standard Association) standards, which generally require long periods. As a consequence, the time elapsing between the beginning of the digitalization process and the implementation of specific safety standards is often long and it is characterized by the complete absence of regulations, especially in the case of emerging technologies. Therefore, the prompt development and establishment of such procedures are of paramount importance to ensure complete safety, also considering the rapid obsolescence of new technologies.

2. Intention of the Paper and Research Method

The presented paper aims at identifying new and emerging hazards for the workers caused by the spread and establishment of 4.0 technologies in production environments, through the analysis of the technical issues that emerge before the implementation of legal regulations. The paper specifically discusses hazards and not risks, since the analysis does not provide a probabilistic assessment. Indeed, hazard identification represents the usual starting point for the evaluation of the deriving risks. The presented analysis was performed following the steps shown in Figure 1.

The first part of the method brings two important results: a transversal view on the state of the research about hazards and risks in the specific field of manufacturing 4.0 technologies, and the evidence that no specific research works are available about the new and emerging hazards for health and safety. The second part overcomes this gap and provides a useful knowledge reference for the safety professionals.

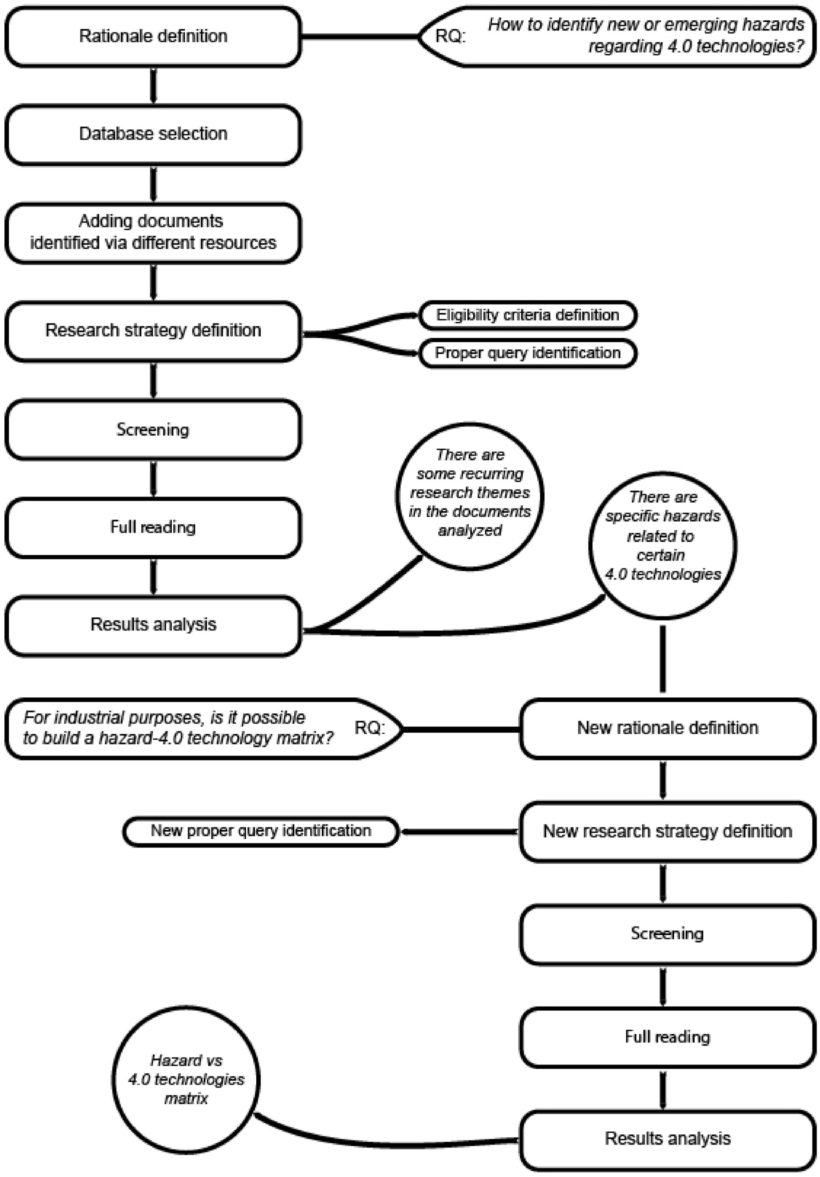

Figure 1. Steps of the research process.

Firstly, the rationale was defined. In the case under consideration, the rationale definition focused on the research of new and emerging hazards for workers for new Smart Manufacturing technologies. Secondly, the reference databases were selected, i.e., Scopus and Pubmed-Medline, to achieve a systematic revision of the existing literature. The Scopus database was selected as the primary source because of its relevance in the scientific field. On the other hand, the Pubmed-Medline database, containing biomedical and life sciences literature, was selected to ensure easier identification of medical, epidemiological, and psychological effects on employees. Both contain only peer-reviewed documents. Additionally, Pubmed-Medline allows to search the whole text of a document, and not just the abstract, thus ensuring a more thorough investigative approach. Moreover, the text contained in the database under consideration is completely indexed, and the suggested similarity features are therefore considerably accurate and reliable. In addition to the above-mentioned databases, other secondary records were added. These records were identified using Google Scholar and further relevant contributions, i.e., EU-OSHA's and other national agencies' documents.

The research strategy aimed at identifying the eligibility criteria of the queries, which were determined by merging two semantic areas: digital transformation and concepts concerning security, safety, and hazards in the workplace. The research key and the obtained results are presented in Section 3. The performed analysis identified recurring cross-cutting topics related to workers' health and safety deriving from the implementation of different technological solutions. However, the results did not reveal the presence of new and emerging hazards. Consequently, a more specific research strategy was defined, i.e., queries precisely aimed at identifying workers' hazards versus each technology as considered in the following Section 4.

3. State of Research—Topics for Health and Safety in a Digitalized Workplace

This research aimed to identify the state of the art on the topic of new risks emerging from the implementation of 4.0 technologies for the health and safety of workers. Therefore, this section comprises three blocks. The first one takes into account the context, e.g., "Digital Transformation" OR "Industry 4.0", "Smart Manufacturing" OR "Digitalization" OR "Smart Factory" OR "Industrie du future" OR "Smart Industry" OR "Factory of the future" OR "Industrie 4.0" OR "4th Industrial revolution" OR "Digital Manufacturing" OR "Made in China 2025". The second block considers the impact, e.g., "Safety" OR "Health and safety" OR "Safety risk" OR "Impact on work" OR "Safety hazard" OR "Work disease". Finally, the third block focuses only on reviews and papers published in journals between 2012 and 2020 written in English. The year 2012 was used as a time threshold because of the rapid technological evolution and the introduction date of the term 'Industry 4.0'. As a result, 379 documents were retrieved. During the screening phase, the abstracts of the selected documents were analyzed to eliminate duplicate documents, as well as documents not directly addressing the topics of OSH and technology as a solution to reduce or avoid hazards. The 64 remaining documents revealed the presence of recurring cross-cutting topics related to workers' health and safety in relation to the different technological solutions implemented. In particular, the identified topics concerned: ergonomics, anticipation of new technology effects, standard and standardization suitability, data management, intellectual property protection, workspace design, possible effects of new technologies on employees, employee 4.0 features, 4.0 technologies, and Risk Assessment methods (Risk Management). Data management and intellectual property protection are not strictly related to the topic of workers' safety defined in the presented contribution, and for this reason, they were not analyzed. As previously mentioned, the topics resulting from the analysis are not independent and completely separated from one another. On the contrary, they encompass topics that are common to more than one technological category.

3.1. Ergonomics

Ergonomics is a branch of science investigating the problems of the human body and the human psychological and physical limits and capabilities. For this reason, this discipline is connected to the topic of working places, as it allows optimal working systems and enhancement of the workers' productivity while improving their mental and physical health. The performed analysis focused on the interactions between the three main elements of a working system: human, machine, and environment. The ergonomic analysis is based on a proactive risk identification approach aimed at anticipating possible issues by thoroughly scheduling the necessary operations to prevent or solve those problems. The knowledge of the possible risks allows not only to face the risks in the best way possible, but it also allows to reflect on the performed actions [11], thus increasing awareness of the workspace and of the interactions that take place in the working environment. Some of the analyzed contributions illustrated the main criteria of Human Factor Ergonomics (HFE), i.e., a discipline that considers the Work System Design as a flexible and iterative process aimed at enhancing the system's performance, as well as the workers' physical and psychological health [12]. HFE focuses on ensuring freedom from harm, freedom from mental impairments, work feasibility, and professional growth potential for work areas [13]. Therefore, the main purpose in this field is to design systems based on safety 4.0 knowledge [14]. Finally, a new topic emerged during this analysis, i.e., the relationship between humans and machines. In this context, the main technologies considered were cobots [11,15,16], autonomous vehicles [17], and virtual reality [18]. The possible risks resulting from the use of these technologies concern both physical and psychological aspects, namely anxiety, excessive workload, depression, possible sense of isolation, fatigue and always-on feeling [8], i.e., the feeling of being always connected.

3.2. Anticipation of the Effects of New Technologies

The potential effects of new technologies can be identified using simulation mechanisms and tools aimed at determining in advance the working conditions or the interactions in a specific working environment. A simulation allows making predictions about possible developments or effects deriving from the implementation of new technologies. Moreover, according to the existing literature, simulation tools are tested to model high-risk environments, (i.e., nuclear power plants [19]), and to design workspaces taking into account the relevance of ergonomics [20], possibly including specific technologies, e.g., robots, from the very beginning [21,22].

3.3. Standardization

Work standardization aims at improving the productivity of production systems, while also ensuring the regulation of the use of machines and technologies to safeguard the workers' safety. ISO (International Standard Association) is the main organization for the regulation of standards and technical criteria. ISO machinery safety standards are hierarchically divided into three groups. Group A contains general standards that provide basic concepts, principles, and key requirements of the machines. Group B contains safety and safeguarding standards applicable to machines with a higher detail level. Finally, group C contains machine-specific standards defining specific requirements applicable only to specific machines [23]. Although ISO proposes specific safety standards, e.g., number 10218 'Robots and robotic devices—safety requirements for industrial robots' [24], in many technological areas there is a complete lack of safety standards, e.g., Power Bed Fusion, a new-generation form of Additive Manufacturing. Moreover, it is possible to observe criteria related to the standardization of Human Factor Ergonomics (HFE), i.e., a discipline that considers the Work System Design as a flexible and iterative process aimed at enhancing the system's performance, as well as the workers' physical and psychological health [12]. Preliminary feasibility analyses aim at investigating and defining the best foundations for the architecture of collaborative working stations [25] or workspaces that may be of crucial importance in specific plants, such as MCR (Main Control Rooms) in nuclear power plants, which have been leading actors of the digitalization and automation process in the past few years [26]. Hence, in similar contexts, the conceptual correlation between regulations compliance and worker's safety plays a crucial role. However, the main issue concerns the commencement of the standards. The period elapsing between the proposal of a regulation and its publication can last several years. Therefore, numerous researchers stress the need to streamline the commencement procedure, to ensure global safeguarding of workers at all times and concerning every technology, thus guaranteeing a safe and efficient technological transition.

3.4. Workspace Design

The design of the workspace is of paramount importance to ensure the workers' safety. These designs are either irreversible or very expensive to remodel and it is crucial to accurately choose the appropriate workspace design by encompassing all the existing elements, as well as possible future ones. In this regard, 3D simulation tools can facilitate the Work System Design process, namely by using collaborative robots, which can examine in advance space management and motion management within the work areas in which human-machine collaboration is expected. For instance, 3D simulation was implemented for the ergonomic design of human-robot collaborative workspaces [24]. Furthermore, it is possible to identify models aimed at designing cobot movements that are 'less stressful' for humans [16], thus reducing potential psychological stress. In general, the purpose is to ensure safer cobot movements without reducing their performance. The presented approach aims at combining the strengths of both workers and cobots. Therefore, it is crucial to establish a balance between accuracy and flexibility, while also bringing together the main RMS (Reconfigurable Manufacturing System) advantages in the context of human-robot collaboration, i.e., modularity, integrability, and diagnosability—the ability to rapidly detect possible issues [27].

3.5. Effects of Technology on Workers

Occupational safety and health experts are increasingly concerned about the possible effects of new procedures, new roles, and new digital tools on the worker's physical and mental health. Psychological stress includes conditions such as anxiety, mental fatigue, the possible feeling of frustration or isolation, and, generally, excessive cognitive workload. Safety experts pay particular attention to the above-mentioned conditions since they can cause accidents within industrial plants. Moreover, investigations also focused on the aspect of robots and on how it is perceived by humans, eventually determining that a humanoid robot is perceived as more reliable than a robot with a different shape or dimension [15]. A further topic considered in this context is, again, ergonomics, here intended as a way of preventing the employees working in unsafe working spaces from being affected by the effects of an inaccurate design. Furthermore, the use of the internet is analyzed as well. The negative effects of inappropriate use of the internet include technological dependence, lack of work-life balance, and inappropriate behavior in the workplace [28]. Other hazards may include the development of the always-on feeling, technostress episodes—a phenomenon that occurs in strictly technological environments—, and possible hazards for the workers connected to privacy violation, i.e., cyberbullying and molesting [8]. Finally, concerning the Additive Manufacturing context, employees working without the necessary protections are exposed to toxic substances that can cause abrasion or eye irritation [29].

3.6. Operator 4.0

According to avantgarde academic literature, operators 4.0 are defined as smart and skilled user personas who can perform well in cooperative environments with robots, while also being assisted by technological tools when needed. Contrastingly, the healthy operator 4.0 subtype implements wearable smart solutions, e.g., tools monitoring for cardiac monitoring. In addition, this subtype has data analytics skills, and it aims at using its biological data with advanced Human-Machine Interface (HMI) and Human-Automation Interaction (HAI) technologies. In this context, technology can be beneficial for productivity, health and proactive safety measures in 4.0 workplaces [13]. For this reason, in the future workers will need to be able to coexist with technology and to successfully cooperate with it. This objective can be achieved by allowing users to become more and more aware of the transformation, and by making them feel involved [7]. Safety training will have a central role in helping people become more aware. In fact, according to a 2020 investigation, the primary cause of technology-related accidents in European industrial plants is the lack of training for the employees [30]. Moreover, several scholars defined the process of training and preparation of the employees as an indispensable mainstay of safety culture in 4.0 companies [14].

The analyses concerning 4.0 technologies focus on the topic of safety with regard to specific technologies. The elements of interest identified in this phase are incorporated in the subsequently presented analyses (Section 4), which illustrate the analysis of hazards for workers concerning specific technologies.

3.7. Risk Assessment Methodologies

To make adjustments in a manufacturing system, it is always crucial to assess the risks connected to the intended operations. Risk definition and quantification is therefore crucial for the efficient identification of the best risk response strategy. Namely, when introducing new Industry 4.0 technologies for process automation, it is important to adequately perform a risk assessment analysis for specific technologies. While some risk response measures may be adequate for a specific technological solution, they may be inadmissible for others [27]. For instance, in the HRC (Human-Robot Collaboration) context, existing researches define risk assessment methodologies based on workspace design. An example is the Axiomatic Design method, which identifies the necessary functional requisites in a specific context and investigates how these requisites facilitate the identification and classification of sources of hazard following the existing standards [25]. Furthermore, as far as cobot implementation is concerned, Activity Allocation logic is defined. These logics aim at supporting the decision-making process for the allocation of specific activities to robots, humans, or, if necessary, to both of them (human-robot collaboration) by using ratings based on different indicators. The implementation of the above-mentioned tools allows managers to perform preventive feasibility analyses of the collaborative processes taking into account all the aspects defined in the outlined indicators [21]. Moreover, these risk assessment methodologies allow determining the differences between different robots. For instance, the Hazard rating number assigns specific risk coefficients to each of the analyzed machines [21]. Finally, it should be noted that the features of different risk assessment methods vary according to their target sector. Nevertheless, according to the latest researches in the field of safety, Resilience Engineering is the most widely used approach [31,32].

The State of research reveals how the topic of new emerging worker challenges and companies implementing new digital technologies is addressed in the literature. However, the result unveil the absence of an analysis of new emerging hazards for the worker that is declined on each 4.0 technology relevant in this sense. To fill this gap, the following research aims to present specific hazards for worker health and safety corresponding to each 4.0 technology that directly impacts humans. These hazards are classified according to predefined hazard categories to provide a homogeneous overview. The detailed overview updates the state of the art and can be a helpful guide for organizations to implement 4.0 technologies safely.

4. New and Emerging Hazards within Digitalized Workplace

The obtained state of the research shows there is not an exhaustive overview of the specific hazards related to the implementation of innovative technologies in manufacturing systems. Therefore, a precise analysis was carried out to analyze different technologies and determine the specific hazards related to the examined technological solutions. The identification of these hazards helps to better recognize risks in the digital manufacturing workplace, such as commonly suggested in legislation (e.g. Italian). The above-mentioned analysis focused mainly on digital innovation within manufacturing systems in terms of specific 4.0 technology implementation. This topic is of paramount importance since the ever-increasing number of technologies in the manufacturing field creates new digitalized environments characterized by specific hazards related to one or more technological solutions. Therefore, the most widely implemented technologies in the manufacturing field were selected to create a reference base for the identification of the hazards and the related specific technology. The Industry 4.0 transformation process is characterized by the implementation of technologies, i.e., IoT, Big Data & Analytics, Cloud, and Artificial Intelligence (AI). Nowadays, these technologies represent an important innovation, and they can significantly change the way of working. However, by creating an underlying level constructed with different innovative solutions—each of them characterized by different features and transversalities—it is difficult to separately analyze all the technologies in terms of new hazards for the workers. Health and safety hazards for the workers are not attributable solely to the above-mentioned technologies, but they should be investigated according to the specific technological solution implemented in each context. Therefore, the presented analysis examined only the technologies presenting significant health and safety hazards for the workers. Against this background, eight categories of technologies were determined: Additive Manufacturing, AGV, AR/VR, Digital Twin, Exoscheleton, Robot/Cobot, Smart Wearable, and Wireless Communication Technologies.

In this phase, the eight categories of technologies and the related subcategories (Figure 2) were considered for the research keys.

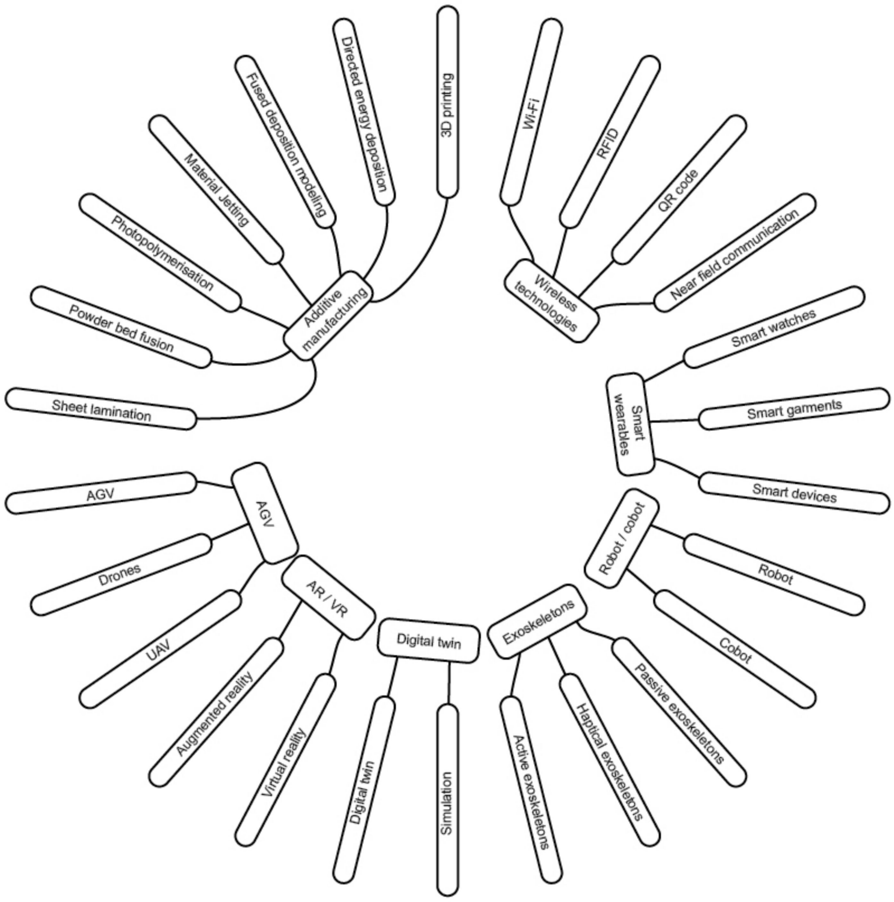

Figure 2. Eight categories of technologies and related subcategories.

As previously mentioned, to provide an exhaustive and detailed analysis, the results obtained by searching two databases, i.e., Scopus and Pubmed-Medline, were combined and examined. In particular, the research key was used to identify hazards for the workers related to specific technological solutions. For this purpose, two different blocks concerning hazards and technologies, respectively, were used: ((“Mechanical risks” OR “Physical agents” OR “Chemical risks” OR “Risks” OR “Hazards” OR “Impact on worker” OR “Safety” OR “Negative Safety” OR “Health and Safety”) AND (“Additive Manufacturing” OR “Directed Energy Deposition” OR “Fused Deposition Modeling” OR “Material Jetting” OR “Photopolymerisation” OR “Power Bed Fusion” OR “Sheet Lamination” OR “AGV” OR “Drones” OR “UAV” OR “Augmented Reality and Virtual Reality” OR “Augmented Reality” OR “Virtual Reality” OR “Digital Twin” OR “Simulation” OR “Exoskeletons” OR “Active Exoscheletons” OR “Haptical Exoscheleton” OR “Passive Exoscheletons” OR “Robot and Cobot” OR “Cobot” OR “Robotics” OR “Robots” OR “Smart Wearable” OR “Smart Devices” OR “Smart Induments” OR “Smart Watches” OR “Wireless Communication Technology” OR “Near Field Communication” OR “QR Code” OR “RFID” OR “SG” OR “Wi-Fi”)). The selection criteria considers in the first block a set of synonyms gathered from the state of the research (single terms or common periphrasis); these terms was tuned to focus specifically on the health and safety field, e.g. excluding the security field, that very often presents the term “risk” or “hazard”. The second block consider all the categories as in Figure 2.

The research was progressively refined, firstly through an Abstract analysis, then through a complete and thorough analysis of the whole body of the documents. The main purpose of these analyses was to eliminate specific confusing terms (e.g., "drones" as a synonym of "male bees"), as well as inconsistent topics, i.e., therapeutic, diagnostical, medical, and pharmacological technological applications, and patient's safety in the medical field. Therefore, only the documents containing at least one occurrence of the word 'hazard' were examined, making a distinction between strictly medical applications and applications related to work in general.

In conclusion, by analyzing the collected results, specific health and safety hazards for the workers were identified.

The risk factors identified for each technology were classified according to the International Standard ISO12100:2010 (Safety of machinery—General principles for design—Risk assessment and risk reduction), and two additional risk categories were integrated to provide comprehensive standards with regards to the context under analysis: organizational hazards, and psychosocial hazards. Organizational hazards occur when the source of risk is connected to procedures, methods, criteria, and organization solutions that are not related to the worker's actions. Psychological hazards derive from the worker's subjective perception of the work and the interaction with the digital technologies. Moreover, in order to create an extended and comprehensive reference in this context, the risk categories of the 12100:2010 were renamed as follows: the "Materials and substances" category was renamed as "Chemical and biological", while the "Environmental" category was renamed as "Work environment and microclimate".

The obtained results are divided into the eight technological categories examined and they are presented below.

4.1. Additive Manufacturing

Additive Manufacturing (AM) technology revolutionizes traditional manufacturing paradigms by assembling objects layer by layer from a 3D virtual model [33]. The materials used in this context are usually plastics, metals, thermoplastics—which can withstand high temperatures and relevant mechanical solicitations—, or acrylic polymers—which can mimic the properties of other materials. To date, this technology represents a constantly growing market. In fact, according to an IDTechEx research presented in the report [34], the global market for 3D devices will reach $31 billions by 2029. However, Additive Manufacturing is connected to unconventional technologies, processes, machines, and competencies, which pose new risks to workers. The hazards related to these technologies can be mechanical, since operators may get trapped by devices with movable parts [35–38], get minor or major skin injuries caused by sharp edges, rough borders and surfaces [35], or collide with falling or projecting objects [35]. Furthermore, electrical hazards may derive from several factors. Firstly, from a malfunctioning of the devices, which may cause burns [35,37–41], secondly, from electrostatic phenomena resulting from dusts and from the accumulation of electrostatic charges on plastics, which may cause uncontrolled energy releases, fires, or explosions [35,38], finally, from damaged wires that may function as conductors [35,37,38], or from unexpected events due to electromagnetic interferences between different equipment, which may cause a malfunctioning [1]. Additional types of hazards found in the literature include thermal hazards, which may cause burns for workers operating close to overheating devices [35,37–39,42]. Moreover, the use of vacuum pumps and air compressors as machine power suppliers may cause hearing damage [37], while exposure to ionizing radiation and laser sources may cause minor injuries and genetic mutations [35,37,43]. Furthermore, operators employing such technologies are exposed to hazardous chemicals, i.e., ultra-fine powders, monomers, organic compounds, or inert gases. This exposure may cause eye damage [29,35,37–40,42], eye fatigue [1,4,6], skin damage, skin sensitization, contact dermatitis [37,39–41], nasal mucosa injuries [35–43], central nervous system damage [1,4–6], reproductive system damage [43], asthma, allergic rhinitis or other consequences of respiratory and lung damages [35–44], metal poisoning [1,3,5–8], loss of coordination, headache and nausea [38], cardiovascular diseases [1,3,5,6], cell damage and genetic mutations [1,3,5–8,11], and long-term storage damages [35–45]. Finally, from a chemical and biological perspective, exposure to flammable and reactive chemical agents may cause burns [42].

In conclusion, this analysis illustrated that some of the processes implemented during Additive Manufacturing pose significant health and safety hazards for employees in their workplace. In addition, the lack of appropriate standards in this respect and the need to safely implement new technologies are repeatedly highlighted in the existing literature [35].

4.2. AGV

The term Automated/Automatic Guided Vehicle (AGV) indicates the vehicles used in the industrial field to handle and transport products within a plant. AGV on-board computers are only used to communicate with the control system through wireless connections, thus allowing the vehicle to move inside the company plant. Therefore, the use of AGVs provides the possibility to revolutionize the company's logistic and manufacturing organizations. AGVs ensure efficient and flexible maneuvers with minimal manpower, high productivity with low costs, and continuous handling operations. In addition, AGVs can be designed to interact with other automated systems, such as automated storage and retrieval systems, thus ensuring even higher flexibility [46]. However, in this context it is challenging to develop a flexible and automated system while also guaranteeing the safety of the humans operating in the same area.

In fact, according to the analyzed literature, AGVs pose mechanical hazards due to the instability of the devices, which may entrap workers or cause damages provoked by the loss of balance or fall of such devices [47]. Furthermore, collisions may occur in case of machine speed monitoring system failure [47,48], emergency brake failure [48], or laser vision system's inability to detect obstacles in the shadow [48]. Finally, loads may fall from the machines in case of braking, and they may collide with the operators [48]. Furthermore, AGVs are also connected to electrical hazards, such as device malfunctioning due to electromagnetic interferences between them, which may cause damages to operators [49,50], and thermal hazards, which are associated with the overheat of the devices, which may cause burns [48]. Moreover, AGVs expose operators to chemical and biological hazards as well, due to the release of acids or corrosive agents from batteries, which may lead to contact damages [48]. Additional hazards related to the use of these technologies pertain to the organization field. Collisions may occur as a result of an inadequate setting of the vehicles' trajectories [46–51], as a consequence of the inadequate weight and sizing of the machines [51], or because of planimetric changes not registered by the vehicles [48]. Technological development allowed vehicles capable to support verbal interaction mechanisms, as well as visual and gesture recognition. However, when the transmitted messages are not correctly processed or understood by the machine, the unexpected actions generated by the machine may pose a risk for the operator [48]. Furthermore, inadequate personnel training represents a source of organizational hazard as well. Employees may be negatively affected both by unknown machine behaviors and by the decrease of satisfaction with their job [48]. The implementation of not user-friendly human-machine interfaces may [52,53] result in feelings of insecurity and danger [48], while the increased control of devices and maneuver errors can lead to psychophysical stress [48]. Operators may also be affected by the limited observability of the operating conditions, which may consequently cause burns [48]. Finally, inadequate computer security systems may cause further risks for the operators, e.g. malware, hacker attacks, or unexpected behaviors of the device [50].

In this regard, some researchers defined a Risk Assessment method for AGV robots specifically designed for material handling during order processing. This process is controlled in a decentralized way using sensors for allocation and navigation [47] and it implies the transport of materials within the production line, i.e., transport between different workstations and material handling in production areas, such as goods receipt areas. However, the performed analysis revealed the lack of detailed and extensive studies in terms of health and safety hazards for the workers.

4.3. AR/VR

The implementation of augmented reality (AR) and virtual reality (VR) systems is often beneficial in working environments. AR and VR allow to keep workers away from dangerous workspaces, and they also support workers during different working phases, both in terms of procedures and hidden hazards, i.e., the presence of hazardous substances such as asbestos, radiations, gases, electric wires, etc. Nevertheless, the use of AR and VR systems poses new health and safety hazards for the workers.

The implementation of these technologies is connected to chemical and biological hazards. For instance, operators may touch plastic and metallic material with superficial body parts, which may cause skin irritation or allergic reactions [54], while inadequate device sanitation may provoke eye diseases [54]. As far as ergonomics is concerned, operators may experience discomfort deriving both from the dimension and the weight of the devices [55–58], and from the stereoscopic display vision [55], which may lead to eye fatigue [55] also caused by a decreased blink rate [56]. Additional factors may also lead to muscle fatigue, i.e., pain in the lower neck area [55,56,59], shoulder pain, upper back pain [59], and hand and arm pain [59]. Furthermore, AR and VR devices limit the workers' visual field, thus leading to possible damages due to their the decreased ability to control their surroundings [54,56,57,59]. In addition, these technologies are also associated with organizational hazards, mainly related to the varying lighting conditions of the workplace, which may cause, for instance, eye dryness [56], glare damages [59], and visual discomfort due to the need to adjust to the different light levels [56]. As far as organizational hazards are concerned, the extended use AR and VR devices may lead to discomfort [55,56,60], eye fatigue [45,55,56,58–60], nausea, dizziness, disorientation, motion sickness, headache [10,25,29,30], social isolation [35,61,62], increased heartbeat and breathing rate [58], as well as gastric damage [58,63], damages caused by distraction [45,54,58,64] and unpredictable long-term musculoskeletal consequences [56,64]. Furthermore, the significant information load may lead to damages caused by cognitive overload [59,64–66]; screen latency, i.e., the difference between the operator's head movement and the image display on the screen, may provoke headaches [55,57,58]; while the overlap between virtual images and real objects may cause eye fatigue due to the different focal lengths [56,58]. Similarly, the difference between virtual images and the real world may reduce the operators' movement coordination [57,58]. Moreover, images may sometimes disappear on VR and AR devices because of the interposition of an object or a person in the visual range of the device. As a result, if no information is provided, operators may make mistakes and hurt themselves [57]. AR and VR technologies are also frequently used to instruct workers in real-time. However, despite the numerous advantages, the implementation of these technologies can lead to an excessive psychophysical workload [67]. AR and VR technologies may lead to a despecialization of job duties, which may consequently cause a decrease in the competencies of the operators, thus posing serious risks for the workers [67]. Inadequate training may lead employees to handle devices without fully understanding their potential and possible responses [67]. According to the analyzed literature, users may also fear privacy violation since the implemented devices can capture images and record videos [55,57]. Finally, psychological hazards should be taken into account as well. Operators may grow accustomed to employ such technologies, thus developing a form of addiction and separation anxiety [45,57], while the excessive physical and mental load can cause technostress [45,58,64–66,68], and the frequent use of technological devices may lead to social isolation [10,35].

In conclusion, AR/VR devices raise several issues for workers' health and safety. In this context, the most thoroughly investigated topic concerns the impact of technology on the musculoskeletal system [55,59,61,69]. In fact, it was proven that some activities and the poor postures workers have while using the above-mentioned technologies can cause musculoskeletal disorders, which can have adverse effects in the long term.

4.4. Digital Twin

In the existing literature, the issues related to Digital Twin technological solutions are mainly connected to their implementation efficiency. For instance, the main problems associated with IoS (Internet of Simulation) solutions concern the choice of the simulation's objective, the trade-off between the desired quality and the simulation's execution speed, and cost assessment. Specifically, this last point implements economic feasibility analyses in order to understand the simulation reproducibility of the environment under analysis, which has a significant impact on the realism of the obtained results [70]. However, the analysis of the existing studies did not reveal significant health and safety hazards for workers.

4.5. Exoskeleton

The implementation of exoskeletons in the workplace raises questions about the workers' health and safety. In this regard, the French Research and Safety Institute for the prevention of occupational accidents and diseases (INRS) provided an overview of new risk factors in the workplace connected to the use of exoskeletons [71]. On the one hand, exoskeletons can help reducing muscle tension in the workplace by physically assisting workers, preventing possible WRMSDs (Work Related Musculoskeletal Disorders), or supporting workers with impairments. On the other hand, however, exoskeletons may pose new hazards for workers' safety and health. In fact, electrical hazards derive from the energy released from such devices, or their shutdown, due to power failures, which may cause unexpected behaviors of the devices, or generate uncontrolled energy releases [72], while inadequate computer security systems may lead to damages caused by malware, hacker attacks, technical programming errors, and privacy violation [73]. Furthermore, overheating devices pose serious thermal hazards, since they may burn the users [72]. Loud noises and vibrations produced by some exoskeletons may also provoke hearing damages and damage to body parts subject to the oscillatory motion [72], and the release of corrosive materials from the implemented batteries within the devices poses chemical and biological hazards that may cause skin irritations and burns [72]. Similarly, the contact between plastic and metallic materials and superficial body parts may provoke skin irritation and allergic reactions [74], while inadequate device sanitation may generate infections [48]. Further hazards connected to the use of exoskeletons are ergonomic hazards. Operators wearing such devices often have limited mobility and are therefore unable to avoid the collision with falling objects [72,74–80], or, contrastingly, they may perform improper movements or overexert themselves, thus provoking muscle damages, i.e., tears [72]. Moreover, the additional weight of the devices and their dimensions may lead to complications, i.e., damages caused by the difference in art-leg kinematic [72,74,81,82], musculoskeletal issues [72,74–77,81,83], muscular fatigue [48–50,53,57,58], minor damages and pressure injuries [72,74,75,77,81], nerve compression [72,74], respiratory fatigue caused by a decreased chest excursion and by an increased chest pressure [72,74,81], discomfort [48–50,52,53,57], cardiovascular issues, wrong weight redistribution between different body parts [74], spine overload [70,77] or damages connected with bad posture [72,77,79,82], with reduced reactivity, e.g., in case of fire [75], with collisions with other operators or robots [77], and with imbalances, slips, trips, and falls [72,75,77,79]. Furthermore, the increased directional load may cause damages linked to dynamic events [72,79]. Additional hazards are then associated with the work environment and the microclimate. Increased temperatures in the workspace may lead to the proliferation of bacteria inside of the devices, causing infections [72], while the reduced working space may cause collisions due to the increased volume of the operators wearing exoskeletons [75]. As far as organizational hazards are concerned, as a consequence of the device's ability to monitor personal data, i.e., localization, operators are concerned with privacy violation issues [73]. Furthermore, inadequate computer security systems may lead to damages caused by malware, hacker attacks, or technical programming errors. Moreover, the general increase of the exoskeletons' physical capabilities may cause cognitive overload [72], while the inadequate employee training may give rise to fears and insecurities both at a personal and professional level [75]. Finally, the implementation of exoskeletons also poses psychological hazards. The operators' excessive reliance on the devices may lead to a decreased attention to security measures, and a muscle density loss [72]. In this context, as a consequence of the constant use of exoskeletons, operators may develop a fear of stigmatization in the workplace, and they may be afraid, for instance, of being perceived as technology-dependent [74]. In conclusion, the hazards related to exoskeleton technologies seem to have a significant impact, especially in the long term. Consequently, the workers' health and safety conditions can be estimated but they cannot be adequately specified yet. Scientific evidence and practical experiences in this field are still limited. Therefore, further studies on exoskeletons should take into account the aspects concerning the user's safety.

4.6. Robots and Cobots

The implementation of automation and robotics within production systems can minimize the need to work in hazardous working environments, e.g., narrow or high-altitude spaces. Moreover, these technologies allow to perform routine or repetitive tasks on fast, precise, and tireless machines, and they also facilitate access to work for people with physical or structural impairments. Although the objective of automation and technologies is to support workers in different circumstances, these technologies may pose several hazards for the users, especially in human-machine collaborative activities or activities where the two subjects work nearby.

The analysis of the existing literature shows several possible hazards connected to robot and cobot implementation. First, mechanical hazards derive from the movement of mobile parts, i.e., arms, limit switches, and other terminals; from the rotational movement of any axis of the robot/cobot; and from the operators' inability, in case they are wearing loose clothing, or they have long hair, to exit from robot's cells or collaborative activities. As a consequence, the above-mentioned risk sources may lead to crushes, cuts, severing, entanglements, dragging, entrapments, impacts, perforations, frictions, or abrasions [84–86]. Additional mechanical hazards include damages caused by the fall or expulsion of materials, products, and tools, due to the inadequate grasp of the arms of robots/cobots [86]. Moreover, sharp edges of the devices may lead to minor or major skin injuries [86], while the insufficient reactivity of robots and cobots during collaborative activities may cause collisions [87]. Further mechanical hazards concern issues related to the human's ability to detect and predict robot/cobot trajectories and vice versa, which may lead to collisions between the interacting agents [87,88], as well as to damages caused by losses of balance, slips, trips, and falls [19]. Maintenance activities, performed at significant heights, can be critical as well when the significant dimensions of the devices generate potential damages connected to falls [84,89], while the hindrance or limitation of the machines' vision systems may cause collisions [90]. Secondly, electrical hazards may arise in case of electromagnetic interferences between different devices, device malfunctioning [89], power supply interruption, with the consequent fall of tools or extractors [86], unexpected potential energy release from storage sources. These hazardous situations may cause burns to the operators [84,86], as well as other damages due to the contact with parts or connections under tension, and the exposition to the electric arc [84]. Thirdly, thermal hazards are only connected to overheated devices, which may cause burns [84]. Furthermore, additional hazards concern the exposure, namely to vibrations [45,68,84,86,89,90] and noises produced by the devices [84,86], ionizing radiations, laser sources, and corrosive or acid agents originating from batteries, which may cause minor skin, eye, or airway damages [84]. Moreover, ergonomic hazards include not user-friendly interfaces, which may cause discomfort and mental stress [86], while the operator's posture during collaborative operations may lead to postural damages [85]. Organizational hazards, on the other hand, concern repetitive tasks performed at the pace of robots/cobot, potentially causing fatigue [19], musculoskeletal stress [86], psychological stress [10,16,23,24], and physical overload [89], as well as additional damages caused by a monitoring decrease [68,86]. In fact, the simultaneous monitoring of several robots/cobots can lead to cognitive overload [48,89]. Contrastingly, a reduction of the activities performed by humans and the consequent decrease in the attractiveness of the job can produce a cognitive underload and damages connected to a decrease in the concentration levels of the operators [48,89,91]. Furthermore, workers may experience significant mental stress when performing operations in the close proximity of the machines [68,88,90], since collisions are a possible consequence of this proximity [45,68,90]. When operators and robots share working spaces they may collide directly [48,88] or indirectly, i.e., with falling objects [48]. Moreover, robots may also be implemented in spaces different than those they were designed for, hence leading to possibly dangerous situations, i.e., damages caused by the unpredictable behavior of the machine or by collisions due to the inadequate workspace [89]. Additionally, inadequate robot movement fluency may cause discomfort [88], cognitive stress [16] and collisions [16]. Moreover, outsourcing during the machines' construction, configuration, installation, and design phases may lead to a significant reduction of the operators' knowledge of such activities, thus increasing the chance of collisions and of their inability to act in emergencies [48,89]. If not adequately trained, employees may see robot/cobot implementation as a threat, and they may fear redundancies or subjugation [48,84,91], unpredictable behaviors of the machines [84,90,91], and the possibility to develop a dependency from third parties, namely repair workers [91]. To avoid unexpected behaviors of the machines, device configuration parameter changes should always undergo an authorization phase, which can also prevent errors made by operators during the amendment phase or the implementation of the machine [86]. Unexpected behaviors of the machines could be also caused by vague or unclearly transmitted instructions [85]; by actions performed by the devices as a result of the operators' behavior, which may scare and shock the workers [84,91]; or by the machine's ability to learn in an autonomous and automated way, which may cause damages to the operators [67]. Furthermore, inadequate computer security systems expose the devices to malware and hacker attacks, causing possible damages to the operators, and it increases the risk of unexpected behaviors of the machines, as well as direct and indirect collisions, i.e., collisions with the machines or with falling chemicals containers or blunt or radioactive equipment [48,67,68,84,89]. In addition, due to the absence of fences for the robots, workers may experience stress [85,90], be scared, and feel insecure [85]. Finally, psychological hazards are connected to the implementation of robots and cobots. These hazards are particularly significant since the interaction with different devices and the reduced contact with the coworkers may lead to social isolation [45,48,67,91], to a feeling of inferiority and subordination to the machines, which can operate faster [89] and are ever more often implemented in workplaces [91]. Possible damages in this context include: increased psychophysical stress, caused by the perception of inadequate safety conditions [88], increased collision occurrences, caused by the excessive reliance on the devices' ability to detect humans and to think [48,84], and feelings of mental stress, fear, and insecurities, caused by the variability and unpredictability inherent with robots/cobots [14].

As previously mentioned, standards for the implementation of these solutions already exist, e.g., ISO TS 15066. However, it is possible to note a lack of guidelines or regulations that comprehensively address all the issues connected to the hazards deriving from the implementation of robots and cobots in industrial settings.

4.7. Smart Wearable

Smart wearables are often used in production environments to monitor working conditions and report risky situations, when necessary. Smart wearables can send alarm signals to one worker or to the people responsible for monitoring the working conditions of a specific production area [92]. According to the existing literature, it is possible to implement several solutions in this regard. The most widely used solutions are the GPS monitoring of the workers' position, and the monitoring of biological and physical parameters, e.g., heart rate monitoring with smart bracelets [93]. Further smart solutions include the use of smart helmets and smart belts. In fact, by simply implementing an electronic system in a regular helmet it is possible to detect different parameters in the working place, i.e., brightness, temperature, and humidity. Moreover, it is also possible to insert led lights that switch on every time a worker on the side of the helmet operates in a particularly dark area, as well as a sound amplifier that allows hearing inaudible alarm signals. Smart belts, on the other hand, implement RFID technologies to control the workers' access to different buildings and to report hazards, i.e., falls [30] and incorrect contacts with the machines.

In this context, electrical hazards derive from possible electromagnetic interferences between the devices, which may damage the operators and deactivate subcutaneous medical devices [94]. The exposition to electromagnetic, ionizing, and non-ionizing radiations may cause superficial damages and genetic mutations [95], while the contact between body parts and plastic or metallic materials may provoke rushes or allergic reactions [96]. Furthermore, the inadequate dimension, weight, and position of the devices can generate ergonomic hazards, which may lead to discomfort for the operators [10,42], long term damages, i.e., to the dominant brachial biceps, general muscle fatigue, mainly in the should area [69], as well as to damages caused by muscular destabilization, i.e., in the area of the middle thoracic spine and the shoulder blade [69]. Moreover, organizational hazards are connected to the prolonged use of the devices, with consequent muscle fatigue [10,43], postural damages, muscle destabilization [69], and technostress [10,42]. In addition, the fact that safety condition monitoring is performed mainly by machines may expose workers to greater risks, reducing the overall surveillance level [10] and, sometimes, even private medical checks [97]. The continuous monitoring and personal data registration, i.e., localization, give rise to a fear of privacy violation [73,97], which, alongside malware and hacker attacks, may also be caused by inadequate computer safety systems [73]. If not adequately trained, workers may not fully understand the devices' behaviors and, consequently, they may be more exposed to hazards [68]. Finally, the continuous use of different technologies may lead to the development of a form of addiction and separation anxiety from such devices [10,42].

4.8. Wireless Communication Technologies

The use of wireless technologies poses new hazards for the workers, who are exposed to new possible hazards, i.e., electrical and thermal. The first hazard category is connected to possible interferences between the devices, and it may lead to damages caused by their malfunctioning [98], while the second category derives from the presence of electromagnetic fields, which may induce elevated heat levels, thus overheating the tissues and causing burns [99]. Furthermore, electromagnetic radiations may also cause superficial damages, cell damages, and genetic mutations [99,100], as well as unpredictable long-term damages [99], oxidative stress and antioxidant reduction, cancer, neuropsychiatric and endocrine changes, teeth development alteration, abnormal postnatal development, cardiac and cardiovascular damages, stimulation of adipose stem cells, and infertility [100]. Moreover, chemical and biological hazards include exposition to hazardous agents, which may lead to long-term storage damages [99,100]. On an organizational level, on the other hand, since health and safety conditions are monitored by the devices, operators are exposed to risks caused by a general decrease in supervision [73]. In addition, when the computer security systems implemented within the devices are inadequate, operators may be increasingly exposed to hacker attacks [98]. Finally, since operators are constantly monitored by technology, they may suffer significant psychological pressure, which is one of the possible psychological hazards connected to the use of wireless communication technologies [42].

Similar considerations can be also made in relation to specific wireless technologies, i.e., Radio Frequency Identification (RFID) and Bluetooth Low Energy (BLE) [92].

The results obtained for each of the analyzed technologies are summarized in Tables 1–8.

Table 1. Hazard detected for Additive Manufacturing (AM).

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
Mechanical	Contact with devices with movable parts	Damages due to entrapment	[35–38]
	Contact with sharp edges, borders, rough surfaces	Minor or major skin injuries	[35]
	Falling or projecting objects	Collision damages	[35]
Electrical	Electric equipment malfunctioning	Burns	[35,37–41]
	Electrostatic phenomena resulting from dusts and from the accumulation of electrostatic charges on plastics	Damages caused by uncontrolled energy releases, fires, or explosions	[35,38]
	Contact with damaged wires that became conductors	Damages caused by uncontrolled energy releases	[35,37,38]
	Electromagnetic interferences between different equipment	Damages caused by malfunctioning devices	[35,37]
Thermal	Overheating devices	Burns	[35,37–39,42]
Noise	Vacuum pumps and air compressors used as machine power suppliers	Hearing damages	[37]
Radiation	Exposure to ionizing radiation and laser sources	Minor injuries and genetic mutations	[35,37,43]
Chemical and biological	Exposure to hazardous chemicals, i.e., ultra-fine powders, monomers, organic compounds, or inert gases	Eye damages	[29,35,37–40,42]
		Eye fatigue	[35,38,40,44]
		Skin damages, skin sensitization, and contact dermatitis	[37,39–41]
		Nasal mucosa injuries	[35–43]
		Respiratory (asthma and allergic rhinitis) and lung damages	[35–44]
		Cardiovascular diseases	[35,37,39,40,44]
		Central nervous system damages	[35,38–40,43,44]
		Long-term storage damages	[35–45]
		Metal poisoning	[35,37,39–42,44]
		Cell damages and genetic mutations	[35,37,39–44]
		Loss of coordination, headache, and nausea	[38]

Table 1. *Cont.*

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
		Reproductive system damages	[43]
	Exposure to flammable and reactive chemical agents	Burns	[42]

Table 2. Hazard detected for Automated Guided Vehicle (AGV).

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
Mechanical	Device instability	Damages due to entrapment	[47]
		Damages to the operators caused by the fall or imbalance of the devices	[47]
	Machine speed monitoring system failure	Collision damages	[47,48]
	Laser vision system's inability to detect obstacles in the shadow	Collision damages	[48]
	Fall of the loads from the machines in case of braking	Damages caused by the collision with objects	[48]
	Emergency brake failure	Damages due to entrapment	[48]
Electrical	Electromagnetic interferences between the devices	Damages caused by malfunctioning devices	[49,50]
Thermal	Overheating devices	Burns	[48]
Chemical and biological	Release of corrosive (or acids) agents from batteries	Contact damages	[48]
Organizational	Inadequate setting of the trajectories	Collision damages	[46–51]
	Inadequate weight and sizing of the vehicles	Collision damages	[51]
	Planimetric changes	Collision damages	[48]
	Human-machine verbal interaction	Damages caused by the lack of understanding of the messages	[48]

Table 2. *Cont.*

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
	Inadequate employee training	Damages caused by unexpected actions of the machine	[48]
		Decreased job satisfaction	[48]
	Non-user-friendly interfaces	Feelings of insecurity and danger	[48]
	Increased device activity control	Psychophysical stress	[48]
	Maneuver errors (made by humans or machines)	Psychophysical stress	[48]
	Limited observability of the operating conditions	Burns	[48]
	Inadequate computer security systems	Damages caused by malware, hacker attacks, technical programming errors, and unexpected behavior of the device	[50]

Table 3. Hazard detected for Augmented Reality (AR) and Virtual Reality (VR).

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
Chemical and biological	Contact of plastic and metallic material with superficial body parts	Skin irritation and allergic reactions	[54]
	Inadequate device sanitation	Eye diseases	[54]
Ergonomic	Dimension and the weight of the devices	Discomfort	[55–58]
	Decentralized display vision	Discomfort	[55]
		Eye fatigue	[55]
	Decreased blink rate	Eye fatigue and eye dryness	[56]
	Workload on lower neck area	Muscle fatigue	[55,56,59]
	Workload on shoulders and upper back	Muscle fatigue	[59]
	Workload on hands and arms	Muscle fatigue	[59]
	Limited visual field	Damages caused by monitoring decrease	[54,56,57,59]

Table 3. *Cont.*

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
Work environment and microclimate	Varying lighting conditions of the workplace	Visual discomfort due to the need to adjust to the different light levels	[56]
		Eye dryness	[56]
		Glare damages	[59]
Organizational	Prolonged use of the devices	Discomfort	[55,56,60]
		Eye fatigue	[45,55,56,58–60]
		Nausea, dizziness, disorientation, motion sickness and headache	[45,54,58–63]
		Social isolation	[61,62]
		Increased heartbeat and breathing rate	[58]
		Gastric damage	[58]
		Damages caused by distraction	[45,54,58,64]
		Unpredictable long-term musculoskeletal consequences	[56,64]
	Significant information load	Cognitive overload	[59,64–66]
	Latency of the screens (images adjust slowly in response to the operator's head movement)	Headache	[55,57,58]
	Overlap between virtual images and real objects	Eye fatigue due to the different focal lengths	[56,58]
	Possibility to instruct workers in real time	Psychophysical overload due to work intensification	[67]
	Despecialization of job duties	Damages caused by the decreased competences	[67]
	Inadequate employee training	Damages caused by unexpected events	[67]
	Possibility to capture images and record videos	Fear of privacy violation	[55,57]
	Difference between the virtual images and the real world	Damages due to reduced movement coordination	[57,58]

Table 3. *Cont.*

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
	Information disappears as a consequence of the interposition of an object/person in the visual range	Damages due to errors	[57]
Psychological	Operators grow accustomed to employ technology	Addiction and separation anxiety	[45,57]
	Excessive physical and mental load	Technostress	[45,58,64–66,68]
	Interaction with technological devices	Social isolation	[45,61,62]

Table 4. Hazard detected for Digital Twin.

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
-	-	-	-

Table 5. Hazard detected for Exoscheleton.

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
Electrical	Uncontrolled energy release from the devices or shutdown, due to power failures	Damages caused by unexpected behavior of the device	[72]
		Damages caused by uncontrolled energy releases	[72]
	Inadequate computer security systems	Damages caused by malware, hacker attacks, technical programming errors, and privacy violation	[73]
Thermal	Overheating devices	Burns	[72]
Noise	Exposition to significant acoustic phenomena	Hearing damages	[72]
Vibration	Oscillatory motion of the devices	Damages caused by mechanical solicitation	[72]

Table 5. *Cont.*

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
Chemical and biological	Release of corrosive materials from batteries	Skin irritation and burns	[72]
	Contact of plastic and metallic material with superficial body parts	Skin irritation and allergic reactions	[74]
	Inadequate device sanitation	Infections	[72,75]
Ergonomic	Limited mobility	Collision damages (e.g., inability to avoid falling objects)	[72,74–80]
	Improper movements or overexertion	Muscle damages (e.g., tears)	[72]
	Additional weight of the devices, dimensions and weight distribution	Musculoskeletal issues	[72,74–77,81,83]
		Muscle fatigue	[72,74–76,78,80–82]
		Damages connected to spine overload	[72,79]
		Postural stress	[72,77,79,82]
		Cardiovascular diseases	[72,74,82]
		Damages caused by the difference in art-leg kinematic	[72,74,81,82]
		Minor damages and pressure injuries	[72,74,75,77,81]
		Nerve compression	[72,74]
		Respiratory fatigue caused by a decreased chest excursion and by an increased chest pressure	[72,74,81]
		Discomfort	[72,74–76,78,80–82]
		Damages caused by imbalances, slips, trips, and falls	[72,75,77,79]
		Damages caused by the wrong weight redistribution between different body parts	[74]
		Collision damages (e.g., with other operators or robots)	[77]
		Damages caused by the reduced reactivity (e.g., in case of fire)	[75]

Table 5. *Cont.*

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
	Increased directional load	Damages linked to dynamic events	[72,79]
	Limited workspaces	Damages caused by the increased volume of the operators	[75]
Work environment and microclimate	Increased temperatures in the workspace	Infections caused by bacteria proliferation inside of the devices	[72]
	Limited workspaces	Damages caused by the increased volume of the operators	[75]
Organizational	Personal data monitoring (e.g., localization)	Fear and perception of privacy violation	[73]
	Increased physical capabilities	Cognitive overload	[72]
	Inadequate employee training	Insecurities and personal and professional fears	[75]
	Inadequate computer security systems	Damages caused by malware, hacker attacks, or technical programming errors and privacy violation	[73]
Psychological	Reliance on technology	Decreased attention to security measures, muscle density loss	[72]
	Constant use of exoskeletons	Fear of stigmatization in the workplace (e.g., employees are afraid of being perceived as technology-dependent)	[74]

Table 6. Hazard detected for Robot and Cobot.

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
Mechanical	Movement of mobile parts (arms, limit switches, and other terminals)	Crushes, cuts, severing, entanglements, dragging, entrapments, impacts, perforations, frictions, or abrasions	[84–86]
	Rotational movement of any axis of the robot/cobot		
	Inability to exit from robot's cells		
	Interaction with loose clothing or long hair		

Table 6. *Cont.*

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
	Inadequate grasp of the arms of robots/cobots	Damages caused by the fall or expulsion of materials, products, and tools	[86]
	Contact with sharp edges and sharp areas	Skin damages	[86]
	Insufficient robot reactivity	Collision damages	[87]
	Legibility and predictability of human and robot/cobot trajectories	Collision damages	[87,88]
		Damages caused by imbalances, slips, trips, and falls	[86,88]
	Maintenance activities performed at significant heights	Damages connected to falls	[84,89]
	Hindrance/limitation of the machines' vision systems	Collision damages	[90]
Electrical	Electromagnetic interferences between different equipment	Damages caused by malfunctioning devices	[89]
	Power supply interruption	Damages caused by the fall of tools or extractors	[86]
	Unexpected potential energy release from storage sources	Burns	[84,86]
	Contact with parts or connection under tension and exposition to the electric arc	Burns	[84]
Thermal	Overheating devices	Burns	[84]
Noise	Exposition to significant acoustic phenomena	Hearing damages	[84,86]
Vibration	Oscillatory motion of the devices	Damages caused by mechanical solicitation	[45,68,84,86,89,90]
Radiation	Exposure to ionizing radiation and laser sources	Superficial skin damages	[84]
		Eye and airway damages	[84]
Chemical and biological	Release of corrosive (or acids) agents from batteries	Skin and airway damages	[84]
Ergonomic	Non-user-friendly interfaces	Mental stress	[86]
		Discomfort	[86]

Table 6. *Cont.*

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
	Posture during collaborative operations	Posture damages	[85]
Organizational	Repetitive tasks performed at the pace of robots/cobot	Fatigue	[86,88]
		Musculoskeletal stress	[86]
		Psychological pressure	[16,45,48,67,68,91]
		Damages caused by monitoring decrease	[68,86]
		Physical overload	[89]
	Simultaneous monitoring of several robots/cobots	Cognitive overload	[48,89]
	Reduction of the activities performed by humans and consequent decrease in the attractiveness of the job	Cognitive underload and consequent damages connected to concentration decrease	[48,89,91]
	Physical human-robot proximity during operating phases	Mental stress	[68,88,90]
		Collision damages	[45,68,90]
	Robot/cobot movement fluency	Discomfort	[88]
		Cognitive stress	[16]
		Collision damages	[16]
	Shared workspaces	Direct collision damages	[48,88]
		Indirect collision damages (object falls)	[48]
	Robot implementation in spaces different than those they were designed for	Damages caused by collisions or unpredictable behaviors	[89]
	Outsourcing during the robot construction, configuration, installation, and design phases	Damages caused by poor knowledge of the machines (collisions, inability to act in emergency situations)	[48,89]
	Inadequate employee training	Fear of redundancies or subjugation	[48,84,91]
		Damages caused by unpredictable behaviors	[84,90,91]
		Dependency from third parties (e.g., robot/cobot repair workers)	[91]

Table 6. *Cont.*

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
	Unauthorized configuration parameter	Damages caused by unexpected behaviors and errors	[86]
	Unclear work instructions	Damages caused by unexpected behaviors and errors	[85]
	Robot/cobot movement predictability	Fear and shock	[84,91]
	Robot/cobot automated learning	Collision damages caused by unpredictable behaviors	[67]
	Inadequate computer security systems	Damages caused by malware, hacker attacks, technical programming errors, direct collisions, indirect unexpected collisions (falling chemicals containers or blunt or radioactive equipment), and unexpected behavior of the device	[48,67,68,84,89]
	Absence of fences in dynamic conditions	Mental stress	[85,90]
		Fear and insecurity	[85]
Psychological	Interaction with technological devices	Social isolation	[45,48,67,91]
	Reduced contact with coworkers	Social isolation	[45,91]
	Robots/cobots are faster than humans	Feeling of inferiority and subordination	[89]
	Increasing robot/cobot implementation	Feeling of inferiority and subordination	[91]
	Perception of inadequate safety conditions	Psychophysical stress	[88]
	Reliance on the robots' ability to detect humans and to think	Collision damages	[48,84]
	Robot/cobot variability and unpredictability	Mental stress	[85,90]
		Fear and insecurity	[85]

Table 7. Hazard detected for Smart Wearable.

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
Electrical	Electromagnetic interferences between the devices	Damages caused by the malfunctioning of the devices (e.g., deactivation of possible subcutaneous medical devices)	[94]
Radiation	Exposition to electromagnetic radiations (e.g., ionizing, and non-ionizing)	Minor injuries and genetic mutations	[95]
Chemical and biological	Contact of plastic and metallic material with superficial body parts	Skin irritation and allergic reactions	[96]
Ergonomic	Inadequate dimension, weight, and position of the devices	Discomfort	[45,73,97]
		Long-term damages to the dominant brachial biceps	[69]
		Muscle fatigue (e.g., shoulder muscles)	[69]
		Damages caused by muscular destabilization in the area of the middle thoracic spine and the shoulder blade	[69]
Organizational	Frequent and prolonged use of the devices	Muscle fatigue	[45,69,73]
		Postural damages caused by muscle overuse or muscle destabilization	[69]
		Technostress	[45,73,97]
	Health and safety conditions monitored by the devices	Damages caused by monitoring decrease	[45,73]
		Damages caused by the decrease of private medical checks	[97]
	Personal data monitoring (e.g., localization)	Fear and perception of privacy violation	[73,97]
	Inadequate employee training	Damages caused by unknown behaviors of the machine	[68]
	Inadequate computer security systems	Damages caused by malware, hacker attacks, or technical programming errors and privacy violation	[73]

Table 7. *Cont.*

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
Psychological	Operators grow accustomed to employ technology	Addiction and separation anxiety	[45,73,97]

Table 8. Hazard detected for Wireless Technologies.

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
Electrical	Electromagnetic interferences between the devices	Damages caused by malfunctioning devices	[98]
Thermal	Heat induced by high-frequency electromagnetic fields	Tissue overheat, burns	[99]
Radiation	Exposition to electromagnetic radiations	Superficial damages, cell damages, cerebral damages, and genetic mutations	[99,100]
		Long-term unpredictable damages	[99]
		Oxidative stress and antioxidant reduction	[100]
		Cancer	[100]
		Neuropsychiatric changes (e.g., cholinesterase increase, deficits in learning, reduced ability to discern familiar from new objects)	[100]
		Endocrine changes (e.g., pancreatic dysfunctions, catecholamine, prolactin, progesterone)	[100]
		Teeth development alteration	[100]
		Abnormal postnatal development	[100]
		Cardiac damages and blood pressure interruption	[100]
		Stimulation of adipose stem cells and possible connection to obesity	[100]

Table 8. *Cont.*

Hazard	Origin/Source of Risk	Consequences for Occupational Safety and Health (OSH)	Bibliographic Sources
		Testicular and sperm damages and infertility	[100]
Chemical and biological	Exposition to hazardous chemicals	Long-term storage damages	[99,100]
Organizational	Health and safety conditions monitored by the devices	Damages caused by monitoring decrease	[73]
	Inadequate computer security systems	Damages caused by hacker attacks	[98]
Psychological	Constant surveillance	Psychological pressure	[45]

5. Discussion

The presented analysis examined the most widely implemented technologies in the manufacturing field to investigate the presence of specific hazards, classified by the hazard categories arising from the combination of the International Standard ISO12100:2010 and two additional categories—organizational and psychosocial hazard—as previously explained. The aim was twofold: investigate the presence of specific workers' health and safety hazards for each of investigated technologies, which have not yet been discussed in detail in the literature, and present them in a common, easy-to-read classification. Results reveal the presence of specific hazards for all the investigated technologies except one, namely Digital Twin.

Firstly, the implementation of additive manufacturing poses mainly electrical, chemical, and biological hazards, followed by mechanical and thermal hazards deriving from the noise and the radiations generated by the devices. Furthermore, according to the existing literature, the use AGVs is connected to mechanical and organizational hazards, as well as electrical, thermal, and chemical and biological hazards. AR and VR technologies, on the other hand, pose significant organizational and ergonomic hazards for the operators, as well as chemical and biological hazards, strictly linked to the work environment and the microclimate, and psychological hazards. The analysis of Digital Twin technology did not provide significant hazards for the workers' health and safety, while it revealed several hazards connected to exoskeletons, mainly ergonomic, electrical, and organizational, and it also showed a smaller number of further hazards, which, however, may lead to significant consequences for the operators, i.e., thermal hazards, chemical and biological hazards, hazards caused by the devices' noises and vibrations, hazards connected to the work environment and microclimate, and psychological hazards. Furthermore, the implementation of robots and cobots exposes workers mainly to mechanical, electrical, organizational, and psychological hazards, and, to a smaller extent, to ergonomic, thermal, and chemical and biological hazards, as well as to hazards caused by the noises, vibrations, and radiations generated by the devices. Moreover, wireless technologies pose mainly organizational hazards, but they may also provoke electrical, chemical and biological, ergonomic, and psychological hazards, as well as hazards connected to radiation emission. Finally, wireless technologies expose workers mainly to hazards deriving from the devices' radiation emissions, and to additional sources of risks, i.e., electrical, thermal, chemical and biological, organizational, and psychological hazards.

In general, despite the high number of cross-cutting and specific risks identified, the analyses on this topic are still scarce. The low implementation level of some technological solutions does not allow to significantly anticipate their effects, which are often only investigable in the short term. Additionally, bureaucracy and technicalities, such as the timeline for standards and regulations approval, often lead to the complete lack of standardization in terms of health and safety for long periods. Moreover, several technologies have not been analyzed yet in terms of hazards for the workers, i.e., Digital Twin. Nevertheless, the non-analyzed technologies affect the workers' safety as well [101]. The reason behind the above-mentioned gap in the existing literature lies in the previously described elements. Furthermore, the performed analysis showed that some of the implemented technologies are not yet able to guarantee the workers' occupational safety and health. Therefore, new technological developments should aim at embedding safety systems and systems for the detection of the workplaces and workers' conditions to safeguard the user. In addition, it should be noted that emerging hazards are not only physical and physiological, but they also involve psychological aspects. For this reason, legislators, researchers, psychologists, and technology manufacturers should work together in a targeted manner to bridge the gap concerning workers' health and safety.

6. Conclusions and Future Research Developments

The innovative contribution of the research was to investigate the presence of specific worker's health and safety hazards for 4.0 technologies that may directly impact new working procedures and conditions resulting from manufacturing context digitization. For this purpose, the presented paper aims at answering the research question presented in Section 2 by focusing on:

- Main thematic areas that should be considered to ensure the workers' health and safety during the transformation process of workspaces and tools.
- The presence of cross-cutting risks to workers among different technological areas.
- The presence of specific risks to workers related to specific technological solutions.

As previously described, digital innovation in manufacturing environments poses numerous risks to workers. Therefore, it is crucial to investigate the extent of the hazards deriving from the specific technological solutions implemented, while also analyzing the hazards that may derive from the combined use of two or more technologies. The combination of different solutions may amplify the harmful effects or generate new hazards in a non-linear way to the individual components. To ensure a safe transition, the above-mentioned aspects should be considered from the initial technology design and implementation phases, which should aim at defining or redefining roles, spaces, tasks, and responsibilities in a shared and conscious way. Therefore, the workers affected by the transformation of workplaces and tools should be informed, formed, and involved to be able to favorably face the change and to take it as an opportunity to improve their skills. The analysis of the eight technological categories illustrates the existing hazards for each of the investigated technologies, as explained in Section 5. In this way, the presented research allows all manufacturing companies to assess whether their new technologies are implemented appropriately to ensure the worker's health and safety. This requires analyses concerning how the 4.0 technology is implemented, considering many elements, e.g practices, procedures, working environments, production layout, safety, and monitoring systems, as well as psychological and cognitive worker issues. Providing a summarized and classified overview of these aspects can make the analysis more effective and comprehensive, as well as allowing organizations to quickly identify relevant aspects in correspondence with the specific technologies they implement. Moreover, it enables both the analysis of currently deployed technologies, aiming at modifying or monitoring certain issues, and pre-emptive analysis of future technologies, with a view to prevention. Since the implementation of Industry 4.0 poses new OHS hazards, mainly connected to human-machine interactions, the complexity of sociotechnical systems results increased. Sociotechnical systems always include a form of human participation in at least one of their life-cycle stages [102]. However, traditional workers' health and safety risks identification and assessment methods are not always able to suitably address the system's properties. For this reason, it is crucial to include new safety assessment paradigms and methods able to address the growing complexity of workplaces, namely by borrowing theories from studies on complex adaptive systems [103].

Future research directions of this study can build resilient systems for risk identification, risk assessment, and response plan design for the risks identified concerning each technological solution. The evolution of the current safety paradigm brings to light Resilience Engineering (RE): a new discipline aimed at managing Safety II in sociotechnical systems, while engineering its counterpart, i.e., resilience [104]. Safety II defines the risk deriving from the numerous non-linear interactions between the system's subparts. It is not possible to separately analyze technical and social aspects in a sociotechnical system [105–107]. It is no longer possible to obtain an overall description of the system by analyzing single components. Considering the recent technological innovation, the rapid evolution of technological solutions, and the mutual complementarity between human workers and machines, it should be crucial to provide systematic descriptions of the relationship of the constitutive function of a sociotechnical system [108]. Furthermore, both the manager and the employees should be involved in the review of the workers' health and security elements. When safety is only supervised by a manager, possible problems may arise, mainly due to their lack of knowledge on all the aspects connected to the practical and operating functioning of the process [105–107]. Further developments connected to RE include the design of an assessment tool for the evaluation of readiness and resilience of the new categories defined in this paper. Moreover, future analyses should also focus on estimating the risks deriving from the probability of an impact, as well as other risks for workers, which were presented in this contribution. Finally, automatic text analysis tools, e.g., Natural Language Processing (NLP) tools, could be developed and implemented to facilitate and accelerate the analysis of the documents, thus allowing to search new emerging hazards and risks in a greater number of databases expanding the starting document sample of the presented analysis. This can result in the continuous identification of additional hazards to worker's health and safety in an increasingly frequent and rapid manner. To the present day, these technologies are a valuable support for researchers during the document analysis and literature review processes.

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Abbreviations

AGV	Automated/Automatic Guided Vehicle
AI	Artificial Intelligence
AM	Additive Manufacturing
AR	Augmented Reality
BLE	Bluetooth Low Energy
EU-OSHA	European Agency for Safety and Health at Work
GPS:	Global Positioning System

HAI	Human Automation Interaction
HFE	Human Factor Ergonomics
HMI	Human Machine Interface
HRC	Human Robot Collaboration
ICT	Information and Communication Technology
INAIL	Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro (Italian National Institute for Insurance against Accidents at Work)
INRS	Institut National de la Recherche Scientifique (French National Research and Safety Institute)
IoS	Internet of Simulation
IoT	Internet of Things
ISO	International Standard Association
MCR	Main Control Room
NLP	Natural Language Processing
OHS	Occupational Health and Safety
QR code	Quick Response code
RE	Resilience Engineering
RFID	Radio Frequency IDentification
RMS	Reconfigurable Manufacturing System
SG	Signaling Gateway
UAV	Unanimated Aerial Vehicle
VR	Virtual Reality
WRMSD	Work Related Musculoskeletal Disorder
WSD	Work System Design

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