POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Opportunities and Challenges of Industry 4.0 in OH&S Management System: A Critical Review

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

Génie industriel

Décembre 2021

POLYTECHNIQUE MONTRÉAL

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Ce mémoire intitulé :

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présenté par **Masoud REZAZADEH**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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RÉSUMÉ

La quatrième révolution industrielle, Industrie 4.0, a été lancée en 2011. Depuis lors, elle a suscité une attention considérable de la part des chercheurs du monde entier. De nombreux articles scientifiques ont été publiés pour présenter les fonctions de l'Industrie 4.0, promouvoir les affaires et augmenter la productivité. Les opportunités de l'Industrie 4.0 pour améliorer la santé et la sécurité au travail (SST) ont également été considérablement explorées. Cependant, quelques publications ont mis en évidence les enjeux de l'Industrie 4.0 en SST. Certains craignent que les réalisations en matière de SST ne soient affectées, ce qui pourrait constituer un obstacle aux progrès de l'Industrie 4.0.

Cette thèse vise à identifier à la fois les défis qui découlent de l'Industrie 4.0 et les opportunités qu'elle ouvre pour les systèmes de management de la SST. Comme point de départ, un historique des technologies constitutives de l'Industrie 4.0 ainsi que les principes fondamentaux qui sous-tendent la gestion de la SST aujourd'hui sont fournis. Ensuite, la méthodologie de cette étude est expliquée qui se compose de trois étapes. Dans la première étape, nous effectuons une revue systématique de la littérature pour acquérir des connaissances de base sur les défis et les opportunités que l'industrie 4.0 crée pour la SST, en appliquant la méthode ProKnow-C. Dans la deuxième étape, une comparaison détaillée entre trois normes de système de gestion de la SST bien connues - CSA Z1000 en tant que norme nationale, OHSAS 18001 en tant que norme internationale et ISO 45001 en tant que norme ISO est effectuée. Dans la dernière étape, nous synthétisons les défis et opportunités identifiés dès la première étape avec les clauses incluses dans ces trois normes. Pour faciliter la synthèse, nous nous concentrons sur la plus inclusive de ces trois normes, ISO 45001. Cependant, les résultats peuvent être généralisés aux deux autres normes.

En conséquence, nous arrivons à cinq conclusions : Premièrement, il n'y a pas encore eu suffisamment d'attention à l'intégration des aspects humains dans les systèmes industriels 4.0. L'inadéquation entre les capacités humaines des travailleurs et la charge de travail produite par les machines dans les interactions homme-machine peut entraîner des erreurs humaines, des accidents

et même des problèmes psychologiques. Il est recommandé de considérer les aspects humains dans la phase de conception d'un système Industrie 4.0.

Deuxièmement, les coûts élevés et les limitations techniques sont deux obstacles principaux pour tirer pleinement parti des opportunités de SST des technologies de l'Industrie 4.0. De plus, le manque de main-d'œuvre qualifiée ainsi que les considérations éthiques sont d'autres obstacles dont il faut tenir compte. Les PME pourraient être plus touchées par ces problèmes en raison de ressources financières plus restreintes pour concurrencer les grandes entreprises.

Troisièmement, les risques probables pour la SST à l'ère de l'Industrie 4.0 sont identifiés et classés en six groupes, y compris les risques biologiques, chimiques, physiques, ergonomiques, psychologiques et de sécurité. Parmi eux, les risques psychologiques pourraient être évidents à mesure que les systèmes homme-machine seront transformés. En plus de ces dangers, une hiérarchie de contrôles des risques, y compris l'élimination, la substitution, les systèmes de sensibilisation, les contrôles administratifs et les EPI pouvant être activés par l'industrie 4.0, est introduite.

Quatrièmement, ISO 45001 est plus complet que les deux normes OHSAS 18001 et CSA Z1000. Les principales différences incluent l'identification des problèmes internes et externes affectant les performances de SST ainsi que les besoins des travailleurs. À cet égard, il est nécessaire de reconnaître les opportunités de la SST ainsi que les risques pour la SST.

Cinquièmement, la synthèse de nos conclusions issues de l'analyse de contenu et des exigences des normes du système de management de la SST montre que dans la phase de leadership, une organisation peut rencontrer des difficultés à mener une culture de SST efficace grâce à la participation des travailleurs parce que les travailleurs de différentes nationalités, origines , et les cultures, avec des perceptions tout aussi diverses de la SST peuvent se réunir pour travailler. Au contraire, l'IdO et l'intégration verticale et horizontale des systèmes pourraient faciliter la communication, ce qui a un effet positif sur la participation des travailleurs. Dans la phase de planification, malheureusement, les lois et réglementations en matière de SST sont à la traîne par rapport à l'Industrie 4.0. Cela soulève des inquiétudes quant au fait que les approches proactives en matière de SST peuvent être affectées. D'autre part, l'Industrie 4.0 peut viser à lever des incapacités technologiques afin de répondre aux obligations légales. De plus, l'Industrie 4.0 peut aider à créer un système d'information efficace et en temps réel et stimuler la gestion des technologies de l'information qui joue un rôle clé dans la planification et la réalisation de ses objectifs en matière de SST dans une organisation. Dans la phase d'accompagnement, une pénurie de travailleurs possédant des compétences techniques et personnelles peut imposer une charge de travail supplémentaire aux employés compétents et les épuiser. D'un autre côté, les méthodes pédagogiques innovantes basées sur la réalité augmentée ont le potentiel d'améliorer l'efficacité de la formation en SST et la sensibilisation des travailleurs aux risques environnants. En phase d'exploitation, si des algorithmes intelligents prévalent, ils peuvent fournir un contrôle en temps réel des aspects SST dans les opérations d'une organisation. Cependant, les situations imprévisibles qui peuvent provenir d'un dysfonctionnement de ces algorithmes et mettre en danger les travailleurs doivent être prises en considération. De plus, la réalité augmentée peut fournir des exercices proches de la réalité pour améliorer la préparation des travailleurs à répondre aux urgences. Cependant, les organisations doivent également être prêtes à répondre aux urgences imprévues résultant de cyberattaques à grande échelle. Dans la phase d'évaluation des performances, dans le cas du développement de l'analyse des mégadonnées et de la vision par ordinateur dans le monde du travail, des évaluations factuelles des performances en matière de SST sont possibles. Il convient de mentionner que ces possibilités doivent être utilisées parallèlement aux outils d'évaluation traditionnels pour refléter l'évaluation réelle de la performance SST. Dans la phase d'amélioration, d'autres avancées dans la gestion de la SST sont attendues sur la base du rythme rapide de la progression technologique, comme la capacité des visions par ordinateur à modéliser la dynamique du mouvement, qui vise à prédire les comportements humains dangereux. Mais la progression technologique pourrait être associée à de nouveaux risques. L'exemple peut être des interfaces cerveau-machine directes qui chauffent les tissus corporels et sont suspectées de provoquer ou de favoriser le cancer.

À notre connaissance, il s'agit de l'une des premières études qui utilisent les critères énoncés dans les normes de système de management de la SST pour analyser les défis et les opportunités de l'Industrie 4.0 et leurs implications pour les travailleurs d'aujourd'hui et de demain. Pour les recherches futures, il est recommandé que des études pratiques soient menées pour évaluer les risques pour la SST découlant de l'Industrie 4.0.

ABSTRACT

The fourth industrial revolution, Industry 4.0, has been launched in 2011. Since then, it has attracted considerable attention from researchers around the world. Many scientific articles have been published to introduce the functions of Industry 4.0, to promote business, and to increase productivity. The opportunities of Industry 4.0 for improving occupational health and safety (OH&S) have also been considerably explored. However, a few publications have highlighted the challenges of Industry 4.0 in OH&S. There are concerns that OH&S achievements may be affected, and this may place an obstacle in the way of Industry 4.0's progress.

This thesis aims to identify both the challenges that arise from Industry 4.0 and the opportunities it opens up for OH&S management systems. As a starting point, a background of the constituting technologies of Industry 4.0 as well as fundamental principles underlying OH&S management today are provided. Then, the methodology of this study is explained which consists of three steps. In the first step, we carry out a systematic literature review to gain background knowledge of the challenges and opportunities Industry 4.0 creates for OH&S, applying the ProKnow-C method. In the second step, a detailed comparison among three well-known OH&S management system standards – CSA Z1000 as a national standard, OHSAS 18001 as an international standard, and ISO 45001 as an ISO standard is made. In the last step, we synthesize the identified challenges and opportunities from the first step with the clauses included in these three standards. To facilitate the synthesis, we focus on the most inclusive of these three standards, ISO 45001. However, the results can be generalized to the other two standards.

Accordingly, we come to five conclusions: First, there has not been sufficient attention to incorporating human aspects in 4.0 industrial systems yet. The mismatch between the human capabilities of workers and the workload produced by machines in human-machine interactions can lead to human errors, accidents, and even psychological problems. It is recommended to consider human aspects in the stage of design of an Industry 4.0 system.

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intelligent algorithms prevail, they can provide real-time control of OH&S aspects in the operations of an organization. However, unpredictable situations that can stem from a malfunction of these algorithms and endanger workers must be taken into consideration. Moreover, augmented reality can provide close-to-reality exercises to enhance the preparedness of workers to respond to emergencies. However, organizations need to be also prepared to respond to unforeseen emergencies arising from large-scale cyber-attacks. In the performance evaluation phase, in the case of the development of big data analysis and computer vision in the world of work, evidence-based evaluations of OH&S performance are possible to conduct. It is worth mentioning that these possibilities should be used alongside the traditional evaluation tools to reflect the real evaluation of OH&S performance. In the improvement phase, more advancements in OH&S management are anticipated based on the rapid pace of technological progression such as the ability of computer visions in modelling motion dynamics, which aims to predict unsafe human behaviour. But technological progression might be associated with new risks. The example can be direct brain-to-machine interfaces that heat up body tissues and are suspected of causing or promoting cancer.

To the best of our knowledge, this is among the first studies that use the criteria stated in OH&S management system standards to analyze the challenges and opportunities of Industry 4.0 and their implications for workers today and tomorrow. For future research, it is recommended that practical studies be carried out to assess the OH&S risks emerging from Industry 4.0.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

3D	Three-dimensional
BCG	Boston Consulting Group
CCOHS	Canadian center for occupational health and safety
CEFRIO	Centre facilitant la recherche et l’innovation dans les organisations
Cobot	Collaborative robot
CPS	Cyber-Physical System
FIR	Fourth industrial revolution
GDP	Gross domestic product
ICT	Information and communication technology
ILO	International labour organization
IoT	Internet of things
IS	Information system
ISO	International organization for standardization
IT	Information technology
MSD	Musculoskeletal disorder
OH&S	Occupational health and safety
OHSAS	Occupational health and safety assessment series
PDCA	Plan, Do, Check, Act
PPE	Personal protective equipment
ProKnow-C	Knowledge Development Process – Constructivist
SME	Small or medium-sized enterprise
UN	United nations

CHAPTER 1 INTRODUCTION

The first industrial revolution, associated with the invention of the steam engine, changed the industry dramatically. On one hand, the production rate increased and factories were found; on the other hand, the number of work-related accidents skyrocketed and their consequences became more severe. To protect workers against these accidents, the concept of "Occupational Health and Safety" (OH&S) was formulated after the first industrial revolution. The purpose of OH&S was to provide a safe, healthy environment. OH&S continued to evolve after the second and third industrial revolutions (following the introduction of electric power and digital information, respectively, into industrial production) with the adoption of legislation and standards [1]. As an important achievement of efforts made over the years, the proactive approach was developed. It plays a key role in preventing work-related accidents and occupational diseases [2]. Based on this approach, OH&S management systems were developed to control risks in a structured way. Today, OH&S management systems are accepted in the workplace because they are useful tools to effectively enhance OH&S performance in organizations. The most reputable standards for OH&S management systems include CSA Z1000, OHSAS 18001 and ISO 45001. CSA Z1000 is a Canadian standard that includes a systematic model for the management of the various topics that can have consequences for OH&S [3]. OHSAS 18001 represents a first attempt to develop an international standard; it has been widely accepted and many organizations around the world have applied its requirements for a management framework to manage OH&S issues in the workplace [4]. In response to the changes in global trade, ISO 45001 was constructed on the basis of previous relevant standards and guidelines, such as OHSAS 18001 and ILO-OSH [5, 6].

The fourth industrial revolution has started and its effects will soon be universally experienced. A report by the European Parliamentary Research Service [7] estimates that global investments in Industry 4.0 grew from US$20 billion in 2012 to more than US$500 billion in 2020. Moreover, United Nations Conference On Trade And Development (UNCTAD) estimates that the market size of Industry 4.0 technologies will increase from US$ 220 billion in 2016 to US$ 2.7 trillion by 2025 [8]. Industry 4.0 is expected to have a major effect on global economies: processes and product qualities will be optimized due to real-time controls, and resource and machinery use and inventory management will improve, supporting the development of smart factories and products [9]. Like its predecessors, the fourth industrial revolution will result in new risk factors affecting OH&S. Jun et al. [10] found a positive relationship between labour turnover and competitive psychological climates and job stresses created by artificial intelligence and robotics technology. Several researchers have focused on controlling ergonomic issues that originated from work with collaborative robots and handheld Internet of Things (IoT) devices [11-13]. Adriaensen et al. [14] recommended adopting complexity thinking approaches to develop new risk assessment models in order to confront the various hazards emerging due to Industry 4.0. Chia et al. suggested a new strategy including control measures based on technology developments, collaborative and sustainable solutions, negotiations between interested parties and development of skills of OH&S practitioners to deal with OH&S challenges in era 4.0 [15]. Salmon and Read [16] highlighted the need to integrate human factors into future work systems. Milijić et al. [17] stated that the organizational and human aspects of OH&S must be reconsidered in the era of Industry 4.0, whereas technical aspects are already quite strong. Badri et al. [2] warned that, if OH&S challenges in the fourth industrial revolution are not identified proactively, the same problems experienced in earlier industrial revolutions will be repeated.

In addition, the Industry 4.0 age may see concerns about the loss of past OH&S successes because, despite numerous technical reports and publications on the benefits of smart production, its impacts on OH&S have not yet been clearly perceived [2, 18]. Thibaud et al. [19] support this opinion, stating that technical issues have attracted more attention in the published research than social challenges such as OH&S. Kadir et al. [20] expressed concern with the lack of attention to human factors and ergonomic issues in published studies related to Industry 4.0. Moreover, technological upgrading and innovation cannot be sustained if the human workforce is not protected from occupational hazards and OH&S is not promoted [21]. Kamp [22] describes agile work in the digital era as safe, healthy work. Key advances in Industry 4.0 technologies are expected to be made by 2025 [23]. The impacts of Technology 4.0 on OH&S must be identified and controlled by then to pave the way for Industry 4.0 in the workplace.

To increase knowledge of how the fourth industrial revolution will affect OH&S practices, this study aims to answer the questions set out below:

1. What challenges and opportunities does Industry 4.0 raise for OH&S performance?

2. Specifically, what kinds of hazards can emerge in the context of Industry 4.0?
3. How can Industry 4.0 facilitate the control and management of OH&S risks?

To respond to these questions, we established the following objectives:

1. To review Industry 4.0 technologies with the aim of examining their implications for OH&S;
2. To conduct a comparative analysis to find the most inclusive OH&S management system standard among three standards of CSA Z1000, OHSAS 18001 and ISO 45001;
3. To analyze these OH&S management system standards for implementation in the age of Industry 4.0 in order to identify new challenges and opportunities;
4. To identify new hazards and OH&S risks that may be associated with Industry 4.0, and related functions for preventing occupational diseases and accidents;

To achieve the first objective, we carried out a literature review using the Web of Science database to gather relevant documents on Industry 4.0. The second objective was accomplished by a detailed comparison of three OH&S management system standards. To meet the third and fourth objectives, we needed to obtain the necessary knowledge on the challenges and opportunities Industry 4.0 presents for OH&S. We conducted a systematic literature review based on the last 10 years of research related to the challenges and opportunities of Industry 4.0 for OH&S applying the Knowledge Development Process – Constructivist (ProKnow-C) method [[24], cited in [25, 26]]. This method provides a structured framework to select a bibliographic referential with scientific recognition and to analyze this referential for a given subject [27]. We used the ProKnow-C method, applying it in three main stages: (1) providing the bibliographic portfolio; (2) analyzing the bibliographic portfolio; and (3) performing a systemic analysis. As a result, we extracted 36 out 117 articles that provided basic knowledge about these challenges and opportunities that Industry 4.0 raises for OH&S. Finally, these findings were synthesized with the clauses of the most inclusive OH&S management system standards.

This thesis contains five chapters. Chapter 2 presents a review of publications concerning Industry 4.0 and its related technologies, OH&S and OH&S management systems. Chapter 3 explains the applied methodology to achieve the stated objectives of this thesis. Chapter 4 discusses the results of the synthesis of opportunities and challenges arising from Industry 4.0 and the requirements of OH&S management systems. Each clause of these OH&S management systems is examined in detail. Finally, Chapter 5 provides a summary of this work and its limitations and makes some recommendations for future studies.

CHAPTER 2 BACKGROUND TO INDUSTRY 4.0 AND OH&S

This chapter outlines a background on three subjects: Industry 4.0, OH&S management, and OH&S management systems. In the first section, we provide background knowledge of the context of Industry 4.0 and its basic aspects. In the second section, we examine articles on OH&S to identify the core of OH&S management. In the third section, a description of the most popular guidelines for OH&S management systems is given. In the fourth section, we explain drivers for studying OH&S implications of Industry 4.0.

2.1 Industry 4.0

The first industrial revolution was launched in Britain in the late 18th century with the invention of the steam engine and the mechanization of production (mass production). It was associated with the widespread use of machines in industrial processes, replacing muscle power with steam power, increasing productivity, and transforming society from an agricultural to an industrial model [28, 29]. In the middle of the 19th century, the second industrial revolution commenced with the introduction of electrical power, which eliminated the limitations affecting the application of steam machines in terms of large size and weight. It also led to the appearance of the assembly line and speedier production [29, 30]. While the first and second industrial revolutions were triggered by the discovery of new kinds of motive power, the third industrial revolution arose out of the entry of information into industry in the 1970s. Thanks to new technologies such as computers and programmable tools, full automation became possible without direct human involvement [29, 31]. After going through three industrial revolutions, we are now in the midst of a fourth one, which was first coined as Industry 4.0 in Germany in 2011 [32]. It is the result of advances in information and communication technologies (ICT), making it possible to upgrade full automation to smart automation so that hierarchical production in flexible quantities is possible [33].

According to Centre facilitant la recherche et l'innovation dans les organisations (CEFRIO), Industry 4.0 can be defined comprehensively as a combination of emerging technologies such as cloud computing, the Internet of Things, cyber-physical systems and big data, to promote work processes, products and deliverable services that enable decentralized decision-making through data collection in real time. These technologies aim to share information in a working system [34].

Based on this definition, organizations can utilize Industry 4.0 to improve the performance of their own products and services. These newly transformed products and services can be applied in carrying out four main tasks: monitoring, control, optimization, and autonomy [35]. It should be noted that other types of technologies can ensure connectivity; however, Industry 4.0 technologies as a group seem to be more flexible and effective for ensuring data exchanges throughout a working system [36]. Boston Consulting Group (BCG) defines the nine main technologies characterizing Industry 4.0 as follows (Figure 2.1) [37]:

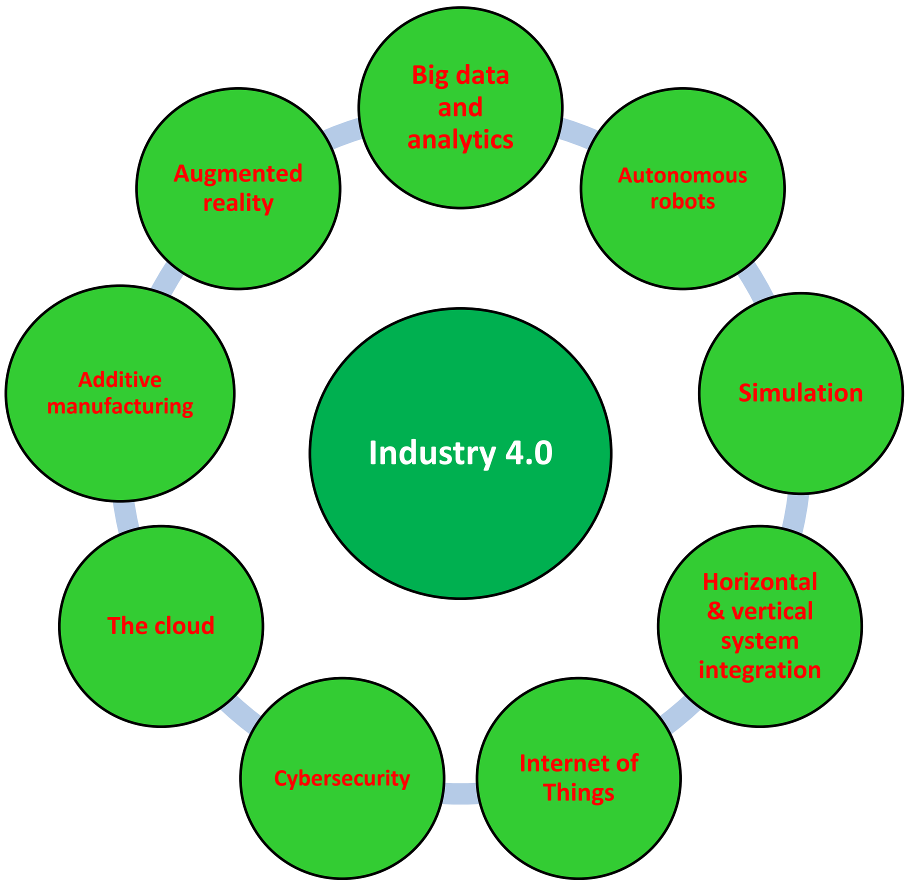

Figure 2.1 Nine main Industry 4.0 technologies

- Big data and analytics

Nowadays, business owners can access a huge amount of data produced by increasingly widespread intelligent devices such as sensors and connected objects. Intelligent, real-time decisions on optimizing desirable trends are now very affordable. These benefits are driven by big data and its comprehensive analysis [38, 39]. Gandomi et al. [40] introduced five main techniques for analyzing big data: text analytics, audio analytics, video analytics, social media analytics, and predictive analytics. In their view, while predictive analytics mainly deals with structured data, it has been more popular than the other four types of analytics which deal with unstructured data. Nevertheless, structured data compose only about 5% of existing big data. Athmaja et al. [41] explained different machine learning techniques that are used for predictive analytics. They concluded that more efficient and advanced machine learning algorithms are needed to deal with complex and heterogeneous datasets.

- Autonomous robots

Robots have been used in different industries to undertake complex tasks for a long time. We are now witnessing new generations of robots with more flexibility, cooperation and autonomy [37] because a high level of machine automation is needed to benefit from the agility associated with Industry 4.0 [42]. According to MacEachen et al. [43], manufacturers can increase productivity by applying automation in their organizations. Pfeiffer [44] supports the idea that robots equipped with embedded sensors, artificial intelligence and increased dexterity play a key role in developing Industry 4.0. According to ISO 8373, autonomous robots not only can move in work areas and perform intended tasks based on a prearranged mechanism but are also able to sense current conditions, detect surrounding situations and change their programs automatically, regardless of human decision-making [45]. Lorenz et al. [46] explain how autonomous robots are able to perform human actions and behave in unexpected situations.

- Simulation

Simulation modelling has been applied to tackle a wide variety of design and engineering problems using mathematical and computing skills. It is a standard tool for developing solutions and validating systems [47]. Schluse et al. [48] believe that, in Industry 4.0, simulation technology is not only used as an engineering tool for development purposes but is also applied inside physical systems to create intuitive user interfaces and training simulators. Since the real and virtual worlds have grown more similar in the era of Industry 4.0, simulation creates a virtual model (digital twin) based on existing realities through real-time monitoring. It can include products, materials, machines, production systems and even humans [37, 38, 49]. Simulations can lead to faster, easier and better-quality decision-making [50].

- Horizontal and vertical system integration

Schuh et al. [23] highlight two important aspects for organizations: integration and self-optimization. Industry 4.0 is also a system involving humans, machines and environmental factors that interact with each other in an enterprise [51]. To benefit from the advantages of Industry 4.0, the systems need to be analyzed as a whole [52, 53]. According to some relevant studies, vertical integration involves the development and execution of activities inside an organization, including organizational structure, human resources, departmental communications, technological and managerial aspects. Horizontal integration refers to networks outside of an organization such as customers, suppliers, contractors and others [50, 54, 55]. Sanchez et al. [56] surveyed system integration in organizations and concluded that it increases their efficiency as data and humans are involved in connecting, communicating, coordinating, collaborating and cooperating.

- Internet of Things

In recent years, many innovative ICT-based devices have changed our lifestyle. Most of them communicate and transfer data through the internet. The same trend to connect everything to a common network has been followed by industry, leading to the introduction of the Internet of Things (IoT) concept [57]. Hozdić [58] defines the IoT as a global network of interconnected objects that communicate using standard methods. Porter and Heppelmann [35] state that the IoT enables one to convert physical objects (i.e., mechanical and electrical devices) or smart objects (i.e., sensors or devices with an embedded computing system) into connectivity objects. It allows one or more connectivity objects to be networked with other connectivity objects with aim of exchanging data in real time [37, 38, 49]. Lee et al. [59] provide an evolved definition of the IoT, based on Cisco, and introduce the concept of the Internet of Everything, which is composed of the Internet of Things, the Internet of Data, the Internet of People and the Internet of Processes. Sanchez et al. [56] add the Internet of Services to those elements because they believe that services such as data storage or clustering are commonly used but cannot be assigned to the categories of things, data, people or processes. By using the IoT to collect data in real time, managers can make good decisions and organizations will have more agility, competitive power, revenue growth, and fewer costs [60].

- Cybersecurity

As Industry 4.0 increases interconnectivity, the threats of cyberattacks are also increased and it is necessary to protect valuable cyber-assets, including data, software and hardware, against unauthorized access [61]. Cisco's 2018 annual report states that more than 80% of IT experts then considered cybersecurity as a high priority; however, only around 40% believed in establishing a standard information security framework in their organizations in case of cyber-threats [62]. Culot et al. [63] point out that cybersecurity is not only about the security of information but is also related to customers' trust. Therefore, it must be considered as a strategic topic in organizations. Cybersecurity fulfills a key role that eventually leads to maintaining enterprises' ability to compete with other businesses. Cybersecurity measures must be applied to identify vulnerabilities and future issues in parallel with expanding the integration of industrial processes through the internet (or GPS technology, wireless networks, etc.) [37, 38].

- The cloud

With Industry 4.0, organizations must store and quickly share an enormous amount of data with other companies or among several workplaces [64]. To do so, cloud technology provides a virtual space for storing data produced by or shared with connected components in the organization. A cloud can be private to the organization or accessible to parties with which data exchanges are essential to the organization [38, 65].

- Additive manufacturing

Additive manufacturing has evolved during the past 30 years. It was initially used as a tool to build prototypes and make patterns; however, now it is a supportive technology for developing and providing a variety of products and services in different fields such as energy, manufacturing, transportation, and even medicine and education [66, 67]. ISO/ASTM 52900 explains the operation of additive manufacturing as a process in which layers of special materials are joined together according to a pre-designed three-dimensional (3D) model. This method of production is the opposite of subtractive manufacturing, in which material is removed during the manufacturing process [68]. Gerbert et al. [37] mention 3D printing as a familiar example of an additive manufacturing method. In this method, a prototype of a customized physical product is made by a 3D printer, mainly for analysis, design and evaluation. ISO/ASTM 52915 recently presented a universal file format that allows designers to determine the shape, colour and composition of a 3D product, including materials and lattices. The file is sent to an additive manufacturing machine to produce the desired product [69, 70]. Horst et al. [71] highlight some important advantages of applying additive manufacturing, such as free design, possibility of manufacturing complex samples, customization in mass production, and minimum waste.

- Augmented reality

Because the digitalization environment is increasing rapidly, an urgent need has arisen for immediate access to digital information in the physical environment. Augmented reality can satisfy this need by enhancing the real physical environment and positioning a layer of digital information, such as pictures, audio, videos and graphics, on top of it [37, 72]. Fraga-Lamas et al. [73] expect that advances in augmented reality technology will enable workers to collaborate more with each other, interact with the processed results of real-time data, and control work operations. In their study, Aleksy et al. [74] introduce one popular application of augmented reality: supporting maintenance and repair workers by providing work instructions textually, visually, or auditorily. Note that some researchers differentiate augmented reality, which does not display an artificial environment, from virtual reality, which presents a whole virtual environment instead of a real one [[75], cited in [76]], [72, 77]. Sanchez et al. [56] point out some of the key benefits of augmented reality including optimization of initial designs, workers training, occupational accident prevention and cost reduction.

2.2 OH&S management

Although the need for safety is a universal one, the roots of OH&S in the modern sense go back to the 18th century and the first industrial revolution. The widespread use of machines and converted workplaces caused a dramatic increase in the number of work-related accidents, diseases and fatalities. The International Labour Organization (ILO) defines OH&S as preventing physical, mental or cognitive adverse effects on workers in the form of disease and accidents arising from their employment; therefore, the ultimate goal of OH&S is to provide a safe, healthy work environment [78-80]. Since the importance of OH&S first became clear, practices have gradually improved. Labour unions to protect workers against job-related hazards were founded, protective OH&S legislation and regulations were passed, and safety measures and inspections were adopted [81]. This approach continued over the years, creating a valuable heritage now known as proactive OH&S management. Liu et al. [82] describe the most important factors of a proactive OH&S program: risk management, regular inspection, and accident investigation to eliminate root causes, and worker training. The advantages of the proactive approach are not limited to enhancing OH&S. In their research, Haslam et al. [83] found a positive link between proactive OH&S and employees' performance. The results of a study by Vredenburgh [84] show that proactive OH&S programs in organizations create economic profits by reducing the cost of lost time and workers' compensation. Väyrynen et al. [79] state that, despite the considerable efforts made to improve OH&S, the current situation is not a desirable one. According to the ILO's statistics, worldwide, 2.78 million occupational fatalities occur annually, causing a lot of human pain and suffering [78]. The economic impact of accidents and ill health is another challenge. Another report published by the ILO estimates that the overall direct and indirect cost of accidents and diseases is equal to approximately 4% of the world's gross domestic product (GDP) [85]. To confront the challenge, the ILO promotes OH&S management systems as an effective solution that has been widely accepted by governments, business owners and employees [86].

2.3 OH&S management systems

OH&S management systems have become a familiar paradigm in the world of work. They are the product of successful attempts to proactively provide a safe and healthy workplace. The history of OH&S management systems dates back to before the Second World War, when large companies set to work to systematically control occupational accidents [87]. Over time, these scattered efforts became more organized, leading to the introduction of the early version of safety management systems in the 1980s [88, 89]. The development of the ISO 9001 quality management system standard in the early 1990s encouraged the international community to issue a single uniform standard for OH&S management systems [90]. As a result, the ILO published some practical guidelines on OH&S management systems under the title *ILO-OSH 2001* [86]. In the last 25 years, several OH&S management systems and guidelines have been introduced [90]. According to Robson et al. [91], OH&S management systems comprise a set of elements to proactively control

OH&S risks and continuously improve OH&S in the workplace. Abad et al. [92] add that OH&S management systems take various facets of OH&S into consideration using a holistic, structured approach. However, some researchers have reported weaknesses of OH&S management systems [93-97]. In general, they have been accepted all over the world, including both developed and developing countries, because their beneficial effects on the rate of occupational accidents, cost and productivity have been demonstrated [91, 92, 98-103].

To carry out this research, we reviewed the CSA Z1000, OHSAS 18001 and ISO 45001, categorized as national, international and ISO standards, respectively. These are some of the most reputable OH&S management system standards recognized by most OH&S practitioners.

- CSA Z1000

Following the introduction of ILO-OSH in 2001 and in view of the great benefit of OH&S management systems, some countries began to develop national standards for OH&S management systems [86]. Thus, the CSA Group published the first edition of the Canadian OH&S management system standard, *CSA Z1000*, and updated it in 2014 [104]. It includes a systematic model for the management of the various set of subjects that can have positive or negative consequences for OH&S, based on the well-known Plan, Do, Check and Act (PDCA) approach, as shown in Figure 2.2. Adoption of this standard helps organizations to reach their OH&S objectives, comply with federal and provincial rules and regulations, and achieve greater growth while respecting their social responsibilities [105].

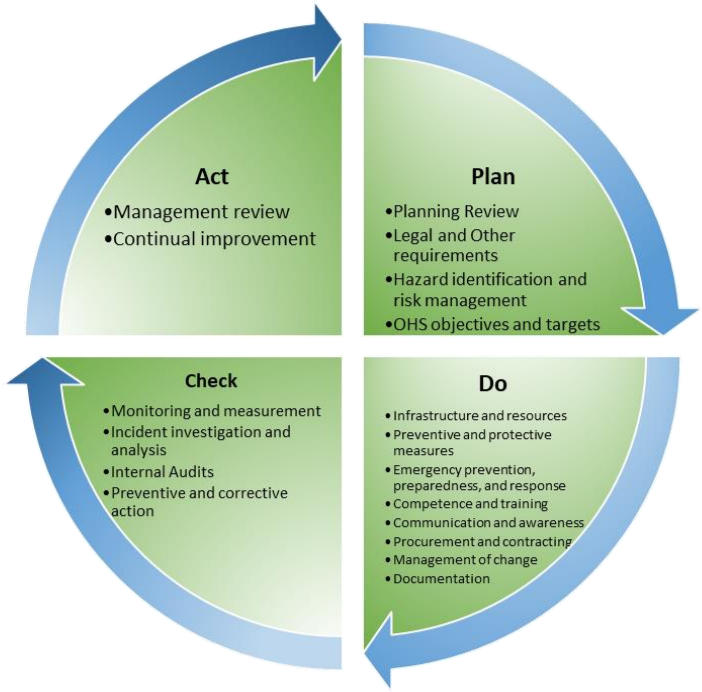

Figure 2.2 Canadian model of an OH&S management system (CSA Z1000)

- OHSAS 18001

As a first attempt to introduce international standards for an OH&S management system, OHSAS 18001 was published in 1999. It has been widely accepted and many organizations around the world have applied the requirements of a management framework to manage OH&S issues in the workplace [4]. It includes a series of requirements that enable employers to control OH&S risks and achieve better OH&S performance by establishing an OH&S management system based on the PDCA model [106], as shown in Figure 2.3.

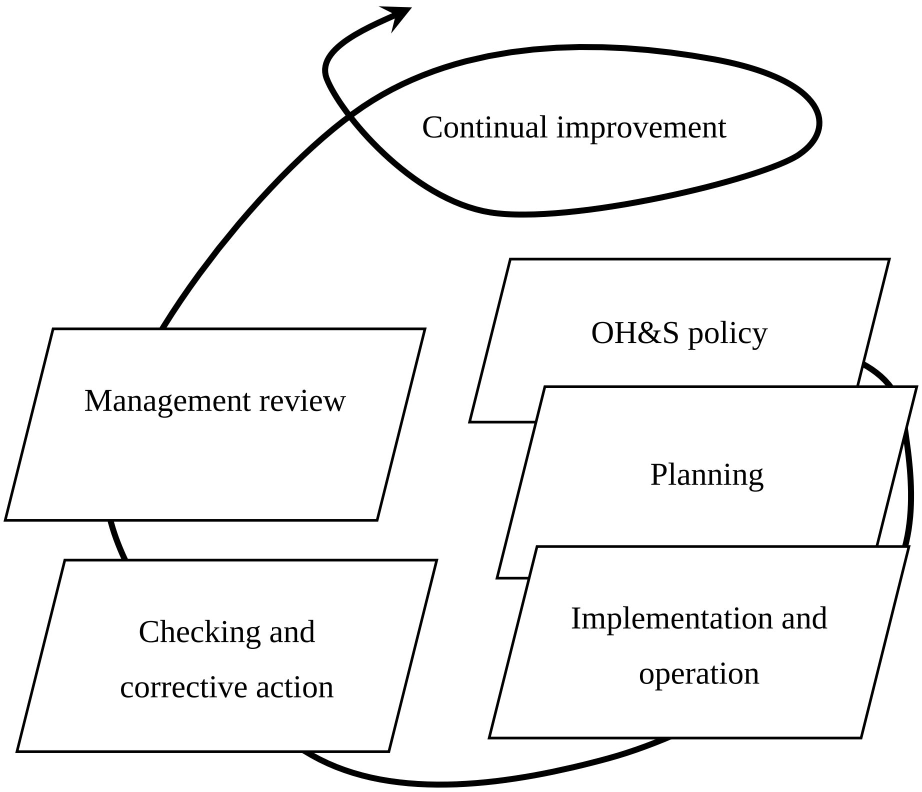

Figure 2.3 OH&S management system model for OHSAS 18001:2007

- ISO 45001

Despite the development of different standards for OH&S management systems [91], the lack of a universal OH&S management system to address the changes in global trade was apparent [5]. One clear piece of evidence of this lack was the catastrophic accident at the Rana Plaza in Bangladesh in 2013. In that tragedy, 1,134 people who were working in a five-storey sewing factory died and more than 2,500 were injured because of a structural collapse neglected by the employer [107]. An important point was that the customers for these products were mainly reputable companies in the garment industry located far from that workplace, which did not carefully monitor whether the factory respected OH&S principles [108, 109]. To cope with this kind of challenge, global efforts were launched. After three unsuccessful attempts, the first version of an ISO standard of the OH&S management systems, under the name of ISO 45001, was formally published in 2018 [[110], cited in [111]]. This standard is constructed on the basis of previous related standards and guidelines, such as OHSAS 18001 and ILO-OSH. As in other ISO standards, such as ISO 9001 and ISO 14001, the approach adopted in ISO 45001 is based on the PDCA structure (shown in Figure 2.4) [6].

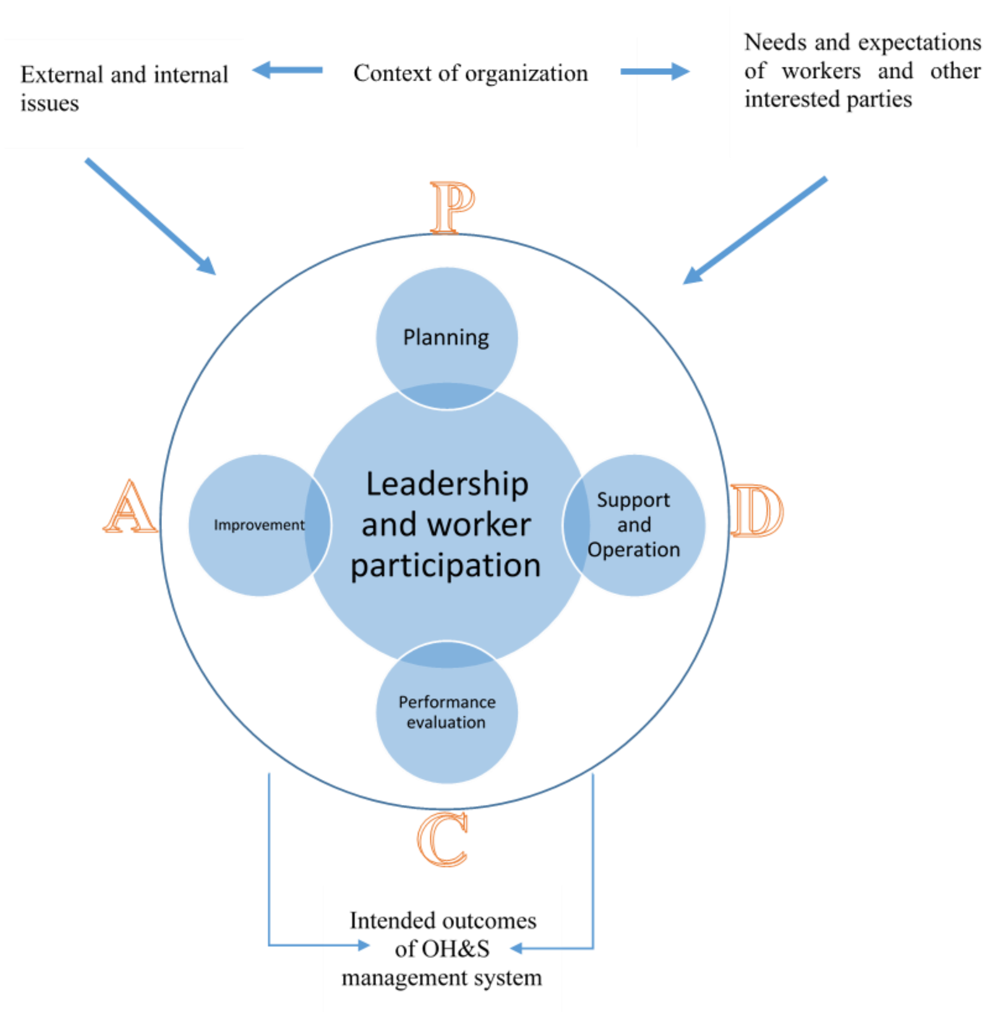

Figure 2.4 Relationship between PDCA and the ISO 45001 framework

2.4 Industry 4.0 and OH&S

The fourth industrial revolution has started and will soon affect businesses everywhere. Like the earlier industrial revolutions, this one will create new risk factors affecting OH&S and will simultaneously raise new possibilities for improving OH&S. As Badri et al. [2] point out, we have witnessed significant progress in the OH&S area after each industrial revolution. Friis [112] supports this view but expresses the worry that achievements have been gained only slowly over time. Badri et al. mention that the proactive approach is a valuable achievement of the third industrial revolution, which must now be applied to the fourth industrial revolution to avoid repeating the same challenges experienced in earlier industrial revolutions. Kamp [22] also says that agile work in the digital era has to be equal to safe and healthy work. Moreover, today OH&S is tied to a business's reputation and cannot be neglected if a company wishes to win in today's context of intense global competition [113-115]. The emergence of Industry 4.0 has provided a resilient infrastructure for innovating and expanding a new generation of industrialization, which will eventually lead to economic growth. This growth can only be compatible with sustainable development if it is accompanied by greater OH&S [116-118]. On the other hand, a published report by the European Agency for Safety and Health at Work (EU-OSHA) foresees that, although the full maturity of Industry 4.0 might take nearly 20 years, key advances such as the development of work automation, a degree of autonomy for machines, artificial intelligence, and 3D printers will be made by 2025. The report continues that this is the deadline when the winners and losers in the contest for the digital revolution will be defined [23]. The intervening period could be the ideal time to identify and control the impacts of Technology 4.0 on OH&S to pave the way for Industry 4.0 at work. However, the major concern is that, despite the importance of the subject, little research has been carried out to study the incorporation of OH&S in the age of Industry 4.0 [2]. In studies of Industry 4.0, its impacts on non-technical factors such as humans (workers) have mostly been ignored [49, 119].

To fill this gap, we analyze the implications of nine Industry 4.0 technologies for OH&S management systems. The results of the literature review show that OH&S management systems are proven tools to proactively promote OH&S performance and cover many factors that affect this issue. In the next chapter, we introduce our methodology for this research.

CHAPTER 3 METHODOLOGY

In this chapter, we describe the methodology applied to this research, as illustrated in Figure 3.1. Our methodology entails three different steps and is applied to answer the research questions. As a starting point, we conducted a systematic literature review to identify the new hazards and current potential of Industry 4.0 to control OH&S risks. Then in the second step, we applied OH&S management system standards as a comprehensive method for evaluating OH&S performance. Given the variety of standards that exist worldwide, we selected three OH&S management systems: OHSAS 18001, CSA Z1000, and ISO 45001. A detailed comparison of these standards was made to find the most inclusive OH&S management system. For this purpose, the commonalities and differences between these standards were examined. Finally, we synthesized our findings from the second step with the clauses of OH&S management systems in order to analyze the challenges and opportunities that Industry 4.0 raises for OH&S management systems.

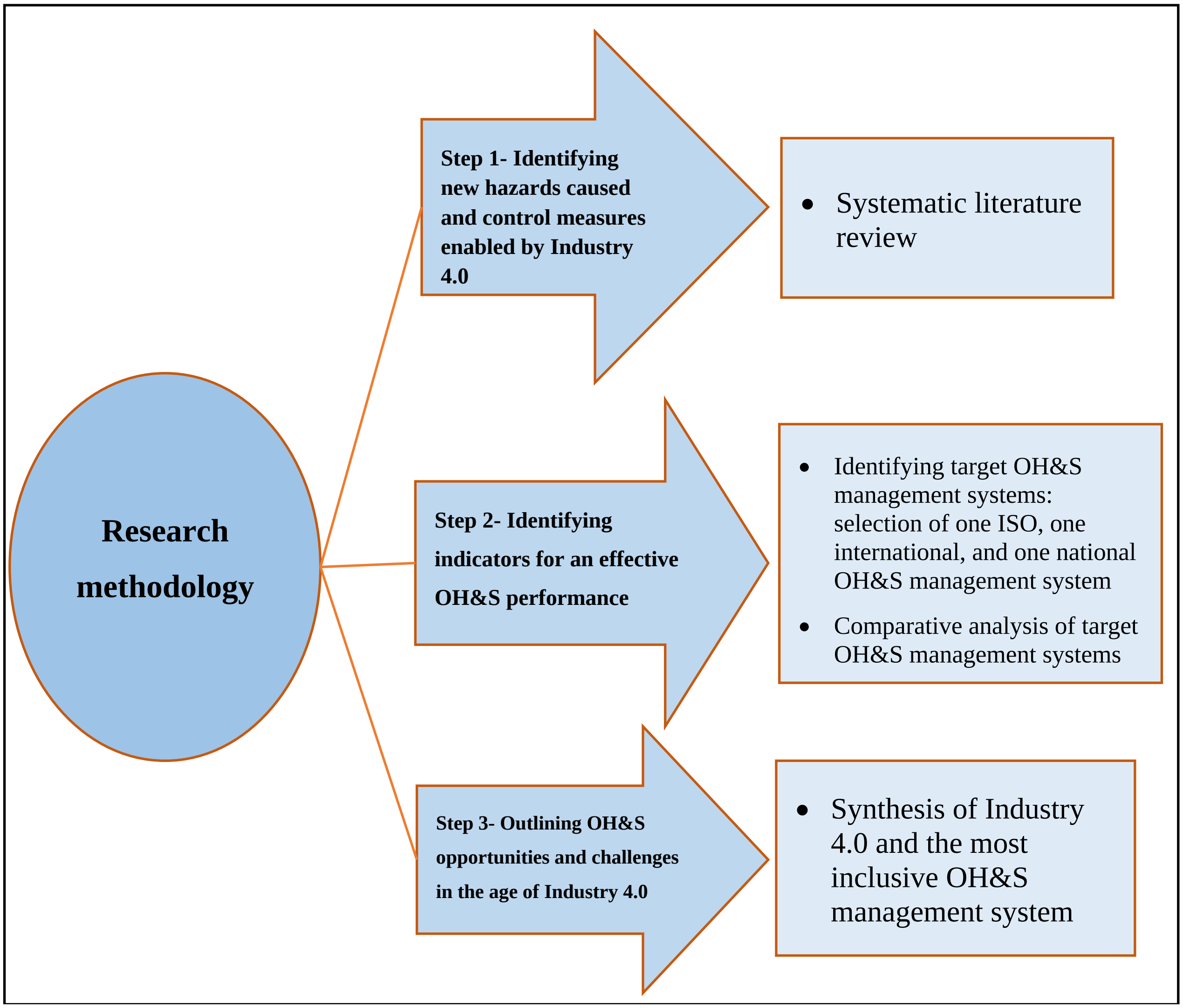

Figure 3.1 Outline of the methodology of this research

The methodology is explained in more detail in the following sections.

3.1 Step 1: Identifying new hazards caused and control measures enabled by Industry 4.0

In the first step of the methodology, we aimed to answer the second and third questions underlying this research. These questions were about the new challenges and hazards that have emerged as a result of Industry 4.0 and the opportunities and control measures enabled by Industry 4.0. to prevent occupational accidents and diseases. For this purpose, we systematically reviewed the literature using the ProKnow-C method (Knowledge Development Process – Constructivist) to collect relevant information. This method presents a structured process for a systematic review of the literature to researchers to gain the necessary knowledge and new developments on a given field [25-27, 120, 121]. The ProKnow-C has main advantages such as selecting papers by keywords; filtering papers closely aligned to the research theme; and identifying the most relevant studies for the creation of the bibliographic portfolio [[122], cited in [123], [124]]. Therefore, many researchers have applied the method for establishing a robust theoretical framework in their studies [27, 124-126].

The ProKnow-C method comprises three main stages : (1) providing the bibliographic portfolio; (2) analyzing the bibliographic portfolio; and (3) performing a systemic analysis [27]. These stages are displayed in more detail in Figure 3.2.

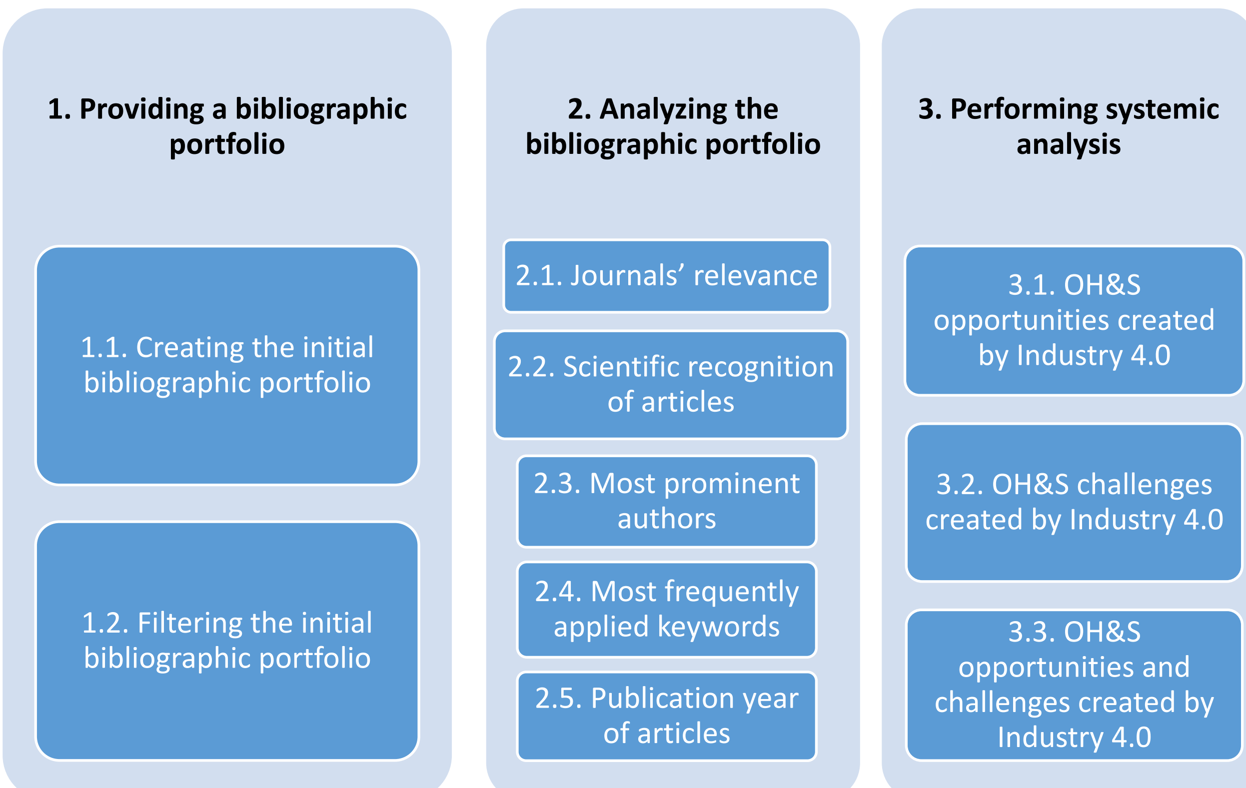

Figure 3.2 The ProKnow-C methodology.

3.1.1 Provide the bibliographic portfolio

The provision of the portfolio of articles had two main phases: (1) creating an initial bibliographic portfolio containing unfiltered articles; and (2) filtering that initial bibliographic portfolio.

The first phase was broken into three steps: (1) defining search keywords; (2) conducting the systematic search; and (3) applying the keyword adherence test.

In the second phase, the initial bibliographic portfolio was filtered in five steps: (1) eliminating repeated articles; (2) aligning the articles by reviewing the title; (3) aligning the articles according to scientific recognition; (4) aligning the articles by reviewing the abstract; and (5) aligning the articles by reading them. These steps are shown in Figure 3.3.

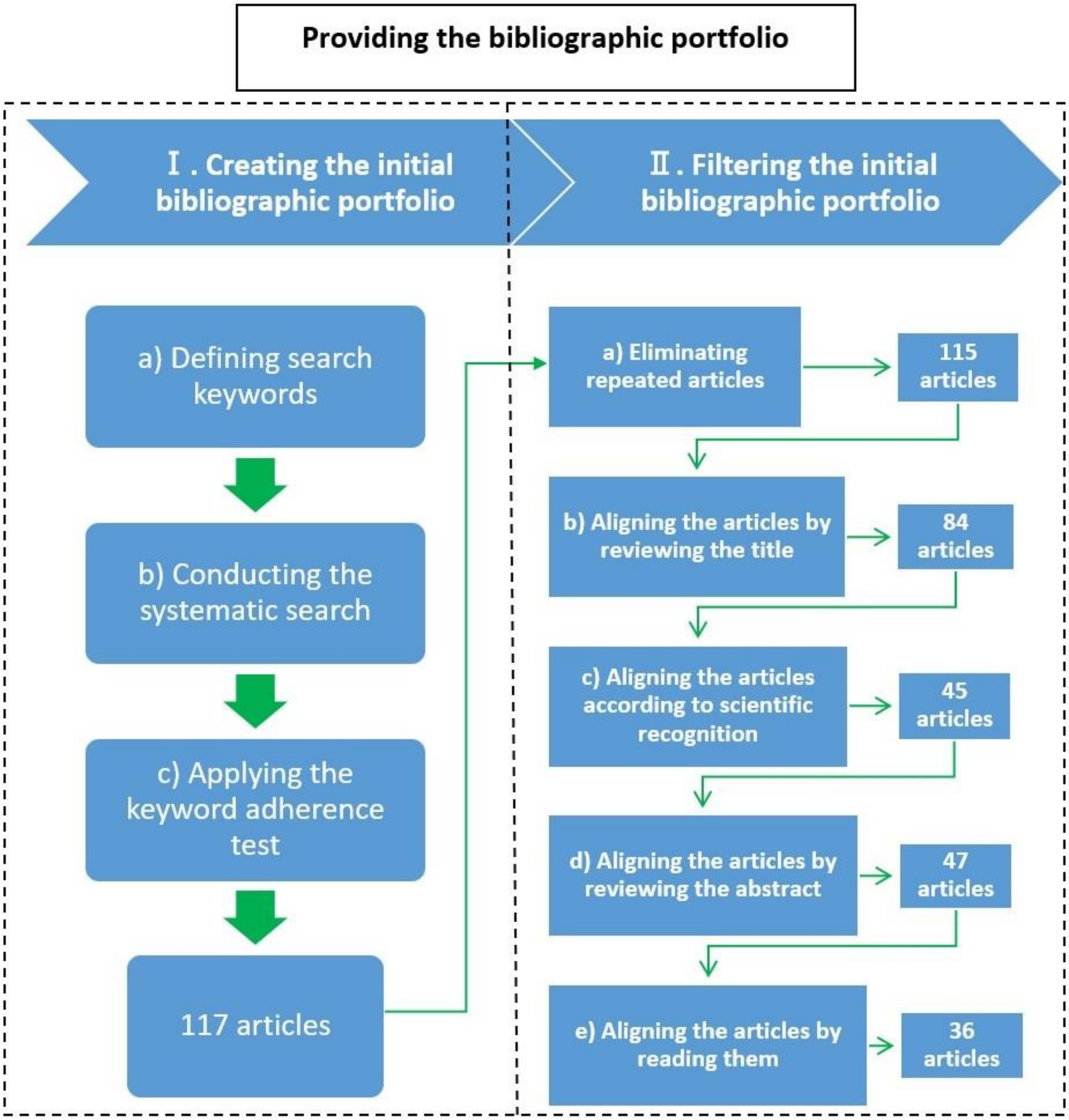

Figure 3.3 Providing the bibliographic portfolio adapted from [127]

These steps are explained in more detail below.

I. Creating the initial bibliographic portfolio

To create the initial bibliographic portfolio, we carried out the following steps:

a) Defining search keywords: To define the search keywords, we first needed to develop the research axes. Considering our perception of the research subject, we developed two axes. The first axis was occupational health and safety, and the second axis was Industry 4.0 and its dependent technologies. Next, the search keywords were defined. Table 3.1 shows the keywords used for the search. At the top of each column, we show the main keywords, "OH&S" and "Industry 4.0," and then their synonyms and related phrases were added.

Table 3.1 Search keywords

Axis 1: OH&S			**Axis 2: Industry 4.0**		
Occupational safety	Occupational health	Occupational security	Industrie 4.0	IoT	Collaborative robots
Psychologic*	Ergonom*	Human factors	Cybersecurity	Big data	The cloud
Industrial health	Industrial safety	Industrial health and safety	Augmented reality	Additive manufacturing	Artificial intelligence
Industrial safety and health	Occupational risks	Occupational health and safety	Horizontal & vertical system integration		Simulation
Occupational safety and health	Health and safety	Safety and health	FIR	Fourth industr*	Smart produc*
Unsafe	OSH		Smart manufactur*	Future factor*	Smart factor*

b) Conducting the systematic search: After defining the search keywords, we imported them into the library databases of Web of Science. We ran an advanced search composed of synonyms of each keyword with the "OR" gate, using the "AND" gate between two main keywords. We also determined the time span of published articles as 2010 to 2019. The reason is that Industry 4.0 was formally introduced in late 2010 and this search was done in 2019. Restricting the search to English documents, we found 117 articles that formed our initial bibliographic portfolio.

c) Applying the keyword adherence test: To complete the creation of the initial bibliographic portfolio, we needed to verify the search keywords' adherence to the research topic. The adherence test was performed by selecting two articles randomly from the initial bibliographic portfolio. The result of the adherence test showed the keywords were aligned with the research subject; thus, there was no need to amend the keywords or add new ones.

II. Filtering the initial bibliographic portfolio

After creating the initial bibliographic portfolio, we started the second phase, filtering. To do this, we applied the following filters:

a) Eliminating repeated articles: As a starting point, out of the 117 articles, 2 repeated articles were found. One of them was a duplicate with the same title but in two different document types: an article and a meeting abstract. For the second repeated article, we also found the same title for two different document types: an article and a correction. Thus, 115 articles were subjected to the title alignment step.

b) Aligning the articles by reviewing the title: To establish whether the articles met the inclusion criterion, their titles were reviewed. If there was any uncertainty about the relevancy of titles, we considered them relevant to the research aims to ensure that no relevant article was missed. As a result, 31 papers out of the 115 were considered not to be aligned with the aim of this research. The papers filtered out in this step had irrelevant titles; this was due to the wide scope of some of our keywords. The keywords in question were "psychologic*," "human factors," "ergonom*" and "simulation" which apply broadly to other fields of science, such as educational, behavioural, and medical sciences, and also the development of products and services. The titles in question were not aligned with the first axis of the research, namely occupational health and safety. Thus, 84 articles remained to be checked for scientific recognition.

c) Aligning the articles according to scientific recognition: To verify the degree of scientific recognition, the numbers of citations for all 84 articles were determined using the Google Scholar database. According to Pareto's principles, 80% of all citations are represented by 20% of publications [27, 120]. In our case, 98٪ of all citations were represented by 45 articles. To better organize the filtering process, these 45 articles and the remaining 39 articles, which had fewer citations, were transferred into two repositories named K and P, respectively.

d) Aligning the articles by reviewing the abstract: The abstracts of the 45 articles in the K repository were read to find which articles were aligned with the subject of our research. As a result, 30 articles remained in the K repository and the other 15 articles were filtered out. At this point, an additional analysis was conducted on the P repository to identify which of these 39 articles could be included in the bibliographic portfolio. We, therefore, separated out two groups of articles in the P repository: first, articles by the same authors as articles filtered by abstract in the K repository; second, articles published in the last three years of this analysis (2017 to 2019) that did not have enough citations. Twenty-seven articles met at least one of these conditions. The abstracts of these 27 articles were read to identify whether they were aligned with the research subject. As a result, we found 17 relevant articles. Adding these 17 articles from the P repository to the 30 articles in the K repository, there was a total of 47 articles that had to be read in their entirety.

e) Aligning the articles by reading them: As the final filter, we read the 47 articles in full to confirm their content's alignment with the research theme. Of these articles, 11 were considered irrelevant to this research; consequently, the other 36 articles formed our bibliographic portfolio on the new challenges and hazards, and opportunities and control measures that may emerge due to Industry 4.0.

3.1.2 Analyzing the bibliographic portfolio

In the ProKnow-C method, the next step after providing the bibliographic portfolio is analyzing the portfolio. This step aims to evaluate the qualifications of the items in the portfolio. To do this, we analyzed the articles in the portfolio based on six parameters: (i) journals' relevance; (ii) scientific recognition of the articles; (iii) most prominent authors; (iv) most frequently applied keywords; (v) impact factor of journals; and (vi) year of publication. These parameters are explained below:

i. Conferences'/Journals' relevance

The first parameter analyzed was the relevance of the conferences and journals where the articles in the bibliographic portfolio were presented or published. Of the 36 articles that compose the bibliographic portfolio, 16 were conference articles and 20 were journal articles. For each conference and journal, only one article was recorded; therefore, no specific conference or journal stood out. The conferences and journals related to a variety of fields, such as computer sciences, industrial engineering, electrical engineering, manufacturing, tourism, and occupational health and safety.

ii. Scientific recognition of the articles

The second aspect to be analyzed was scientific recognition of the articles in the bibliographic portfolio. Of the 36 articles, the largest number of citations referred to the article "Occupational health and safety in the industry 4.0 era: A cause for major concern?", by Adel Badri, Bryan Boudreau-Trudel, and Ahmed Saâdeddine Souissid, published in 2018, in *Journal of Safety Science*, with 97 citations. Other frequently cited studies were "An internet-of-things (IoT) network system for connected safety and health monitoring applications," by Mehmet Rasit Yuce, Fan Wu, and Taiyang Wu, published in 2019, in *Journal of Sensors*, with 65 citations, and "Internet of things (IoT) in high-risk environment, health and safety (EHS) industries: A comprehensive review," by Thibaud Montbel, Huihui Chi, Wei Zhou, and Selwyn Piramuthu, published in 2018, in *Decision Support Systems*, with 63 citations.

iii. Most prominent authors

The third parameter to be analyzed in the bibliographic portfolio was author prominence. Among the authors of articles in the portfolio, Dušan Tatić stood out with two journal articles. Two teams of authors had two articles (one journal and one conference article). They were Mehmet Rasit Yuce, Fan Wu, and Taiyang Wu, and Yoonsook Hwang and Kyong-Ho Kim.

iv. Most frequently applied keywords

The fourth parameter was the most keywords mentioned in articles. "Augmented reality" was the most frequent keyword; it was used 10 times. The keywords "ergonomics" and "Internet of Things" were used six times each, while "occupational safety" was used in five articles.

3.1.3 Performing systemic analysis

Performing systemic analysis is the process of analyzing the content of the articles making up the bibliographic portfolio. This phase aimed to address the new directions and trends related to the research subject and formed a conceptual foundation based on knowledge gained from reading the articles.

We listed the 36 articles alphabetically that appears in Table 3.2.

Table 3.2 A general outline of articles in the bibliographic portfolio

#	Article titles	Authors	Citations	Year
1	ActSen – AI-enabled real-time IoT-based ergonomic risk assessment system	Low et al.	0	2019
2	Advanced industrial tools of ergonomics based on Industry 4.0 concept	Gasova et al.	29	2017
3	An augmented reality system for improving health and safety in the electro-energetics industry	Tatic, D	2	2018
4	An ergonomic customized-tool handle design for precision tools using additive manufacturing: A case study	Gonzalez et al.	2	2018
5	An internet-of-things (IoT) network system for connected safety and health monitoring applications	Wu et al.	65	2019
6	Augmented reality for health and safety training program among healthcare workers: An attempt at a critical review of the literature	Corvino et al.	1	2019
7	Augmented reality smart glasses in the workplace: Industry perspectives and challenges for worker safety and health	Kim et al.	12	2016
8	Automatic selection of ergonomic indicators for the design of collaborative robots: A virtual-human in the loop approach	Maurice et al.	5	2014
9	Big data platform for health and safety accident prediction	Ajayi et al.	4	2019
10	Can complexity-thinking methods contribute to improving occupational safety in Industry 4.0? A review of safety analysis methods and their concepts	Adriaensen et al.	1	2019
11	Combining semantic web and IoT to reason with health and safety policies	Goynugur et al.	1	2017
12	Current research and future perspectives on human factors and ergonomics in Industry 4.0	Kadir et al.	20	2019
13	Design and implementation of a wearable sensor network system for IoT-connected safety and health applications	Wu et al.	11	2019
14	Design of cockpit ergonomic evaluation simulation system based on augmented reality	Shi et al.	0	2019
15	Effects of augmented-reality head-up display system use on risk perception and psychological changes of drivers	Hwang et al.	10	2016
16	Effects of cyber-physical production systems on human factors in a weaving mill: Implementation of digital working environments based on augmented reality	Kerpen et al.	16	2016
17	Effects of the displaying augmented-reality information on the driving behavior of the drivers with specific psychological characteristics	Hwang, Y and Kim, KH.	1	2016
18	Hotel employee's artificial intelligence and robotics awareness and its impact on turnover intention: The moderating roles of perceived organizational support and competitive psychological climate	Li et al.	43	2019
19	Human factors and ergonomics evaluation of a tablet-based augmented reality system in maintenance work	Aromaa et al.	4	2018
20	Human factors/ergonomics implications of big data analytics: Chartered Institute of Ergonomics and Human Factors annual lecture	Drury, CG	16	2015
21	Industry 4.0, innovation and design. A new approach for ergonomic analysis in manufacturing system	Laudante, E	20	2017
22	Internet of things (IoT) in high-risk environment, health and safety (EHS) industries: a comprehensive review	Thibaud et al.	63	2018
23	IoT based industrial safety measures monitoring and reporting system using accident reduction model (ARM) control algorithm	Rajmohan, P and Srinivasan, PSS	2	2019
24	IoT based safety and health monitoring for construction workers	Mehata et al.	0	2019
25	IoT gateway and industrial safety with computer vision	Zubal et al.	4	2016

Table 3.2 A general outline of articles in the bibliographic portfolio (continued and end)

26	M+: A novel IoT device for reducing the physiological & psychological effects of noise pollution on humans	Kanade, VA	0	2019
27	Methodological proposal for use of virtual reality VR and augmented reality AR in the formation of professional skills in industrial maintenance and industrial safety	Velosa et al.	8	2018
28	Need for a new workplace safety and health (WSH) strategy for the fourth industrial revolution	Chia et al.	5	2019
29	Occupational health and safety in the industry 4.0 era: A cause for major concern?	Badri et al.	97	2018
30	Optimizing makespan and ergonomics in integrating collaborative robots into manufacturing processes	Pearce et al.	19	2018
31	Projects in Industry 4.0 framework and its effects on occupational safety	Milijic et al.	0	2019
32	The application of augmented reality technologies for the improvement of occupational safety in an industrial environment	Tatic, D and Tesic, B	34	2017
33	The fourth industrial revolution and its impact on occupational health and safety, worker's compensation and labor conditions	Min et al.	17	2019
34	The occupational health and safety dimension of Industry 4.0	Leso et al.	8	2018
35	Using principles from the past to solve the problems of the future: Human factors and sociotechnical systems thinking in the design of future work	Salmon, PM and Read, GJM	1	2018
36	Women's occupational health: Improving medical protocols with artificial intelligence solutions	Gerassis et al.	1	2019

The articles were divided into three groups: (i) articles that addressed the opportunities created by Industry 4.0 to control OH&S risks; (ii) articles that focused on the OH&S challenges and risks created by Industry 4.0; and (iii) articles that covered both sides, namely opportunities and challenges. Content analysis for each group appears in the next chapter.

3.2 Step 2: Identifying Indicators for an effective OH&S performance

In the previous step, we identified the documents related to the opportunities and challenges of Industry 4.0 for different aspects of OH&S. However, our objective is to analyze these opportunities and challenges. Therefore, we needed to define a set of indicators that represent effective elements of desired OH&S performance. For this purpose, in the second step, we selected OH&S management systems. As discussed earlier, these are comprehensive frameworks to evaluate OH&S performance in organizations and serve the purpose. Among other OH&S management systems, we chose three OH&S management systems: ISO 45001 – an ISO standard; OHSAS 18001 – an international standard; and CSA Z1000 – a national standard. These standards are recognized by most OH&S practitioners.

To begin the work, we need to examine all the clauses of ISO 45001 and search OHSAS 18001 and CSA Z1000 for equivalent requirements. This comparison helped us to become aware of the differences and commonalities in the contents of each standard. Consequently, we were able to produce a synthesis of our findings and the most inclusive OH&S management system standard (section 3.4). We were also able to generalize the results to the other two standards. This comparison was done for the ten main parts of ISO 45001: Scope, Normative References, Terms and Definitions, Context of the Organization, Leadership and Worker Participation, Planning, Support, Operation, Performance Evaluation, and Improvement. Overall, we reviewed 43 clauses and sub-clauses of ISO 45001. This comparison appears in Table 4.1 in detail.

As a result, four main differences were revealed between CSA Z1000 and OHSAS 18001 versus ISO 45001. These were understanding the organization and its context, understanding the needs and expectations of workers and other interested parties, assessing both OH&S opportunities and OH&S risks, and adding outsourcing into the organization's operation control process. These clauses are found in ISO 45001, but there are no equivalent requirements in OHSAS 18001 and CSA Z1000. These differences are important because they reveal the new directions introduced by ISO 45001 and provide a more accurate perception of the necessary criteria for OH&S performance evaluation.

3.3 Step 3: Outlining OH&S opportunities and challenges in the age of Industry 4.0

In the third step of the research, we found ISO 45001 to be the most inclusive OH&S management system standard. Therefore, in the fourth step of the research, ISO 45001 was chosen for our synthesis of the clauses of the standard, as OH&S performance indicators, and our findings concerning the implications of Industry 4.0 for OH&S. Accordingly, the opportunities and challenges identified, originating in each Industry 4.0 technology, were addressed in the 43 clauses and sub-clauses of ISO 45001, as shown in Figure 3-4.

As a starting point, we selected the first clause of ISO 45001 and the first technology associated with Industry 4.0. This clause of the standard was examined in terms of how it is influenced by the selected technology. Where opportunities or challenges existed in our findings presented in section 3.3, we searched for complementary studies to support our findings with more evidence or examples. To do this, all the related references in the articles that constituted our bibliographic portfolio (section 3.1.1) were scanned. In specific cases in which more information was needed, we also searched relevant websites to use relevant publications. Moreover, we searched the existing literature to gain detailed information on specific cases. We continued this iterative process for all the clauses of ISO 45001 and all the technologies. The results obtained from this process are presented in chapter 4.

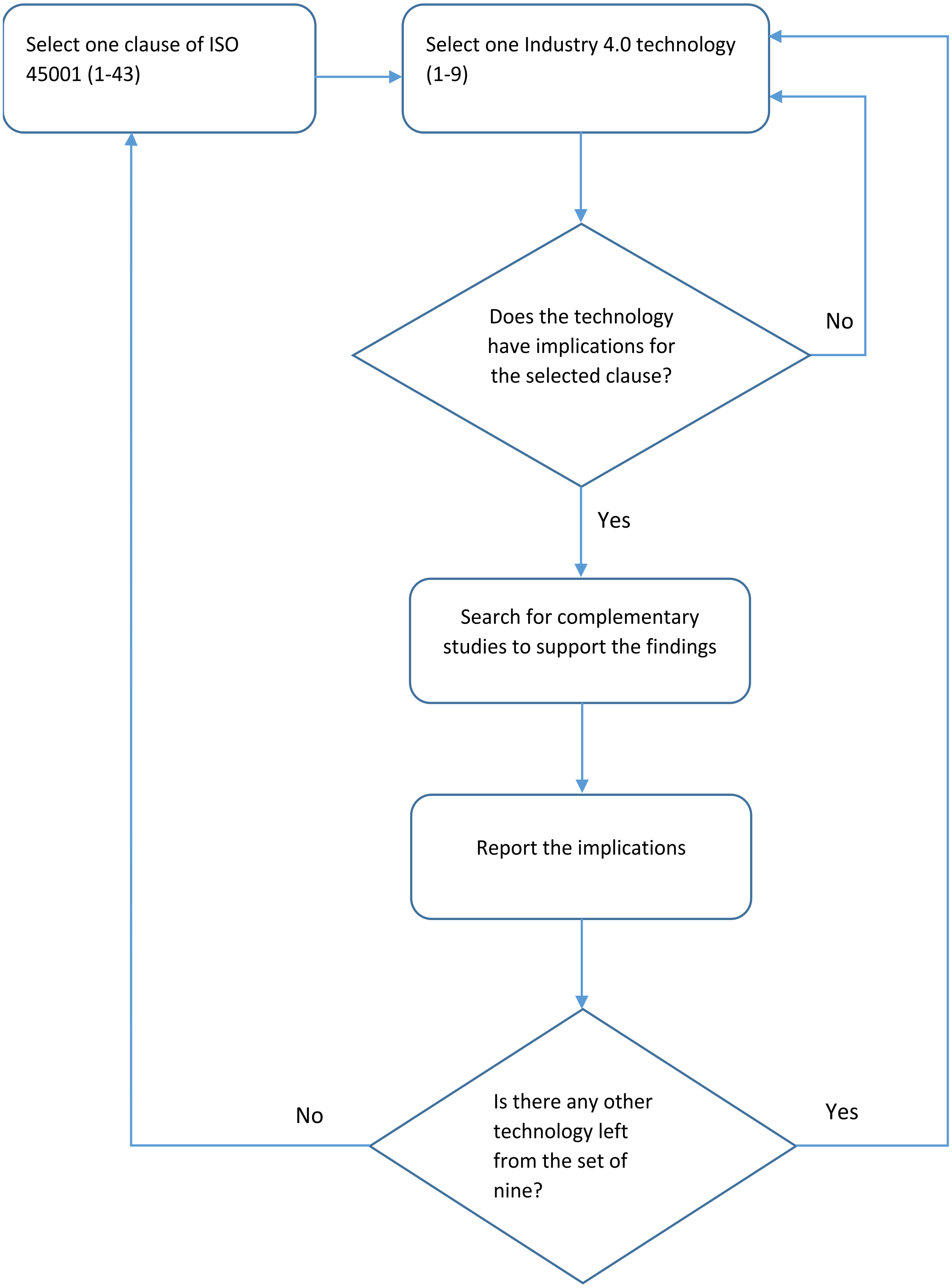

Figure 3.4 Process of synthesizing Industry 4.0 technologies with clauses of ISO 45001.

CHAPTER 4 RESULTS & DISCUSSIONS

As described in Chapter 2, a background of different Industry 4.0 technologies was provided. Then in Chapter 3, in the first step, we carried out a systematic literature review to identify the challenges and opportunities of Industry 4.0 for OH&S. As a result, a set of 36 related documents was reviewed (See Table 3.2). In the second step, we compared OHSAS 18001 and CSA Z1000 with ISO 45001 to determine the corresponding requirements. A synthesis of the findings from the review of the 36 documents and clauses of ISO 45001 was then prepared in the third step. In this chapter, the results of these steps are presented and discussed in the form of the challenges and opportunities Industry 4.0 creates for OH&S management systems.

4.1 The results of step 1: Identifying new hazards caused by and control measures enabled by Industry 4.0

- Content analysis

Twenty of the 36 articles focused on the application of Industry 4.0 technologies to manage OH&S risks. Two of them – #6 and #21 – were developed theoretically. Article #6 used a literature review to address the application of augmented-reality-based technology to provide OH&S training for workers in the health care sector. The evidence suggested that augmented reality can increase risk perception and safe behaviours among workers. However, impacts on human users' cognitive abilities or mental fatigue were reported as probable side effects. Article #21 recommended using innovative approaches based on virtual reality to consider ergonomic principles when designing an Industry 4.0 working system. A big advantage is that these methods allow designer-ergonomists to proactively assess key ergonomic factors and provide optimal conditions for work processes.

The other 18 articles discussed Industry 4.0's capacity to improve OH&S empirically, rather than theoretically.

Three of those articles – #3, #27 and #32 – discussed using augmented reality to train workers in OH&S topics. Articles #3 and #32 introduced an augmented-reality-based system that instructs workers how to perform their tasks while meeting OH&S requirements. The results confirmed the positive role of augmented reality technology in enhancing workers' understanding of OH&S risks.

Article #27 proposed a method to teach OH&S guidelines to engineers in laboratories in which real or close-to-real work conditions are provided. A survey conducted afterward revealed that, overall, the participants evaluated the method positively.

Articles #5, #13, #23 and #24 presented the use of wearable sensors in an IoT-based system to monitor workers' health and OH&S conditions in the workplace. The same idea was applied in article #26 on reducing the physiological and psychological consequences of noise for workers. These articles provided details about technical aspects such as hardware, software and cloud implementation. The results of the experimental tests highlighted the systems' remarkably accurate performance. Article #25 described the design of an IoT network, including a camera system in combination with intelligent software, to identify hazardous situations and prevent occupational accidents. Despite the technological limitations that will have to be overcome in the future, the results of the implementation of the IoT network in two case studies showed that the method can improve safety in the workplace. The aim of accident prevention was also pursued in article #9 but using a different method. In that article, the authors proposed an architecture for analyzing a big data set of previous occupational accidents. The purpose was to predict the likelihood of OH&S risks and warn workers about probable accidents. The results showed the suitability and reliability of the analytic system for identifying OH&S risk factors. The idea of analyzing big data was also implemented in Article #36. In that study, a machine learning technique was applied to 172,026 medical examination records of women workers to reveal latent risk factors that can endanger women's occupational health. As a result, it was revealed that the risk factors of high BMI and poor sleep quality should be considered in women workers' medical protocols. Articles #15 and #17 investigated the effects of physiological stress on driving behaviours using an augmented reality head-up display system. The experimental results proved that the "problem evading" (it involves avoiding facing problems rather than coping with them) characteristic is positively correlated with drivers' reaction time to dynamic objects while the "anti-personal anxiety" (it indicates less tendency to be in front of others and more difficulty in building new relationships) characteristic is negatively correlated with reaction time. Article #11 established an OH&S regulatory policy framework for different concepts and complex situations that can occur in an underground mine. Thanks to IoT and artificial intelligence (AI) algorithms, policy conflicts can be identified and resolved automatically.

Article #1 presented an ergonomic tool to assess risks of musculoskeletal disorders (MSDs) in real time using IoT sensors to collect data and machine learning techniques to classify the data. Article #2 proposed a quick, mobile application to evaluate the workspace and workers' postures based on standards. By applying augmented reality, a virtual model of a worker is built and displayed on the screen of the mobile device so virtual and real working conditions can be compared. As a result, ergonomic non-conformities are identified quickly. Article #4 focused on the ergonomic design of a surgical hand tool's handle using 3D printers. The dimensions of the manufactured samples were optimized relative to each surgeon's anthropometric data. Article #14 described a simulation platform to evaluate the ergonomics of aircraft cockpits. Augmented reality technology was applied to integrate a virtual 3D model of cockpit equipment and space into a physical cockpit frame. Thus, the ergonomic weaknesses of different designs for the cockpit's interior could be identified in the early stages of the design before an actual product was manufactured.

Twelve of the 36 articles focused on the OH&S risks posed by Industry 4.0. Five studies were conducted empirically while the other seven were theoretical.

The empirical articles were #8, #18, #19, #30 and #31. Article #8 developed a method to control ergonomic MSD risks that workers are exposed to when they work with collaborative robots. A virtual human model was simulated to identify applicable ergonomic indicators among 30 indicators for a task to be executed with a collaborative robot. Another study on MSD risks is presented in article #19, in which the authors evaluated the postures and work situations of industrial maintenance operators when using an augmented reality guidance system in their tablets. The results showed that poor postures maintained for a long time can increase MSD risks. Article #30 developed a standard task-modelling method to assign tasks to workers considering the amount of human physical stress in order to increase the productivity of work with collaborative robots.

Article #18 analyzed the impacts of the application of intelligent robotization technology upon workers in the hospitality industry. The results of interviews with 550 hotel employees revealed that the workers with the greatest awareness of the technology were more likely to intend to leave their jobs. This mostly happened because competitive psychological climates and job stresses were created by the new technology. Nevertheless, organizational supports, including boosting communications, promoting teamwork, and developing interpersonal skills, can substantially decrease the turnover rate.

In article #31, the authors compared the assessment of four main OH&S aspects in two industrial revolutions: 3.0 and 4.0. These aspects were organizational, human, environmental and technical. The assessments were carried out according to the opinions of project managers in different industries, collected with a questionnaire. The results showed that organizational and human aspects must be reconsidered in the era of Industry 4.0. Environmental aspects are relatively more dominant in Industry 3.0 compared to Industry 4.0, while technical aspects are considerably stronger in Industry 4.0 than in Industry 3.0.

The remaining seven articles studied the capacity of Industry 4.0 to manage OH&S risks from a theoretical perspective. Article #10 recommended adopting complexity-thinking theories to develop new risk assessment models in order to confront the variable hazards emerging due to Industry 4.0. In the proposed model, system components such as humans, machines and the relationship between them are considered as a whole and not analyzed separately. This attitude may be appropriate for solving issues in socio-technical systems such as Industry 4.0. Article #35 examined the literature to demonstrate that socio-technical systems' theory-based approaches facilitate the integration of human factors into the future work system. Since work systems will depend heavily on technology, a failure in this regard could have serious consequences for OH&S. Article #12 conducted a systematic literature review to determine the level of attention to human factors and ergonomic issues in published studies related to Industry 4.0. The results showed that published research on this subject is rare. Accordingly, the authors recommended carrying out more empirical studies and extending the scope of research to cover the topic at organizations' strategic and tactical levels, in addition to the operational level. Article #20 considered the issues of a big data analytics approach to be applied in ergonomics and human factors sciences. The significant problem reported in the study was the approach's dependence on data correlation. If data is gained from inappropriate situations or interpreted with invalid algorithms, the extracted findings will be meaningless and spurious. Thus, they may mislead ergonomic practitioners who want to select valid programs to improve ergonomics, such as training. Another challenge that must be dealt with is privacy protection and respect for ethics. Data collection and use need permission from workers, who need to know how and why the data will be used.

Article #28 argued for the necessity of developing a total OH&S strategy to protect workers against the impacts of rapid transformations in technology and employment relationships in the age of

Industry 4.0. The strategy must involve adaptive measures based on Industry 4.0 technologies and negotiations between interested parties.

Article #29 reviewed the OH&S impacts of changes in the era of Industry 4.0 based on a literature search. Emphasizing the need for a proactive approach, the authors addressed future OH&S challenges in four areas: (1) new hazards arising out of the new organization of work; (2) the lack of regulations to embed OH&S in workplace; (3) the inability of OH&S management systems to adapt to the flexible, complex processes in workplace 4.0; and (4) the need for new risk management approaches that are compatible with working in real time and analyzing a huge amount of collected data. Since there are few publications related to the OH&S challenges of Industry 4.0, the OH&S experts called for collaboration with business owners to conduct holistic studies of how to manage the changes.

Article #33 stated that the boost in globalization due to the fourth industrial revolution is associated with the introduction of new business models that do not follow common employment standards. Working time and circadian rhythms may be disturbed. Consequently, the risk of cancers and occupational diseases will increase. Employment relations may be changed and, as a result, traditional OH&S regulations and social supports may not apply to workers. The change can also cause additional mental pressures.

Four of the 36 articles focused on both OH&S risks and opportunities created by Industry 4.0. Two of these (#7 and #16) were conducted empirically. Article #7 collected the opinions of experts in different industries about the implications of smart glasses as an augmented reality head-worn display tool. All the interviewees confirmed the useful role of this tool in training workers and promoting safe work practices at the workplace; at the same time, most of them believed that applying this technology can decrease workers' environmental awareness and distract their attention from OH&S situational risks. Article #16 addressed the positive and negative impacts of the application of Industry 4.0 in production systems in terms of human factors. The authors considered the increasing complexity of production processes in digital working environments to constitute a fundamental change that requires workers to have a new set of skills. On the other hand, the results of an experiment verified that augmented-reality-based smart glasses can greatly help workers to deal with the complexity of their tasks.

Articles #22 and #34, on the other hand, were conducted theoretically. Article #22 highlighted the potential of IoT technology to improve OH&S in high-risk industries and also addressed the challenges through a comprehensive review of publications. The authors concluded that technical issues attract more attention than social challenges like OH&S in the published research. The challenges include inaccurate data collection, data security and privacy protection, and technical limitations to overcome the complexity of work. On the other hand, all the publications examined in this article confirmed that IoT technology can play a significant role in controlling human errors, which are a contributing factor in catastrophic accidents. In article #34, a critical review of the literature was carried out to identify the pros and cons for OH&S of the application of Industry 4.0. The main issues listed are job-related stress due to the complexity of work and accidents involving humans and collaborative robots. On the other hand, real-time monitoring of workplace conditions can improve workers' health. In addition, the application of collaborative robots can prevent or reduce workers' exposure to risk factors such as dangerous chemicals, vibration and manual handling.

4.2 The results of step 2: Comparative analysis of target OH&S management systems

A detailed comparison of ISO 45001 with CSA Z1000 and OHSAS 18001 for each clause is done and the main differences are shown in Table 4.1.

Table 4.1 Comparing ISO 45001:2018 with OHSAS 18001:2007 and CSA Z1000-14

ISO 45001: 2018	CSA Z1000-14	OHSAS 18001:2007	Main differences
Introduction	0 Introduction	Introduction	
0.1 Background			* There is no main difference.
0.2 Aim of an OH&S management system			* There is no main difference.
0.3 Success factors			* In addition to key factors stated in CSA Z1000 and OHSAS 18001, ISO 45001 refers to more items that promote OH&S culture, participation of workers, and creation (or identification) of OH&S opportunities to achieve desired OH&S performance.

Table 4.1 Comparing ISO 45001:2018 with OHSAS 18001:2007 and CSA Z1000-14 (continued)

ISO 45001: 2018	CSA Z1000-14	OHSAS 18001:2007	Main differences
0.4 Plan-Do-Check-Act cycle	4.1 General		* Leadership and worker participation are at the center of the PDCA cycle in ISO 45001. Continual improvement has the same central place in OHSAS 18001. There is not such a central place for leadership and worker participation in the PDCA cycle of CSA Z1000 but this participation is stated in clause 4.2.1 as a crucial factor in the success of an OHSMS.
0.5 Contents of this document	0 Introduction		* Both ISO 45001 and CSA Z1000 mention that their structures can be aligned with other management systems for subjects like social responsibility.
1 Scope	1 Scope	1 Scope	* There is no main difference.
2 Normative references	2 Reference publications	2 Reference publications	* ISO 45001 has no normative reference. But CSA Z1000 and OHSAS 18001 make a reference to International Labour Organization: 2001, Guidelines on Occupational Health and Safety Management Systems (OSH-MS).
3 Terms and definitions	3 Definitions	3 Terms and definitions	ISO 45001 defines two additional terms, OH&S opportunity and outsource, in the list of terms and definitions.
4 Context of the organization	4 Occupational health and safety management system	4 OH&S management system requirement	
4.1 Understanding the organization and its context	Not found	Not found	* Contrary to CSA Z1000 and OHSAS 18001, ISO 45001 requires the organization to go beyond the requirements of the OH&S management system and identifies the external and internal subjects which can prevent or postpone achieving the OH&S objectives.
4.2 Understanding the needs and expectations of workers and other interested parties	Not found	Not found	* ISO 45001 emphasizes that the workers and interested parties are an important part of the context of the organization so that the organization shall take into account these parties and identify their OH&S concerns, demands and rights. In this regard, the workers who do not work under the control of the organization such as subcontractors and suppliers, usually have been paid less attention.

Table 4.1 Comparing ISO 45001:2018 with OHSAS 18001:2007 and CSA Z1000-14 (continued)

ISO 45001: 2018	CSA Z1000-14	OHSAS 18001:2007	Main differences
4.3 Determining the scope of the OH&S management system	Not found	4.1 General requirements	* CSA Z1000 does not mention how to determine the scope of an OH&S management system. OHSAS 18001 emphasizes only on definition and documentation of the scope. ISO 45001 states clearly that an organization shall determine the scope with respect to external and internal issues (4.1), the needs and expectations of its interested parties (4.2), and current and planned operation. Considering these factors in the determination of scope helps an organization to specify the scope factually and prevents the interested parties to be misdirected.
4.4 OH&S management system	4.1 General		* ISO 45001 puts emphasis on the systematic structure of an OH&S management system. The OH&S management system shall consist of a set of intended processes interacting with each other to achieve the OH&S objective of an organization.
5 Leadership and worker participation	4.2 Commitment, leadership, and participation	4.4 Implementation and operation	
5.1 Leadership and commitment	4.2.1 General 4.2.2 Management commitment and leadership	4.4.1 Resources, roles, responsibility, accountability and authority	* ISO 45001 assigns a new duty, in addition to other duties in OHSAS 18001 and CSA Z1000, to top management to create, lead and enrich a culture for protecting OH&S achievements within an organization.
5.2 OH&S policy	4.2.4 Occupational health and safety policy	4.2 OH&S policy	* ISO 45001 states that the OH&S opportunities shall also be taken into account in developing OH&S policy in addition to other factors listed in OHSAS 18001 and CSA Z1000.
5.3 Organizational roles, responsibilities and authorities	4.2.2.1 Responsibility, accountability, and authority	4.4.1 Resources, roles, responsibility, accountability and authority	* Contrary to OHSAS 18001 and CSA Z1000, ISO 45001 does not require an organization to appoint a top management representative to assume responsibility of the OH&S management system but instead, it shares the responsibility of different parts of the OH&S management system with workers wherever they are authorized to do so. It indicates that the OH&S is not only not restricted to certain workers within an organization but shall also include all the workers depending on the level of their authority. * In all three OH&S management systems, the top management of an organization shall accept the overall

Table 4.1 Comparing ISO 45001:2018 with OHSAS 18001:2007 and CSA Z1000-14 (continued)

ISO 45001: 2018	CSA Z1000-14	OHSAS 18001:2007	Main differences
			responsibility of the OH&S management system and will be accountable for its performance.
5.4 Consultation and participation of workers	4.2.3 Worker participation	4.4.3.2 Participation and consultation	* ISO 45001 presents a more detailed interpretation of the consultation and participation of workers than OHSAS 18001 does. CSA Z1000 is partly similar to ISO 45001 in setting requirements for consultation and participation of workers. ISO 45001, while requiring the organization to involve all workers in the implementation of the PDCA cycle of an OH&S management system and eliminating relevant barriers, distinguishes between the activities which shall be consulted with workers and those which shall involve the participation of workers. ISO 45001 also insists on the involvement of shop floor workers in these two types of activities.
6 Planning	4.3 Planning	4.3 Planning	
6.1 Actions to address risks and opportunities			
6.1.1 General	4.3.1 General	Not found	* ISO 45001 outlines principal factors in planning an OH&S management system similar to what CSA Z1000 does but in more detail. Also, it mentions the importance of the assessment of the changes in the organization's content, the OH&S management system, and its work processes as far as the determination of the outcomes of the planned changes before the implementation is necessary.
6.1.2 Hazard identification and assessment of risks and opportunities 6.1.2.1 Hazard identification 6.1.2.2 Assessment of OH&S risks and other risks to the OH&S management system	4.3.4 Hazard identification and risk assessment	4.3.1 Hazard identification, risk assessment and determining controls	* ISO 45001 introduces some better-categorized items to take into consideration in the hazard identification process. The organization of work, leadership and cultural factors, and social concepts are new items that shall get involved. Also, it put emphasis on any change in the understanding of hazards.

Table 4.1 Comparing ISO 45001:2018 with OHSAS 18001:2007 and CSA Z1000-14 (continued)

ISO 45001: 2018	**CSA Z1000-14**	**OHSAS 18001:2007**	**Main differences**
6.1.2.3 Assessment of OH&S opportunities and other opportunities for the OH&S management system	Not found	Not found	* It is a new section in ISO 45001 that requires an organization to assess the opportunities which can improve the performance of the OH&S management system. These opportunities can be found in the changes made to the OH&S management system comprising the organization, the objectives, and its operations.
6.1.3 Determination of legal requirements and other requirements	4.3.3 Legal and other requirements	4.3.2 Legal and other requirements	* No difference is found. ISO 45001 replicates what an organization needs to do about the OH&S rules and the other non-compulsory but accepted regulations related to OH&S.
6.1.4 Planning action	Not found	Not found	* This is a new section in the OH&S management system introduced by ISO 45001 and states that an organization shall determine the mechanism of implementation of the planned actions. In fact, it is an interface between what has been planned and what is being implemented within the organization.
6.2 OH&S objectives and planning to achieve them	4.3.5 Occupational health and safety objectives and targets	4.3.3 Objectives and programs	
6.2.1 OH&S objectives			* ISO 45001 provides more detail about how the OH&S objectives shall be determined. It introduces several input factors such as consultation with workers to the process of OH&S objective determination. OHSAS 18001 points to consultation with interested parties instead of workers only.
6.2.2 Planning to achieve OH&S objectives			There is no main difference.
7 Support	4.4 Implementation	4.4 Implementation and operation	
7.1 Resources	4.4.1 Infrastructure and resources	4.4.1 Resources, roles, responsibility, accountability and authority	There is no main difference.

Table 4.1 Comparing ISO 45001:2018 with OHSAS 18001:2007 and CSA Z1000-14 (continued)

ISO 45001: 2018	CSA Z1000-14	OHSAS 18001:2007	Main differences
7.2 Competence 7.3 Awareness	4.4.4 Competence and training	4.4.2 Competence, training and awareness	There is no main difference.
7.4 Communication 7.4.1 General 7.4.2 Internal communication 7.4.3 External communication	4.4.5 Communication and awareness	4.4.3.1 Communication	There is no main difference.
7.5 Documented information	4.4.8 Documentation		
7.5.1 General	4.4.8.1 General	4.4.4 Documentation	There is no main difference.
7.5.2 Creating and updating	4.4.8.2 Control of documents	4.4.5 Control of documents	There is no main difference.
7.5.3 Control of documented information	4.4.8.3 Control of records	4.5.4 Control of records	There is no main difference.
8 Operation	4.4 Implementation	4.4 Implementation and operation	
8.1 Operational planning and control			
8.1.1 General	Not found	4.4.6 Operational control	* ISO 45001 requires an organization to determine criteria to control processes in its OH&S management system. This topic is minimally and conditionally mentioned in OHSAS 18001. Ergonomic topics can also be considered in defining these criteria to ensure alignment between work and worker.
8.1.2 Eliminating hazards and reducing OH&S risks	4.4.2 Preventive and protective measures	4.3.1 Hazard identification, risk assessment	* There is no main difference.

Table 4.1 Comparing ISO 45001:2018 with OHSAS 18001:2007 and CSA Z1000-14 (continued)

ISO 45001: 2018	CSA Z1000-14	OHSAS 18001:2007	Main differences
8.1.3 Management of change	4.4.7 Management of change	4.4.6 Operational control	* The information about management of change has been extended from one sentence as part of clause 4.4.6 operational control of the OHSAS 18001 to a separate clause in the ISO 45001. More details about items that changes can originate from are mentioned in ISO 45001. But CSA Z1000 gives more attention to this topic than the other two codes.
8.1.4 Procurement	4.4.6 Procurement and contracting		
8.1.4.1 General	4.4.6.1 Procurement		* There is no main difference.
8.1.4.2 Contractors	4.4.6.2 Contracting		
8.1.4.3 Outsourcing	Not found	Not found	* This is a new requirement in ISO 45001 and makes it obligatory for organizations to control OH&S aspects of outsourced operations based on legal regulations. CSA Z1000 and OHSAS 180001 describe that outsourcing can be intended as a preventive measure to eliminate OH&S hazards.
8.2 Emergency preparedness and response	4.4.3 Emergency prevention, preparedness, and response	4.4.7 Emergency preparedness and response	* There is no main difference.
9 Performance evaluation	4.5 Evaluation and corrective action	4.5 Checking	
9.1 Monitoring, measurement, analysis and performance evaluation	4.5.1 General 4.5.2 Monitoring and measurement	4.5.1 Performance measurement and monitoring	
9.1.1 General			* There is no main difference.
9.1.2 Evaluation of compliance	4.5.6 Evaluation of compliance	4.5.2 Evaluation of compliance	* There is no main difference.
9.2 Internal audit	4.5.4 Audits	4.5.5 Internal audit	
9.2.1 General			* There is no main difference.

Table 4.1 Comparing ISO 45001:2018 with OHSAS 18001:2007 and CSA Z1000-14 (continued and end)

ISO 45001: 2018	CSA Z1000-14	OHSAS 18001:2007	Main differences
9.2.2 Internal audit program	4.5.4 Audits	4.5.5 Internal audit	* There is no main difference.
9.3 Management review	5 Management review and continual improvement 5.1 General 5.3 Review input 5.4 Review output	4.6 Management review	* There is no main difference.
10 Improvement			
10.1 General	5.2 Continual improvement	Not found	* ISO 45001 and CSA Z1000 have an independent clause based on which an organization must specify opportunities coming from performance evaluation to improve its OH&S management system. This implies the importance of OH&S improvement in the aforementioned standards.
10.2 Incident, nonconformity and corrective action	4.5.3 Incident investigation and analysis 4.5.5 Nonconformities — Preventive and corrective action	4.5.3.1 Incident investigation 4.5.3.2 Nonconformity, corrective action and preventive action	* ISO 45001 and OHSAS 18001 require an organization to communicate with internal and external interested parties about nonconformities, but in CSA Z1000, such communication is only necessary for incidents and not nonconformities.
10.3 Continual improvement	5.2 Continual improvement	Not found	* In addition to 10.1, ISO 45001 requires an organization to improve its OH&S management system by promoting OH&S supporting culture and participation of workers.

As expected, the results show that ISO 45001 is the most inclusive standard compared to CSA-Z1000 and OHSAS 18001. As the main differences, ISO 45001 requires that an organization goes beyond the requirements of the OH&S management system and identifies the external and internal factors which can prevent or postpone achieving the OH&S objectives. An important part of these factors includes OH&S-related needs and concerns of workers and interested parties. In this regard, the control of OH&S concepts in outsourced operations must also be defined within the scope of the organization's OH&S management system. Moreover, in addition to OH&S risks, the OH&S opportunities which can improve the performance of the OH&S management system need to be assessed. Due to the importance of this issue, OH&S opportunities of Industry 4.0 and its technologies are examined in this study.

4.3 The results of step 3: Outlining OH&S opportunities and challenges in the age of Industry 4.0

4.3.1 Scope

OH&S management systems can be applied by organizations of any size, type, or activity field. However, large firms are better prepared than Small or Medium-sized Enterprises (SMEs) to fully utilize the advantages of Industry 4.0 [128]. A guide by European Commission [129] defines SME as an enterprise with less than 250 employees and either a maximum annual turnover of EUR 50 million or a maximum annual balance sheet of EUR 43 million. But, the adoption of Industry 4.0 technologies needs high investment and an advanced level of expertise. For instance, German producers are expected to invest EUR 250 billion to incorporate Industry 4.0 technologies in their production processes over 10 years until 2025. Simultaneously, there is a demand for about 400,000 labours mainly with competencies in software and IT [37]. It seems that constraints on financial resources, knowledge resources, and technological awareness are key factors for SMEs to benefit less from the advantages of Industry 4.0 [128]. Thus, SMEs tend to focus on the monitoring aspects of Industry 4.0, mainly through the cloud and IoT technologies [130].

4.3.2 Normative references

Both OHSAS 18001 and CSA Z1000 cite ILO-OSH 2001 and its audit matrix in reference publications. The management models underlying these standards were developed based on the well-known PDCA concept and continuous improvement approach. This traditional approach is not flexible enough to deal with the major changes originating in Industry 4.0 [2]. Nevertheless, there is no normative reference for ISO 45001, which may be due to the introduction of an updated management structure (Figure 2) in that standard [80]. This new structure not only includes the PDCA cycle but also addresses external and internal issues that affect the processes of an OH&S management system. Economic crises, global warming, the COVID-19 pandemic and, particularly, the emergence of Industry 4.0 are good examples of external issues. Therefore, compared with the OH&S management systems mentioned in this thesis, ISO 45001 has more potential to consider the OH&S implications in the age of Industry 4.0.

4.3.3 Terms and definitions

In addition to the terms defined in CSA Z1000 and OHSAS 18001, two new terms, "OH&S opportunity" and "outsource" are presented in ISO 45001. The emergence of Industry 4.0 may raise some questions regarding defined terms in OH&S management systems. For example, are persons who work for online platforms such as Uber considered to be employees of the organization? In addition, Industry 4.0 enables widespread remote work. This means that the place of work can be a home or even a public place. Are these locations considered workplaces? If so, how can an organization assure safe and healthy conditions for its workers? These questions are addressed in the following sections.

4.3.4 Context of the organization

Unlike CSA Z1000 and OHSAS 18001, ISO 45001 requires organizations to go beyond the requirements of an OH&S management system. Its requirements include identifying the internal and external subjects that can prevent or postpone the achievement of OH&S objectives. Accordingly, the identification of Industry 4.0 implications is a necessity for appropriate OH&S performance in the ISO 45001 framework. Many authors such as Sony and Naik [131], and Beier et al. [132] believe that Industry 4.0 can be considered as a socio-technical system in which technical (non-human) and social (human) elements interact in a specialized framework (organization). From this perspective, OH&S challenges and opportunities resulting from this transformation can be expressed in three main forms: (1) work tools and equipment; (2) work organization and management; and (3) workforce qualifications [23].

i. Work tools and equipment

Industry 4.0 emerged from new digital industrial technologies [46], which increase flexibility, agility and customized production [133]. In a socio-technical system like Industry 4.0, changes originating from one element (technology) affect other elements (human and organization). One of the most significant consequences stemming from these changes is psychological problems such as mental strain on employees. Scheer [[134], cited in [135]] concludes from the preceding studies that mental work demands in workers can be altered by technological changes. IoT, as a key technology of Industry 4.0, enables a new kind of system integrating information and physical objects called Cyber-Physical System (CPS). A CPS can interact with the physical world and humans [136], and records, monitors, coordinates and controls operations in real time. Examples of CPS can be seen in intelligent highways, medical equipment, building and environmental control, and process control [137]. Regarding these capabilities, CPS allows the manufacturing industry to enhance flexibility in production processes in order to meet customers' demands. In such a cooperative system, tasks are flexibly distributed between workers and work equipment. This situation leads to a combination of manual tasks and automated works in which humans and machines complement each other. Thus, there will be an increasing number of human-machine interactions. Dombrowski and Wagner [135] explain that this means the workers must be also more flexible which needs a higher level of cognitive ability. A lack of cognitive ability can be linked to increased mental stress.

In particular, companies are deploying more and more cobots and autonomous machines. According to the International Federation of Robotics, more than 2.7 million robots were working in industry worldwide in 2020, compared with around 1.6 million in 2016 [138, 139]. This growing trend will lead to a remarkable degree of interaction between humans and machines [140], a situation that may result in various new OH&S risks. For example, a research report issued by Health and Safety Executive (HSE) [141] discusses workers and autonomous robots can collide with each other; MSDs can appear due to a lack of precise information for workers on how they should work with autonomous machines and failure to adapt work to them in terms of load, time and pace; and work stress might arise due to sudden movements by autonomous robots and an inability to control them. These mentioned results are supported in the work of Jocelyn et al. [142]. Moreover, the broad application of intelligent robotization technology can cause competitive psychological climates in the workplace and job stresses in the workers. In their survey, Li et al. [10] are able to show if organizations fail to support their employees through boosting communications, promoting teamwork, and developing interpersonal skills, the consequences of these job stresses are likely to manifest themselves in a high labour turnover rate.

On the other hand, some researchers such as Johnston et al [143] explain that autonomous robots can take human workers’ place in risky situations such as confined spaces. Gambao et al. [144] also state that autonomous robots can protect workers from the consequences of labour-intensive tasks such as manual handling. In our opinion, given the exorbitant price of autonomous robots, it is still too early to expect work environments to be largely robotized.

ii. Work organization and management

IoT allows people to work anytime and anywhere. Accordingly, non-standard employment in the form of online work platforms will become more common. Rani and Furrer [145] express that in this way, new types of flexible works in terms of hours and place of work will emerge. Kawachi [146], and Tran and Sokas agree with this opinion and foresee the proportion of part-time and temporary jobs will increase rapidly. These changes can raise concerns about the fuzzy boundary between private and professional life [147]. As a result, workers can experience a high level of occupational stress and related disorders [148]. Moreover, big data enables organizations to adopt digitalized management practices to distribute work, evaluate employee performance, and recruit and dismiss employees [149]. A workbook issued by Health, Safety Executive (HSE) [150] argues that if the distribution of work is beyond workers' capabilities in terms of pace and schedule, or if the workers are not able to control the content of work and respect OH&S standards, unsafe behaviours can arise, and sick leave and work stress can become prevalent. Therefore, we can assume such consequences for employees working under digitalized management practices as well. Moreover, a real-time evaluation of workers and competitive practices for assigning tasks to them can provoke stress-related pressures [151]. Many researchers such as Hagendorff [152] raise growing concerns about the ethics of decision-making based on artificial intelligence. From this point of view, it can have side effects for OH&S. Furthermore, the widespread application of technology can cause work dehumanization [153]. In this condition, workers have to follow commands issued by a computer algorithm without receiving support from their supervisors and human relationships. Stacey et al. believe that this makes the atmosphere of the workplace less pleasant for workers and they might feel they have lost their active role [23]. According to the workbook of HSE [150], these situations also may not only increase occupational accident rates but also can cause serious stress-related difficulties, particularly if they are associated with an organizational inability to manage these transformations. On the positive side, in their work, Wu et al. [154] and Low et al. [155] show how intelligent algorithms can enable constant monitoring of OH&S and early detection of major errors in the workplace. As a result, these features can help protect workers from accidents and improve OH&S conditions. Given the issues discussed above, we come to the conclusion that the disadvantages of using digitalized management methodes in the

4.0 era are currently more highlighted than its advantages. The lack of addressing these challanges can even lead to the failure of digitalized management implementation.

iii. Workforce qualifications

Regarding the third aspect, workforce qualifications, Industry 4.0 transforms the qualifications people require to work in the Industry 4.0 age. As work processes become more complex in terms of understanding and operation, the need for better-educated employees increases. Hecklau et al. [156] argue that the necessary qualifications can include a broad range of technical, methodological, social and personal competencies. These qualifications can be applied for both blue- and white-collar workers [157]. The first serious challenge is a lack of sufficient competent workers [158], which can increase the work pressure on existing skilled workers. Educating the current workforce to give them new skills is another option to deal with this shortage; however, it can be time-consuming and can make the newly trained workers occupationally exhausted [159]. Badri et al. mention also that during the intervening period, the workers might encounter various OH&S risks that they do not yet know exactly how to cope with [2]. Moreover, online work platforms allow workers to freely choose new jobs. If the new workers are not skilled enough, the probability of work-related accidents may increase [23]. In our view, organizations should be encouraged to start training their existing workforce now to prepare them in the coming years as Industry 4.0 becomes more popular. This solution can be useful for employers and workers, and also economically viable.

ISO 45001 emphasizes that organizations must take into account the concerns and rights of workers and interested parties. Since Industry 4.0 enables telework, an organization might be confronted with a diverse range of workers with different languages, ages, cultures and time zones, or even physical limitations. Identifying and meeting their various OH&S needs can be challenging. Moreover, some studies such as Chia et al. [15] and Min et al. [160] indicate that in the new business models such as online work platforms, it is not clear who is responsible for OH&S. Tran and Sokas [161], and Christie and Ward [162] mention that employers and employees want to shift this responsibility onto each other. Furthermore, such workers lack labour unions, which can be powerful interested parties involved in collective bargaining over their OH&S needs. Badri et al. [2] also believe that related regulations have not yet been issued [2]. The overall situation makes it difficult for organizations to identify these workers' OH&S needs.

However, ISO 45001 clearly states that organizations must determine the scope with respect to external and internal issues and the expectations of interested parties. As already mentioned, Industry 4.0 allows workers to work anywhere with an internet connection, such as homes, public spaces and even mass transit. If an organization outsources its activities, those activities must still be included within the scope of its OH&S management system. The inclusion of all activities in different job sites within the scope of such a system can be challenging for organizations.

4.3.5 Leadership and worker participation

4.3.5.1 Leadership and commitment

ISO 45001 posits a new duty for an organization's top management: the duty to create, lead and enrich a culture of protection for the organization's OH&S achievements. Since digitalization is often associated with internationalization [22], it is expected that workers of different nationalities, backgrounds, and cultures will be employed. These diverse workers can have equally diverse perceptions of OH&S, which makes it difficult to create and lead an effective OH&S culture inside an organization. Nevertheless, according to Digmayer and Jakobs [163], an OH&S culture can be fostered through effective communication between different parts of an organization [163]. Therefore, we can expect that IoT, alongside vertical system integration, plays an important role in facilitating communication.

4.3.5.2 OH&S policy

ISO 45001 states that, in addition to OH&S risks, OH&S opportunities must also be taken into account in developing OH&S policy. Although the OH&S opportunities created by Industry 4.0 are known, to a great extent, the related OH&S risks have not yet been fully identified [2].

4.3.5.3 Organizational roles and responsibilities

Unlike OHSAS 18001 and CSA Z1000, ISO 45001 does not require an organization to appoint a top management representative. Instead, it imposes an obligation to assign OH&S responsibility to workers for the parts of the OH&S management system that they are authorized to control. This means that although the top management of an organization has ultimate responsibility and authority over the overall performance of the OH&S management system, every employee in the organization must have a clear understanding of its role and responsibility in improving the performance of the OH&S. While the organization assigns OH&S responsibilities to employees, it must also ensure that the requirements for performing these responsibilities are efficiently met. Under certain circumstances, meeting these requirements may not be properly possible. In this condition, Industry 4.0 technologies can be a great help. For instance, Wierzbicki et al. [164] discuss that the Coronavirus Disease 2019 (COVID-19) pandemic created a serious shortage of Personal Protection Equipment (PPE), including medical masks and face shields, worldwide. This situation made it difficult for many health centers to provide these products required by their staff. They also mention that at that time when the production capacity of developed countries was saturated and developing countries could not afford to import the products, immediate demand for the PPE was satisfied by applying additive manufacturing technology and 3D printers. This experience reminds us of the capability of this technology to fabricate PPE on a mass scale, at a low cost and in a short time.

Concerning the OH&S responsibilities of employees in the workplace, vertical system integration is another technology of Industry 4.0 that can affect OH&S responsibilities of employees in the workplace positively and negatively. Vertical system integration can flatten an organization's structure and likely removes middle managers. Consequently, workers can become more autonomous and gain more control over their tasks adapting workloads, schedules to themselves and considering OH&S aspects and well-being. But if middle managers are replaced by intelligent algorithms connected to big data, the results may not be desirable. Also, using IoT sensors, these computer programs collect data related to some specific working conditions such as temperature, humidity and amounts of harmful gases, or personal OH&S data including vital signs. If a dangerous situation due to these factors is detected, the intelligent algorithm sends a danger signal [165, 166]. This kind of system can result in more effective control of these specific OH&S risks, however, it is still not able to control a broad range of work conditions related to OH&S. Moreover, if the IoT sensors are damaged, have an electrical fault, suffer from a cyberattack, or are inadequately maintained, the entire system fails or data collected are misinterpreted, resulting in unreliable outputs. This situation may likely yield to unpredictable dangerous conditions in some work environments. In addition, this intelligent system may also cause excessive dependency for workers. Since the workers are alerted to hazards by the warning from the intelligent system, any system failure that may arise from the above-mentioned causes, makes workers much less able to detect and control surrounding OH&S risks because of lack of practice that can lead to reduced situation awareness. Consequently, as Stacey et al. [23] explain, workers become less autonomous and we can expect that they are probably less likely to assume their OH&S responsibilities.

4.3.5.4 Consultation and participation of workers

ISO 45001, and CSA Z1000 to some extent, present a more comprehensive interpretation of worker consultation and participation than OHSAS 18001.

As we have seen, Industry 4.0 can increase telework. Face-to-face interactions may be eliminated and workers may not be able to informally speak about OH&S issues at workplace [23]. Consequently, workers cannot encourage each other to participate in OH&S projects and improve the performance of an OH&S management system. However, it is possible to use this interconnectedness to collect workers' opinions about OH&S matters, regardless of the level and type of their work. It can provide a basis for consultation with and participation by the relevant workers. In addition, online work platforms provide a wide range of jobs – mainly simple ones like service duties performed in people's homes or other premises. Many new workers take these jobs and they can easily change jobs. Therefore, they might not have enough experience or motivation to participate in improving the OH&S conditions of these temporary jobs.

As mentioned in section 4.3.4 (ii), the decision-making based on artificial intelligence has raised concerns about ethical considerations. In his comprehensive examination of applying principles of AI ethics and safety to the design and implementation of algorithmic systems, Leslie [167] explains that intelligent algorithms are not able to incorporate emotions into their decisions. In other words, the structure and features of these algorithms are designed by their human developers to interpret a big amount of data. Thus, the algorithms have the potential for replicating their developers' preconceptions and biases. He continues that in intelligence algorithms, a high dimensional correlation among big data forms the basis of the decisions made which is far beyond the analytical capabilities of human reasoning. These cases bring into question the correctness and transparency of the decisions made. This situation will be exacerbated if somehow the consequences of these decisions are associated with racism, gender discrimination, unfairness, injustice and inequality. Furthermore, invasion of privacy is another important challenge of applying artificial intelligence systems discussed by this author. Since the function of these systems heavily relies on the classification and analysis of data including personal data related to workers, utilization of the data without obtaining workers' consent or for any purpose other than predetermined purposes leads to disclosure of their personal information. Knowing the above, we can conclude that workers' trust and confidence in artificial intelligence systems are vulnerable. Organizations that intend to use these intelligent systems, particularly in OH&S-related programs such as wearable sensors for monitoring workers' safety and health in real time, must plan to remove or control the mentioned challenges because they are serious obstacles to the participation of workers in achieving OH&S objectives. To avoid these negative consequences, Morley et al. [168] propose that the following ethical objectives should be considered in the implementation of OH&S monitoring algorithms that require data collection: firstly, the aim of such programs is the well-being of workers (justification); secondly, unnecessary personal data related to workers are not collected (optimization); and thirdly, the probable adverse consequences are assessed and mitigated (minimization of harm).

4.3.6 Planning

Unlike OHSAS 18001, ISO 45001 outlines the principal axes for planning an OH&S management system, in a way similar to CSA Z1000 but in more detail. It introduces a new clause regarding opportunities to improve the performance of an OH&S management system. As a relatively new technology, Industry 4.0 creates new OH&S risks and opportunities. Although these opportunities are widely known, the OH&S risks have not yet been fully identified. These two subjects are discussed separately in the following sections.

4.3.6.1 OH&S risks of Industry 4.0

The probable OH&S risks in the Industry 4.0 age are likely to result from new OH&S hazards. We group these hazards into six categories, as suggested by the Canadian Centre for Occupational Health and Safety (CCOHS) [169].

i. Biological hazards

Biological hazards are created by biological agents such as viruses, bacteria, insects and animals and can endanger workers' health. There is no direct relation between Industry 4.0 and emerging new biological hazards.

ii. Chemical hazards

Chemical hazards are related to using, storing and handling chemicals, ranging from simple detergents to very dangerous chemical preparations. Industry 4.0 can create this type of hazard in two ways:

- the new materials used in additive manufacturing equipment, such as 3D printers, can pose dangers for workers [170];

iii. Physical hazards

Physical hazards are natural factors that endanger workers' physical health. Typical examples include temperature, radiation, magnetic fields and noise. Some scenarios related to Industry 4.0 include the following:

- workers may be exposed to electromagnetic fields due to the rapid increase in the number of IoT devices [23]. Forecasts say that this number will increase to nearly 50 billion by 2030 [171];

- working adjacent to welder cobots can expose workers to welding radiation and laser emissions [172].

- cobots can also cause noise and vibration when working [23].

iv. Ergonomic hazards

Ergonomic hazards arise when work is not matched to workers' characteristics. This is mainly a result of ignoring human capabilities and limitations when designing work systems. Industry 4.0 may be associated with certain ergonomic problems such as the following:

- Industry 4.0 may increase sedentary work by reducing physical activities and motions [173]. Prolonged sitting enhances the risk of work-related MSDs [174];

- working with handheld IoT devices for a long time can cause musculoskeletal discomfort and muscle strain [175];

- widespread automation can change the content of the work, making it more supervisory. Thus, one worker might be assigned to supervise several machines in different locations. At peak times, this worker will have to deal with high cognitive demands. Moreover, full human-machine interaction in real-time does not allow workers to adapt work to themselves in terms of load, time and pace [23].

v. Psychological hazards

Psychological hazards originate from an imbalance between workers' professional duties and their abilities to perform those duties. According to this definition, bullying and violence at the workplace are also psychological hazards. Industry 4.0 can pose psychological hazards for workers in the following ways:

- the development of artificial intelligence approaches enables constant monitoring of workers' performance, as noted in item iv. Moreover, interactions between employees will be decreased if human labour, such as that provided by middle managers, is rapidly replaced by intelligent programs [176]. These cases will increase occupational stress and anxiety [151, 177, 178];

- the shortage of skilled workers in the age of Industry 4.0 is a significant challenge [179]; if it causes chronic job demands on existing workers, concentration loss and burnout are to be expected [180];

- job insecurity, particularly among unskilled or semi-skilled labourers, causes fear and anxiety [181];

- workers' confidential information can be stolen through cyber-attacks for the purpose of bullying or revenge [182];

- the increase in cognitive workload and workers' inability to adapt to their new work described in section 4.6.1.4 can result in mental health problems [23].

vi. Safety hazards

Other hazards related to tools and equipment are placed in the category of safety hazards, which can inflict harm on human body. We also assign occupational diseases to this category. Some relevant cases related to Industry 4.0 are described below:

- worker entanglement and collisions with cobots are probable hazards in the workplace. However, more severe unforeseen accidents might result if autonomous machines incorrectly interpret commands [183] or due to cyber-attacks [142, 184];

- the increase in sedentary work, as noted in section 4.6.1.4, might raise the premature death rate, due to cardio-metabolic disorders, and breast cancer in women [185]. It should be noted that physical inactivity is identified as a risk factor for breast cancer [186].

- the rapid rate of technological advances can cause unintentional accidents for two main reasons: first, failure to upgrade old technological infrastructures; and second, unfamiliarity with new technology [23].

4.3.6.2 OH&S opportunities of Industry 4.0

Industry 4.0 and its associated technologies introduce new opportunities which can greatly help organizations to manage OH&S risks. We categorized these opportunities based on the hierarchy of controls recommended by ISO 45001:

i. Elimination of hazards

Industry 4.0 can allow employees to work remotely using IoT-connected devices. As a result, the employees do not need to frequent areas where they are liable to be injured. Moreover, augmented reality technology enables the integration of a virtual 3D model of equipment and space workstation into a physical sample as Shi et al. [187] and Laudante [188] propose. Thus, the hazards arising from ergonomic weaknesses of different designs for the workstation could be identified and eliminated in the early stages of the design before an actual product was manufactured.

ii. Substitution

The deployment of autonomous robots is an effective alternative to replace workers in labour-intensive or dangerous tasks. These cobots can also pose their own OH&S hazards; nevertheless, the resulting OH&S risks are reduced.

iii. Awareness-raising systems

One of the most important functions of Industry 4.0 in OH&S is constant monitoring to avoid employees working in unhealthy or dangerous conditions. This is enabled by a wide range of IoT sensors and wearable devices integrated into workers' clothes or worn on the body, such as gloves, smart watches, and glasses. This possibility is discussed in many studies such as Romero et al. [189], Awolusi et al. [190], Gašová et al [191], Mehata et al. [192], and Kanade [193]. In this way, data related to OH&S indicators such as vital signs or vibration and noise can be continuously collected, analyzed and then workers at risk are warned. However, we believe that the technical limitations and the relatively long time required to commercialize these products should not be overlooked.

iv. Administrative controls

Worker training, one of the main forms of administrative measures for controlling hazards, can be fundamentally transformed in the Industry 4.0 era. Augmented reality and virtual reality can provide OH&S training, including both theoretical content and empirical knowledge [194]. Therefore, workers can receive more adequate training and acquire a clear understanding of hazards and how to cope with them [195, 196].

v. Personal Protective Equipment (PPE)

PPE is considered to be the lowest-priority action for protecting workers against hazards. Wearing PPE in the workplace is usually obligatory; however, it can be undermined by non-compliance, mainly due to poor ergonomic design [197]. PPE is provided in a limited number of standard sizes and may not ensure a correct fit for all users [198]. To overcome these problems, additive manufacturing technology is a possible solution. Wesemann et al. [199] state that this technology, also known as 3-D printing, allows designers to have more freedom in developing customized prototypes of PPE and enables engineers to produce PPE quickly and easily [199]. As a result, workers have PPE that provides excellent protection without impairing their personal comfort at the workplace. This opportunity is showed in studies conducted by Jafferson and Pattanashetti [198], Huang et al. [200], and Sterman et al. [198, 200, 201].

Despite the above-described opportunities, there are still serious obstacles to their implementation. Making full use of these opportunities requires overcoming economic and technical problems. For instance, real-time monitoring of various OH&S indicators related to work conditions or psychological factors needs different sensor configurations. Nasiri and Khosravani [202] explain that these sensors must be capable of high stretchability (amount of strain which a sensor can tolerate), high sensitivity (accuracy and efficiency of a sensor), minimum response time and a wide range of detection (range between the minimum and maximum amount of a parameter which can be measured by a sensor). It is very difficult to have all these features at the same time. The authors mentioned that sensors with high stretchability usually have low sensitivity; in tactile sensors, sensitivity and detection range are inversely related; sensors made of polymer have longer response times compared to other sensors; a significant increase in range of detection is still a challenge. Another important challenge is the comfort of users when using wearable sensors in direct contact with the body. In practice, this comfort should be accompanied by small size and flexible components in the sensors, but it is not always possible. For example, Heo et al. [203] state that sensors made of carbon-based materials and textile-based configurations, although lightweight and biocompatible, must be more sensitive and durable to be usable in practice. Based on the aforementioned information, we come to this conclusion that to benefit the full potential of OH&S opportunities of Industry 4.0, relevant development must take place, which will be costly and time-consuming however it needs much time and money. Furthermore, existing literature indicates a proof-of-concept implementation of predictive IoT wearable systems [204]. In other words, the feasibility of such systems is demonstrated; however, commercialization of these systems is in its infancy. Models need to be developed so that they can process large amounts of data gathered by IoT sensors and produce logical results. The models need to be tested and then validated in real shopfloors. Thus, it is a complicated process that requires research, and spending a lot of time and money.

4.3.6.3 Determination of legal requirements

All three OH&S management systems require an organization to identify mandatory OH&S requirements, as well as optional ones that it decides to accept.

The OH&S regulatory authorities and standard-setting bodies have usually lagged behind technology. We see the same trend in the fourth industrial revolution as well [2]. This can affect proactive approaches in OH&S, and the result can be work-related accidents due to new hazards arising from technology.

OH&S regulations have been criticized for weaknesses such as relying on other social, economic and political conditions [43]; reducing the organization’s OH&S performance to a basic level that meets only legal OH&S requirements [205], and inability to integrate OH&S into operations [2]. In spite of these criticisms, compliance with OH&S regulations is one of the main practices enabling organizations and workers to prevent occupational accidents and diseases [206-208]. However, in some cases, such as mining industry, a lack of technological enablers is a major obstacle to organizations, which are not able to fully meet their legal obligations; for example, a technology to facilitate emergency self-escape does not fully exist yet [209]. It seems that Industry 4.0 can satisfy some technical demands, particularly by applying IoT, big data and cloud computing to problems. Regarding the above-mentioned example, Wu et al. [210] present a dynamic information platform for underground coal mines. It consists of four main systems including a 3-

D virtual mine system, safety diagnosis system, safety inspection system and emergency rescue system. IoT-based solutions can also help an organization implement health and safety regulations in the workplace [211].

4.3.6.4 OH&S objectives and planning to achieve them

ISO 45001 provides details on how OH&S objectives must be determined, measured and achieved. It states that OH&S objectives can be set at the strategic, tactical, or operational levels; still, they should be connected to OH&S opportunities, risks, and performance criteria.

Information systems (IS) play a supporting role in achieving organizational objectives [212]. The creation of an IS involves gathering, processing, storing and sharing information. To fulfill these functions, information technology (IT) is a major component of each IS [213]. Despite these benefits, aligning IS with organizational objectives has always been a major challenge [212, 214, 215]. Indeed, the management of IT capabilities in an effective and timely manner, consistent with organizational strategies, faces some serious limitations [216]. Nevertheless, the age of Industry 4.0 and big data is associated with IT advancements that can overcome these limitations. For instance, the emergence of the intelligence concept can help the organization to promptly collect, analyze and disseminate data and information [217, 218]. It can positively impact both strategic and tactical decision-making [218]. In this regard, proposed safety intelligence ([219], cited in [220]), which aims to convert a huge amount of raw OH&S data to meaningful information which is essential for OH&S management, can considerably sharpen fragmented OH&S data and raise information to a meaningful level that facilitates development of an action plan to achieve OH&S objectives [220]. For example, analysis of 172,026 medical examination records of women workers has revealed that high BMI and poor sleep quality are latent risk factors and should be considered in women workers' medical protocols [221]. Another example is presented in the work of Ajayi et al. [222]. They analyze large sets of data on work-related accidents in 5,000 projects of a construction company over 13 years in the United Kingdom (UK). The goal is to discover potential factors affecting the likelihood of accidents. Injury distribution showed that the top 5 injured body parts are fingers (23 percent), hand (13 percent), back/buttocks (12 percent) and ankle (8 percent). The top 5 operations which these injuries are arising from are pulling (stringing), lifting, loading/offloading, manual handling and cutting because workers need to use those body parts for performing these operations. Since most of the construction operations are done outdoor, some accidents can be linked to seasonal conditions. Thus, accidents distribution by season revealed that most accidents happen in winter (29 percent), followed by fall (25 percent), spring (24 percent) and summer (23 percent). The last factor analyzed was the regions with the highest accident rate. The same analyses can be done for other factors contributing to accidents such as age of workers, type of project (overhead lines, cabling, offshore, etc.), project contract (new built, maintenance, renovation, etc.), severity cost and total cost of project. Using big data analytics and simulation architecture, a company is able to identify accident causation variables and increase accuracy of preliminary prediction of OH&S challenges in a new project. This helps the company to be well prepared to control OH&S risks and also to prevent deviations in achieving OH&S objectives.

4.3.7 Support

ISO 45001 explains the main elements that support an OH&S management system, including resources, competence, awareness and communication. This content is the same as the content in OHSAS 18001 and CSA Z1000.

4.3.7.1 Resources and competence

Industry 4.0 consists of modern technologies that can be considered necessary resources in the future world of work because they can significantly improve the performance of an OH&S management system. Nevertheless, most organizations do not have the required infrastructures to reap the benefits of Industry 4.0 [223, 224]. As the greatest barrier, significant financial resources must be available to exploit technologies of Industry 4.0 to the full [128]. The implementation cost of some technologies of Industry 4.0 is still too expensive, particularly for SMEs [36]. This can limit using opportunities of Industry 4.0 to improve OH&S performance. This is even more important given that SMEs represent 90% of companies in Europe [129].

One of the most important infrastructures for this purpose is competent human resources, referring to both the technical and personal aspects of workers. Technically, a worker 4.0 must have a basic knowledge of IT and data analytics and the ability to interact with robots and new autonomous machines [225]. Moreover, the worker’s personality must be receptive to frequent changes, virtual collaboration, self-administration and self-learning. Otherwise, the workload can seriously affect the worker’s OH&S [23]. In order to promote competency, augmented reality can encourage innovation during workers’ initial and periodic OH&S training [226-229]. Moreover, augmented reality can also be applied to identify workers who may be not fully competent to perform some tasks [230, 231]. In this way, these workers can be retrained to reach a reasonable level of competence in the given tasks or be assigned to tasks which are more coherent with their skill level.

4.3.7.2 Awareness

The labour force in the world is aging rapidly [232]. International Labour Organisation (ILO) estimates that workers aged 60 and over (older workers) will make up about 21 percent of the labour force in the world by 2050 [233]. Older workers can encounter declines in their cognitive abilities [234] which affect their memory, concentration and, eventually, learning capacity [235]. This can be exacerbated when they have to learn new and complicated information in a dynamic environment or under time pressure [236]. The fast pace of technological change in the Industry 4.0 age makes work processes increasingly complex and requires workers to learn quickly and frequently [23]. Therefore, if workers, particularly older workers, are unable to understand and use (master) recent technologies, they may not be aware of related hazards and therefore may not implement proper preventive measures. On the other hand, the future generations of workers are generation z and alpha which refers to those born between 1995 to 2010 and 2011 to 2025 respectively [237]. They are "technology literate" generations who have grown up in the era of technology and the Internet [238]. Since these generations are in the midst of technological advancements, they can better deal with the above-mentioned challenges though this new generation still needs to be taught in order to percieve mechanism of work processes too. Moreover, augmented reality can enhance the environmental awareness of OH&S hazards among workers [239-241]. These hazards can include paths crossing energy lines, the existence of dangerous substances and safety instructions required to avoid human error. Increased awareness can prevent work accidents [242].

4.3.7.3 Communication

Industry 4.0 can transform communications with all interested parties, externally and internally. Communication can be facilitated by horizontal and vertical systems integration. As a result, all internal and external stakeholders can share OH&S decisions and issues immediately. The main obstacle to extending digital communication is human limitations. As Stacey et al. [23] state, Industry 4.0 means people can work anywhere and anytime; therefore, limiting factors can include different languages, ages, cultures and literacy levels among the various workers.

4.3.7.4 Documented information

Thanks to the cloud, the limitations of storage space for documents related to an OH&S management system are removed. Moreover, we do not have to worry about retrieving them in case of fire, loss, or unforeseen events. In addition, OH&S documents and records are to a certain extent safeguarded against the threat of unauthorized access, cyber-attacks, and computer viruses by cybersecurity technology. Nevertheless, if cybersecurity measures fail, confidential documents such as medical records might be in danger of being stolen. In addition, unauthorized changes to OH&S documents can be made by stealing an authorized identity.

4.3.8 Operation

ISO 45001 outlines the required measurements to control OH&S risks in an organization's operational process. A new requirement that it imposes is the assignment of responsibility for controlling OH&S impacts of outsourced processes. In other words, outsourced functions are defined within the scope of the organization's OH&S management system, while the external organization that performs the function is excluded.

Big data and IoT enable data to be collected and exchanged on a large scale. As mentioned previously, real-time control of organization-related operations using artificial intelligence is possible; still, this can cause anxiety and stress for the employees involved [151], particularly if they do not know what data is collected, how it will be analyzed, and why it is being collected [23]. Ethical considerations are of paramount importance to human workers as discussed in section 4.3.5.4.

4.3.8.1 Eliminating hazards and reducing OH&S risks

A combination of Industry 4.0 technologies can be applied to reduce OH&S risk. For example, additive manufacturing like 3-D printers can be used to produce a wide range of customized tools [243] and PPE. These products can be made more user-friendly in terms of weight, comfort, strength, and resistance and can provide a better level of health and safety protection for workers [200]. Moreover, wearable IoT sensor network systems can monitor environmental parameters such as temperature and humidity and also physiological parameters like body temperature and heart rate. This possibly protects workers from exposure to dangerous situations in the workplace [244, 245].

However, a malfunction of any technology can cause a sequence of failures and lead to unpredictable situations that endanger workers. Moreover, Stacey et al. [23] believe that the severity of OH&S risks might increase substantially because, despite the widespread automation related to Industry 4.0, a few repetitive or difficult tasks remain that robots are not able to do. Furthermore, full automation can remove many tasks which need physical strength and online work platforms provide easier access to a wide range of works including low-skill jobs. Therefore, these allow workers to work longer and retire later which can mean exposure to OH&S risks for a more extended time and consequently, cumulative effects of OH&S risks.

4.3.8.2 Management of change

As discussed in section 4.4, Industry 4.0 brings about a dramatic transformation in the world of work. Most managers are aware of these transformations but they experience difficulty in applying the transformation to their organizations [[246], cited in [247]. Traditional change management use structured approaches which are often composed of specific steps including planning, control and coordination to be closely followed. Cameron and Green [248] explain that this situation may be associated with some rigidities; for instance, managers determine priorities and decide on resource allocation, the flow of information among the personnel is restricted, and the employees are less able to participate. They conclude that these approaches are more useful when there is a small level of uncertainty in the environment. However, considerable uncertainty exists in the digital transformation context resulting from the fast pace of technological changes [249]. To deal with this problem, organizations need to develop their dynamic capabilities as an ability to adapt to environmental changes [247]. Information and communication technology (ICT) capabilities play a facilitating role in developing dynamic capabilities [250]. Moreover, concerning OH&S change management, an organization can apply simulation technology to predict the probability of OH&S risks or to estimate the effect of opportunities arising from changes [251, 252] before these changes are implemented. On the other hand, Industry 4.0 technologies are rapidly improving. If workers cannot adapt to change, the outcome could be mental pressures or work-related accidents, as discussed in section 4.3.4.ii [150].

4.3.8.3 Procurement

As additive manufacturing equipment becomes more popular, non-original spare parts for this equipment can be problematic. They can lead to accidents during the normal functioning of the equipment [23]. Therefore, organizations must control the procurement process for these products so that it is consistent with their OH&S management system. Moreover, an organization might not be able to control its contractors' operations or outsourcing functions if they use an online work platform to hire workers. As discussed earlier, it is not clear who is responsible for OH&S in an online work platform. Nevertheless, thanks to IoT and data exchange, small sensors embedded in PPE or wearables have the potential to enable real-time monitoring of unsafe conditions [253], harmful chemicals [254] and physical factors [255], primary vital signs that can be relevant to workers' psychological condition [256] and even some ergonomic criteria [257] in the workplace. In the future, these possibilities promise to help organizations to have more control over contractors' operations and outsourced activities.

4.3.8.4 Emergency preparedness and response

Any organization can encounter unforeseen situations that turn into emergencies, such as a malfunction of autonomous robots leading to dangerous behaviour, large-scale cyber-attacks that can cause failures in the normal functioning of applied technologies, and the inability of artificial intelligence to make ethical or right decisions. However, Industry 4.0 can greatly help an organization cope with emergencies. First, augmented reality and simulation can be applied to deliver close-to-reality exercises to workers [258]. Second, as mentioned in section 4.3.6.3, a dynamic information platform consisting of IoT, big data and cloud computing can enable the organization to be more prepared for emergencies and prevent them from turning into a crisis [210]. Third, emergency service centers such as fire stations, medical centers and police stations can be connected to the organization using horizontal system integration.

4.3.9 Performance evaluation

The requirements for performance evaluation stated in ISO 45001 are similar to those in OHSAS 18001 and CSA Z1000. In this phase, an organization has to determine whether its OH&S target objectives have been met by its OH&S performance.

As mentioned in section 4.3.8.1, Industry 4.0 promises to make it possible to monitor and measure the necessary OH&S performance criteria in real-time. This data is processed as big data and the results are stored in the cloud. The results can be shared with all stakeholders inside and outside the workplace thanks to IoT, and horizontal and vertical systems integration.

4.3.9.1 Evaluation of compliance

Real-time monitoring of OH&S aspects in operations leads to collecting a large amount of OH&S-related data. Organizations will be able to process this huge data through big data analytic technology and carry out evidence-based evaluations of their performance for broad aims such as compliance with OH&S requirements. The results can reveal the organization's commitment to legal OH&S regulations and can be used as evidence in legal proceedings. It is worth mentioning that a big data set is not necessarily superior to a small data one. Drury [259] mentions that if this big data is of poor quality owing to be gathered badly, e.g. not having sufficient validity and reliability, it may lead to spurious results. Nonetheless, a certain amount of visual OH&S-related data can also be gathered by computer vision [260, 261]. Computer vision is a useful tool that converts the real world into digital information that can be understood by intelligent algorithms such as machine learning [262]. Deep learning is one machine-learning approach [263] that has greatly developed computer vision [264] so that algorithms can now automatically recognize some specific unsafe conditions and dangerous behaviours in the workplace [265, 266]; expected to have more cases in the future. Nevertheless, deep learning visual models are not able to depict causality [267]. As a result, an algorithm alone cannot detect all various unsafe conditions or actions. For example, concerning the risk of falling from a height when working on a scaffold, an algorithm may only detect the non-wearing safety harness. Therefore, we need other algorithms to identify other causes of falls from a height, such as approaching unprotected sides or defects in the scaffolding structure. To overcome this limitation, multiple algorithms must be applied which makes it costly [268]. Consequently, results may fail to reflect the true state of compliance. For this reason, it is suggested that the results of other OH&S monitoring tools, such as anomaly reports, be used along with deep learning models to thoroughly evaluate OH&S performance [267].

4.3.9.2 Internal audit

Industry 4.0 also enables organizations to greatly facilitate planning and conducting remote internal audits. Remote audit refers to applying technology to collect information, carry out an interview with an auditee, and other stages of an audit when face-to-face interactions are not possible [269]. Picciotti [270] explains that in this type of audit, auditors can perform the audit activities anywhere regardless of the distance from the auditee location. The technology applied in a remote audit usually includes video/telephone conference and remote means, which improves communications among participants and access to organizational documents, respectively. A few weeks after the Covid-19 pandemic, the international auditing community recommended auditees, auditors, and certification bodies to use remote audits as an alternative to on-site audits. To ensure the effectiveness of a remote audit, the level of risk to meeting the audit objectives must be evaluated before conducting the audit. Picciotti proposes that this evaluation includes the level of confidence between auditors and auditee's employees, the access to the auditee's documents, prevention of malfunction of videoconference platforms and stability of Wi-Fi. Moreover, to carry out an audit smoothly, the auditors need to know the general tools and various functions of different videoconference platforms, but not all auditors may be fully familiar with these technical capabilities. The auditee companies need to prepare their organizational documents in electronic form while most companies may still retain a great part of their records in hard copy form, particularly small companies. In addition, making a paperless backup of the documents is very time-consuming. Finally, the auditors need to see how the work activities are arranged and done in the operations area. It is mostly done by someone holding a video recorder and moving on the shop floor. This approach might not be effective enough because it only gives the auditors a restricted view of the work environment without full details. The auditors might fail to gain a clear visual and sensory perception of what is being performed on parts of the shop floor because the auditee selects the parts that he/she wants to show the auditor, and OH&S-related risks such as humidity, temperature, harmful fumes and chemicals. In this way, audit objectives are not fully met. Thus, information-gathering methods such as observation and sampling in the workplace may be restricted because auditors are deprived of face-to-face communication.

Since the auditors are outside the workplace but need to inspect different places in the workplace, a virtual reality-based system can be applied to aid them in getting a better understanding of the real environment in the workplace. This system presented in the work of Greiner et al. [271] constitutes a microphone and a camera attached to a person inside the workplace, and virtual reality glasses worn by an auditor. When the person walks into the workplace, the microphone and camera record what he or she hears or sees. This information is sent to the auditor at a 360-degree viewing angle so that he or she can watch around freely. In addition, the virtual reality glasses provide a 3-dimensional video of the sent information which offers more depth than 2-dimensional recording.

4.3.10 Improvement

ISO 45001 and CSA Z1000 place more stress on continual improvement of the OH&S management system than OHSAS 18001. Unlike ISO 45001, CSA Z1000 and OHSAS 18001 do not address the promotion of an OH&S-supporting culture in the improvement process.

Following the rapid technological change, further improvements can take place in the OH&S area. For instance, to predict unsafe human acts, computer vision must be capable of modelling motion dynamics. At present, this is not fully possible; however, in view of improvements in convolutional neural networks and long short-term memory, it could be done in the future [267]. Long Short-Term Memory (LSTM) is a kind of neural network with a stronger ability to learn and predict sequential data. In combination with convolutional neural networks, it can greatly improve the efficiency of the models for identifying unsafe actions of human workers in the worksite. On the other hand, some technological progress can be associated with new risks. For example, it is forecast that direct brain-to-machine interfaces might begin to appear in industry restrictedly by 2025 [23]. We can expect that this possibility may be applied to enhance safety where move is restricted, or users need to quickly respond to a probable safety-critical situation to save time. Under these conditions, workers may be exposed to high-level electromagnetic fields [23], which are suspected of causing or promoting cancer; heating of body tissues is a definite impact [272]. Moreover, technostress must be taken into account when a new generation of information and communications technologies arrives on the scene. As an OH&S consequence, workers who are unable to deal with the technological change will be obliged to tolerate extra anxiety and strain added to existing stress in the workplace [273]. Another example is the nascent 5G WiFi network, which can expose workers to more intensive electromagnetic fields. Some researchers claim that this not only will harm the skin and eyes but will affect the whole body [274].

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

In this chapter, we conclude our work by summarizing the contributions we have made to the study of the implications of Industry 4.0 for OH&S and answering the research questions. We also discuss the limitations of this research and recommend directions for future research.

This thesis aimed to describe the wide range of challenges and opportunities Industry 4.0 can create for OH&S. To do this, in chapter 2, we provided a background of the different technologies that constitute Industry 4.0 and also the fundamental principles underlying OH&S management today. In chapter 3, we explained the methodology of this study which consisted of three steps. First, we conducted a systematic literature review to provide basic knowledge of the challenges and opportunities Industry 4.0 creates for OH&S, applying the ProKnow-C method. Second, we made a detailed comparison between three well-known OH&S management system standards – CSA Z1000, OHSAS 18001 and ISO 45001, at the national, international and ISO levels, respectively. Third, we addressed the identified challenges and opportunities by examining the clauses included in these standards. In chapter 4, we presented the results of each step of the methodology separately. There are five main conclusions that can be drawn from the discussion.

1. The bibliographic analysis revealed broad applications of Industry 4.0 in different fields of business. In recent years, more researchers have been interested in working on this subject. Thus, we can predict that this trend will continue in the future, leading to major improvements in the use of Industry 4.0 technologies in manufacturing and the supply of goods and services, and better identification of the associated OH&S risks. The articles that comprehensively analyzed upcoming OH&S challenges have attracted more readers' attention in terms of the number of citations. The ability of Industry 4.0 to allow real-time OH&S monitoring in the workplace is also interesting to researchers. In addition, researchers have devoted considerable attention to augmented reality and IoT in their studies. Ergonomics, occupational safety and work-related psychological problems were the most popular fields of research. Moreover, the results showed that there were almost twice as many articles on using Industry 4.0 to improve OH&S as articles on OH&S risks created by Industry 4.0. It proved that OH&S challenges have been considered less in the development of Industry 4.0. This is more evident when we consider that 7 out of 12 articles on the OH&S risks of Industry 4.0 were developed theoretically, while

18 out 20 articles on the OH&S opportunities of Industry 4.0 took an empirical approach. This may raise some concerns about the lack of practical studies on how to control OH&S risks in the era of Industry 4.0 [275]. We believe that it could be due to insufficient attention to incorporating human aspects in 4.0 industrial systems. From a socio-technical point of view, humans and machines are considered as two main elements of the 4.0 industrial system. If the human capabilities of workers do not match with the workload produced by machines, an imbalance can be created in human-machine interaction. This might cause human errors, accidents, and even psychological problems. To avoid further problems, human aspects must be taken into account in the stage of design of an Industry 4.0 system.

2. At present, taking full advantage of OH&S opportunities of Industry 4.0 faces two major obstacles: high cost and technical limitations. For example, the widespread application of autonomous robots or augmented reality technology in workplaces is costly, or constant monitoring of all OH&S indicators such as vital signs needs a variety of IoT sensors, which is not practical yet. Nevertheless, the fast pace of technology development may overcome these limitations. The shortage of skilled labour and ethical considerations should not be neglected, which likely poses important obstacles. These obstacles might affect particularly SMEs as they have more limited financial resources to compete with large companies. We also concluded that psychological hazards should be highlighted much more due to the fundamental transformation of the interaction of workers with technologies associated with Industry 4.0. Further advances in the adoption of Industry 4.0 technologies in OH&S depend on political, economic, and social drivers.

3. We identified probable OH&S hazards in the Industry 4.0 age and classified them into six groups including biological, chemical, physical, ergonomic, psychological, and safety hazards. Among them, the psychological hazards are expected to become more apparent in the future as human-machine systems will be developed more. The consequences of these hazards can be job satisfaction, occupational stress, anxiety, and eventually loss of concentration and burnout, which may arise due to dehumanization of work such as constant monitoring of workers, and the replacement of human supervisors with intelligent algorithms. Adequate attention to ergonomic considerations when designing human-machine systems can reduce psychological risks. In this case, some safety risks can be positively affected too since the loss of concentration and burnout can be considered as an indirect cause of safety risks. In addition to these hazards,

Industry 4.0 can present opportunities to control OH&S risks. We introduced them in the form of the hierarchy of controls: elimination, substitution, awareness-raising systems, administrative controls, and PPE.

4. ISO 45001 is more comprehensive than the two standards of OHSAS 18001 and CSA Z1000. The main differences are in requiring an organization to identify potential internal and external issues affecting OH&S performance. In this regard, it is absolutely necessary to pay attention to the needs of workers and identify the opportunities of OH&S along with OH&S risks.

5. We synthesized our findings on the challenges and opportunities that Industry 4.0 represents for OH&S performance considering the requirements of ISO 45001. In terms of leadership, Industry 4.0 can accelerate the process of globalization in a different form than what has been ever known. It means people are able to stay in their own country and work in offices in another country. They come from different nationalities, backgrounds, and cultures, with equally diverse perceptions of OH&S. This makes it difficult for an organization to lead an effective OH&S culture through worker participation. Nevertheless, IoT and vertical and horizontal system integration could play a major role in facilitating communication, which is important to increase worker participation and consultation with employees.

   In the planning phase, OH&S regulatory authorities are lagging behind Industry 4.0. This may affect proactive OH&S approaches that can prevent occupational accidents before they occur. Industry 4.0 can overcome the lack of technological enablers, which may be a major obstacle preventing an organization from meeting its legal obligations. Industry 4.0 enables an organization to create an effective, real-time information system and overcome the limitations of information technology management, which is key to planning and achieving its OH&S objectives.

   In the support phase, a shortage of competent workers, in terms of technical and personal skills, is anticipated, which is a serious concern for OH&S performance. The rapid rate of technological change in the age of Industry 4.0 can make work processes increasingly complex; therefore workers need to learn quickly and regularly. Organizations need a proper structure and a strong learning culture to support their workers for a lifelong learning process. Also, it is necessary to pay attention to the principles of ergonomics in the design of human-machine systems. Industry 4.0 can encourage educational innovation through augmented reality. If this prevails in the world of work, the training process is facilitated and worker awareness is enhanced.

In the operation phase, AI-based algorithms allow for real-time control of organization-related operations. However, a malfunction can lead to unpredictable situations that endanger workers. Moreover, the positive and negative effects of changes on OH&S can be predicted using simulation technology. An organization must also be prepared to deal with unforeseen emergencies arising from large-scale cyber-attacks. On the other hand, workers can be given close-to-reality exercises to enhance their ability to respond to emergencies.

In the performance evaluation phase, thanks to big data, AI and computer vision, a large amount of visual OH&S data related to dangerous conditions and unsafe behaviours can be provided. This allows organizations to conduct evidence-based evaluations of their performance. Nevertheless, intelligent algorithms are still unable to recognize certain unsafe conditions or actions. Thus, these evaluations may not reflect the real situation.

In the improvement phase, more developments in OH&S will be expected to keep up with the rapid pace of technology advancement. For example, computer vision will be capable of modelling motion dynamics, which helps to predict unsafe human acts. Still, some technological progress is associated with new risks. For instance, direct brain-to-machine interfaces are expected to come out by 2025. They are suspected of causing or promoting cancer and they undeniably heat up body tissues.

The results in this study were obtained based on our best knowledge of a synthesis of the systematic literature review. This does not necessarily cover all the OH&S implications arising out of the Industry 4.0 technologies. In addition, a major part of the positive and negative implications of Industry 4.0 on OH&S reported in these articles needs to be practically studied in real workplaces to ensure their effectiveness and accuracy. Therefore, it is recommended that future research be devoted to practical projects in collaboration with OH&S experts and industry owners. Furthermore, we searched for both risks and benefits for OH&S of each technology associated with Industry 4.0. Given the wide range of this search, we could not conduct an in-depth analysis of each technology. Future studies should focus on individual technologies and describe the state of art for each one.

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