The role of Industry 4.0 technologies in improving safety performance and safety management systems in manufacturing environment

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Abstract: Industry 4.0 revolution is broadly reshaping the manufacturing environment, increasing technological level and digitalization of systems with the purpose of enhancing productivity and reaching the highest level of efficiency in production of goods. Since safety and health at work (OHS) is one of the critical components of success of industrial systems, as it allows to achieve the maximum efficiency of the manpower, it is crucial to exploit new technologies to improve this aspect of the organization, both in terms of boosting the safety performance (prevention and mitigation of injuries and physical/mental diseases) and strengthening the safety management system (risk analysis and identification/comprehension of disease causes). The aim of the paper is to synthesize and present the main applications of Industry 4.0 technologies to safety through the analysis of the most important and recent scientific papers concerning the topic, pointing out advantages and benefits which can be achieved through the utilization of advanced tools as collaborative robots, exoskeletons and wearable technologies, sensors, Internet of Things, Cloud, Augmented Reality and Big Data.

Keywords: Industry 4.0, Workplace Safety, Safety Management, Advanced Technologies

1. Introduction

Occupational health and safety (OHS) plays a key role in the success of an organization: on one side injuries and occupational diseases can be related to various kinds of costs for the business (Riano-Casallas & Tompa, 2018), on the other a safe and healthy environment is the first condition to allow workers to reach high levels of individual performance, increasing efficiency and quality of the processes (Savković et al., 2021). Thus, industrial systems that aim at excellence try to reach the highest levels of health and safety for their workers, both driving the work environment and the employees towards a proper culture and sensibility (International Nuclear Safety Advisory Group, 1999), and through the utilization of the most advanced technologies proposed by the Industry 4.0 revolution; this applies in particular to manufacturing systems, where despite of technological development humans will continue to play active roles (Reiman et al., 2021), even if those roles may change over time, shifting toward roles where the human acts utilizing new technologies, collaborating with them or supervising them.

Technologies introduced by Industry 4.0 can have a great impact on safety systems, which has to be properly projected in order to use them to create a healthier and safer environment. First, new tools can enhance organizations' safety performance, intended as accident number or rate (Liu et al., 2020), improving safety, well-being and work conditions of operators, helping them in performing difficult or hazardous activities, protecting them with automatic systems capable to detect risk condition or replacing them in the conduction of tasks precise and complex but also monotonous and alienating (Savković et al., 2021), which may lead to distraction and, consequently, to accident and injuries; after that, new technologies can be used to improve the safety management system, intended as the organized approach to manage and enhance safety, which contains organizational structures, accountabilities, policies and procedures to analyze risk factors with the aim of adopting effective actions to solve and remove those factors and prevent accidents (Forcina et al., 2024; Liu et al., 2020).

Despite the great interest Industry 4.0 topics have aroused in the academic world since the German Government presented the related manufacturing strategy in 2013 to integrate and extend manufacturing processes at intraorganizational and interorganizational levels (Liu et al., 2020), few researchers took care of integrating safety and Industry 4.0 (Forcina et al., 2024; Liu et al., 2020; Savković et al., 2021), while it is extremely important to underline and explore the connection between the two areas, especially since the next evolution of the industrial world, Industry 5.0, will be focused on corporate social responsibilities and will insist on attention to mankind (Coelho et al., 2023; Xu et al., 2021; Leng et al., 2022), making workers' safety indispensable. Thus, through a

literature review, the aim of this paper is to show the link between these two areas, highlighting Industry 4.0 tools and techniques that are able to help organizations, now and in the future, in reaching high health and safety levels and, through that, in achieving excellence in operations; particularly, it was decided to distinguish tools that can enhance directly the safety performance (accident rates) from the ones which can improve it through the boost of the safety management system: it is believed that this demarcation, currently lacking in reviews found in the literature (Savković et al., 2021; Forcina et al., 2021), can help the clearness and the precision of the discussion, allowing a deeper understanding of technological tools' potentiality in OHS and providing a basis for future research about applications in one field (s. performance) or the other (s. management).

2. Background

Since the terminology can vary dude to cultural difference and to the evolution of vocabulary, it is important to clarify exhaustively what is meant by the key words and concept of the study, and also, in this case, to explain the distinction made between "safety performance" and "safety management".

Safety performance is intended in scientific literature as the number of incidents and accidents (i.e. incidents that lead to an injury) (Mearns et al., 2003) or accident rate (Liu et al., 2020). The improvement of safety performance can drive the organization to financial success (Savković et al., 2021), as it is well-known that injuries, illnesses and fatalities represent not only suffering from the human point of view, but also, they produce an economic loss (Riano-Casallas & Tompa, 2018). Lots of studies took care of studying and classifying safety-related costs and the most common approach proposes the division in direct costs (value of resources employed to prevent, detect and health problems or their effects), indirect costs (value of lost production due to accidents or injuries) and intangible costs (related to non-monetary consequences, e.g. loss of reputation) (Riano-Casallas & Tompa, 2018); whilst it is evident that the improvement of the safety performance leads to a reduction in both indirect and intangible costs, a major concern is the increase of the direct costs necessary to this improvement: in this regard, the technological process and the large-scale deployment of innovative Industry 4.0 tools can help in maintaining low this kind of costs, encouraging firms with the aim of moving forward in safety field (Sherwani et al., 2020).

Safety Management is defined as "an organized approach to manage and improve safety" (Forcina et al., 2024) or "the overall management function that determines and implements the safety policy" (Liu et al., 2020) as it includes organizational structures, accountabilities, policies, procedures, roles and functions concerned with promoting organizational safety and protecting people from safety risks; being related to decision-making, planning, organizing and control activities to achieve safety objectives (Forcina et al., 2024), it clearly has a primary impact on the safety performance, even because it facilitates the development of a strong safety culture. Two main aspects of safety management are safety policies, which involve risk identification, risk mitigation, standards and human factors-based system design, and safety training, which concerns safety performance control, incidents reporting and investigation, auditing, and continuous improvement projects and challenges (Forcina et al., 2024).

3. Methodology

The methodology chosen to properly conduct the literature review is the Systematic Literature Review (SLR), performed consistently with recommendations by Xiao & Watson (2019) for a stand-alone review, i.e. supposed to make sense of a body of existing literature (Rousseau et al., 2008) without the aim to serve as a background for an empirical study, but simply willing to describe the state of the art. Hence, the review has been organized in the three major stages and conducted with the 8 steps proposed by Xiao & Watson (2019).

Research questions chosen to drive the review process are:

- Which Industry 4.0 technologies can most significantly enhance safety performance of manufacturing systems?
- Which Industry 4.0 technologies can most significantly enhance safety management of manufacturing systems?

Initially, electronic databases have been used to build a library of papers, by whom a backward searching has been performed to enrich the set of articles included in the review.

Thus, a set of related keywords has been selected and used to perform the research on Scopus and Google Scholar, which allow to reach not only journal articles but also "gray literature", such as conference proceedings, thesis, and reports. To avoid leaving aside articles interesting for the purpose of the study, in Scopus research the selected keywords have been searched within "Article title, Abstract, Keywords", with the appropriate function. In order to properly balance the degree of exhaustiveness with an appropriate precision level, as suggested again by Xiao & Watson (2019) and Wanden-Berghe and Sanz-Valero (2012), some specific technology names has been included in the keywords for further research, basing the selection of such technologies on the works from Forcina et al. (2024) and Savković et al. (2021). The research has been limited to document written in English and, because of the newness of the topic to be discussed and its continuous evolution, it was decided to consider only works published in the last five years (since 2019). The first selection of papers from the database, based on the evaluation of their title, led to 121 documents. As suggested by Xiao & Watson (2019) at this stage the articles have been included in case of doubt, and consequently, in the following screening based on the review of abstracts, a large portion of the papers has been excluded, because they didn't fit with the research questions; the main reasons were they were related to different contexts (e.g. construction, process industry) or

they aimed to evaluate safety risks of industry 4.0 technologies instead of their benefits. The last screening phase, based on full text review, has been conducted on 55 papers and, at the end, 38 papers have been included in the first library. The selection process can be seen in Table 1.

Table 1: library selection process

Keywords	No. of papers selected by title	No. of papers selected by abstract	No. of papers selected by full text
"Industry 4.0", "Safety"	21	12	11
"Industry 4.0", "Safety Performance"	14	5	3
"Industry 4.0", "Safety Assurance"	6	3	3
"Industry 4.0", "Safety Management"	15	8	6
"Collaborative Robots", "Safety"	8	6	2
"Exoskeletons", "Workplace Safety"	14	4	2
"Wearable technologies", "Workplace Safety"	13	6	3
"Internet of Things", "Workplace Safety"	13	5	4
"Cloud", "Workplace Safety"	10	3	2
"Big Data", "Workplace Safety"	7	3	2
Total	121	55	38

Out of 38 papers, 8 were themselves literature review: they have been used as starting point for the backward searching phase, which led to 19 additional papers. Hence, the set of papers included in the review at the end hosts a total of 49 elements (reviews contained in the first library have been excluded after the backward searching phase), and it is visible in Appendix 1.

As seen in Fig.1, 14 papers out of 49 (28.57%) are conference proceedings, showing how much interest the researched topics have aroused in academic environment in last years. About publishing journals, from where 30 papers out of 49 come (61.22%), most of them are journals dedicated to safety science and technology ("*Safety*", "*Safety Science*", "*International Journal of Safety and Security Engineering*"), while others are from journals specifically concerning applications of new technologies ("*Frontiers in Robotics and AI*", "*Sensors*", "*Advanced Intelligent Systems*", "*Internet of Things and Cyber-Physical Systems*").

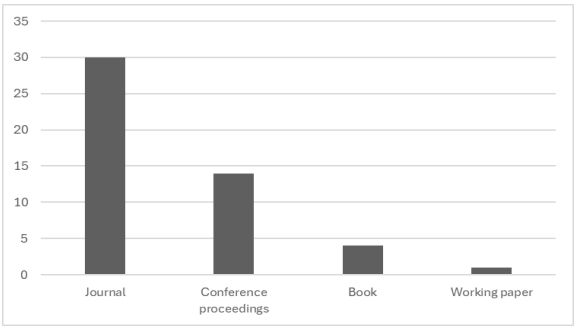

Figure 1: Distribution of papers based on type

Fig. 2 shows the countries of affiliation of the first author of the selected documents; Italy is the most represented country with 8 papers. Also, it can be noticed that the total number of countries reaches 23, showing the worldwide spread of the researched topics.

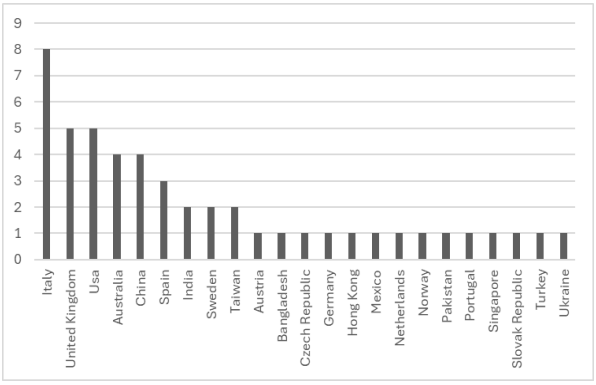

Figure 2: Distribution of papers based on country of affiliation of first author

4. Discussion

As said, it was decided to distinguish between tools that can directly enhance the safety performance of manufacturing systems and tools that can improve it through the upgrading of the safety management system. So, in this section, the results of the review will be discussed separately according to this criterion. It should be noticed that reviewed documents haven't been divided in two categories, but from each one contribution have been taken about both safety performance and safety management improving tools.

4.1 Enhancing Safety Performance

To enhance safety performance, two main methods are:

- to avoid/block accidents;
- to protect workers from accidents consequences.

As emerged from the review, there are Industry 4.0 tools to implement both alternatives.

Collaborative robots (or co-bots) represent one of the technologies that can most impact on safety performance. They are intended as systems related to the theory of cognitive machines that, thanks to special sensors and control methods related to the theory of cognitive machines, can autonomously and actively take cognizance of their surroundings and analyze their activity (Polak-Sopinska et al., 2020), being able to work together in shared spaces and physically interact with humans (Douthwaite et al., 2021). The operations that can be carried in this way are numerous and varied (from screwing and drilling to welding), but the greatest part concerns assembly and material handling (Segura et al., 2022). From the safety point of view, co-bots can firstly contribute to the improvement of the health of workers by replacing them in dangerous and physically demanding activities and facilitate the performance of precise and monotonous activities (Mattsson et al., 2016); then, co-bots have built-in sensors that allow them to recognize workers' intentions and movements, analyze them and consequently adapt their actions: they can reduce or increase their speed depending on the proximity of the worker, stop the work when he enters a certain area and continue when the workspace is vacated or even directly change activity to one that does not endanger the occupational safety of employees (Bragança et al., 2019). More specifically, according to Sherwani et al. (2020) the main safety features of collaborative robots are:

- Safety-Rated Stop Monitoring: the co-bot can instantly stop its movement if it finds that an operator has entered its workspace;
- Hand Guiding: a user can safely teach the robot to follow specific working trajectory;
- Speed and Separation Monitoring: the robot is able to vary its movement according to location of the human;
- Power and Force Limitation: the robot can automatically reduce its force in case of unintended contact to not harm the person.

So not only with the use of collaborative robots' productivity and product quality can be enhanced without affecting occupational health, but also experts and researchers agree that it can help in preventing injuries and accidents and ensuring the safety and well-being of human workforce (Sherwani et al., 2020; Segura et al., 2022).

Exoskeletons represent another important tool that can improve the safety performance: their main impact is on the operations' ergonomics and thus on preventing long-term harm or injuries and accidents caused by a deterioration of human conditions and physical abilities. To understand the great importance of this kind of injuries, it is enough to know that musculoskeletal injuries were by 2020 the reason for 23% of sick leave days in Germany, causing production loss worth an estimated 17 billion euro annually (European Agency for Safety and Health at Work, 2020). Exoskeletons are defined as wearable devices that augment, enable, assist and/or enhance physical activity through mechanical interaction with the body (ASTM F3323-20, 2020); they are body-worn devices that support the body and reduce physical demand (i.e. strength and endurance) (Kong et al., 2018), mitigating stress/compression force on the lower back, shoulders, elbows, and wrists (Polak-Sopinska et al., 2020) and thus protecting the user against injuries to these parts of the body and generally against Work Related Musculoskeletal Disorders (WRMSDs). In practice, exoskeletons provide support for the body during the positioning or use of tools, handling objects or similar activities (Bogue, 2015): Savković et al. (2021) distinguish active exoskeletons, that actually support the movement of workers who perform fatigue activities, and passive exoskeletons, used to support the bodyweight (e.g. being set as a chair for workers that have to stand for a long period of time). Several studies report the result of using this kind of devices on muscular load and activity in different contexts: Wei et al. (2020) found that using an exoskeleton while lifting result in 35-61% lower muscle activity and 22% lower metabolic cost, while Bosch et al. (2016) indicate 35–38% lower back muscle activity and lower discomfort in the low back. Hence, in manufacturing environment, these devices can provide safer and more ergonomic conditions for the workers, which are increasingly various in terms of age, gender and level of fitness (Polak-Sopinska et al., 2020), improving their general health.

Besides exoskeletons, other wearable devices can improve the safety performance: in many cases PPE has been improved with Industry 4.0 features and tools. The main improvement is due to the addition of sensors to monitor in real time workers vital signs, wrong postures, chemical/humidity/heat exposure (Liu et al., 2020; Costin et al, 2019; Cheung et al., 2018; Chang et al., 2020), and generally hazardous situations that can cause accidents in order to warn in case of potential harm or danger to people; usually this is obtained through the transmission of collected data to a system capable of risk-assessment and decision making (Gorli, 2017). Even with augmented and virtual reality PPE can be improved, enabling workers to see real-time information and alarms (Liu et al., 2020).

4.2 Enhancing Safety Management

As said, safety management main objectives are to define policies, to mitigate risks and to put into practice the continuous improvement of safety performance. Hence, safety management requires access to a variety of information and data to analyze unsafe factors and suggest the adoption of effective measures to eliminate them and to prevent incidents (Forcina et al., 2024); it is of paramount importance to use high-quality data, as the general data-science knowledge suggests ("garbage in, garbage out"), as well as to collect a proper amount of information: in this regard three Industry 4.0 technologies may help in collecting, storing, managing and processing data, and they are Internet of Things, Cloud and Big Data.

Internet of Things (IoT) is intended as a network of physical objects, with built-in sensors, actuators or other digital devices, that are connected via the Internet (Savković et al., 2021) and allow plant facilities and

equipment to exchange data with each other and to collect them without requiring human-to-human or human-to-computer interaction (Markulik, 2019). Empirical studies have proven that IoT devices can generate a large amount of data, which can be analyzed to identify patterns and trends that can help factory managers improve safety procedures and prevent accidents in the future (Tsang et al., 2018; Bordel et al., 2019; Barata & da Cunha, 2019; Molka-Danielsen et al., 2018; Illa & Padhi, 2018). Usually, the data collected this way are stored and transferred with the Cloud computing, which is a type of Internet-based computing that provides shared computer processing resources and data to computers and other devices on demand (Markulik, 2019), enabling remote accessibility in real time to data (Forcina et al., 2024). In this way, every equipment in the factory generates data that are collected through the IoT and stored in the Cloud, so that real-time performance can be monitored and analyzed, compared with historical data and problems that may arise (Lee et al., 2014). Often the amount of data collected, both structured and unstructured and with different levels of quality, is too large to be processed using traditional database and software techniques: in that case Big Data techniques are used to guarantee safety management based on efficient information (Forcina et al., 2024). Since Big Data analytics' aim is to understand phenomena through research of cause-and-effect relationships, it can be used to find complex patterns, establish statistical cohesion of data, and reduce the number of uncorrelated attributes for a better safety decision making (Ajayi et al., 2020). So, the combination of these three technologies (IoT, Cloud, Big Data) can have an extremely positive impact on workers' safety and health, allowing to identify the possibility of accidents and harmfulness and to eliminate and control hazard before accidents happen (Savković et al., 2021; Mattsson et al., 2016). This conclusion goes along with Heinrich's safety pyramid theory (Savković et al., 2021), according to which there is a statistical relationship between accidents with different levels of severity (i.e. one fatality every thirty serious disabling injuries and every three hundred minor accidents, with the newest approaches that include even near-misses, unsafe actions, unsafe conditions and at-risk-behaviors) which implies they share the same causes: therefore, removing the causes of low level accidents means the removal of the ones that cause high severity injuries; in this regard, new technologies can help in identifying and recording data about the lowest levels of the pyramid (near-misses, unsafe actions, unsafe conditions and at-risk-behaviors), which are by nature less visible, and to detect and remove their causes

Digital Twin (DT) represents another potentially useful tool for safety management. It is commonly considered as an evolution of simulation model, based on a digital replica of a physical object (an equipment) which is deeply integrated with IoT technologies, allowing the twin to be updated directly from the physical world and, vice versa, to provide feedback to the real equipment (Agnusdei et al., 2021). In the safety domain, DT can support operational decisions to preserve the integrity and safety of assets and workers and, by running a parallel simulation, it can predict the behavior of its physical counterpart based on early symptoms of upcoming criticalities, allowing the operator to address issues before accidents occur (Eckhart et al., 2019).

Lastly, it is important to mention the employee training phase, which has a direct impact on safety and health as it can reduce the number of mistakes made by workers that can lead to accidents. Augmented and virtual reality find great application in training: they can be used to shorten the time required to learn tasks, but also to practically present dangers and risky situation that may arise and to show how to cope with them (Chia et al., 2019).

5. Conclusion

Since health & safety of workers is crucial to reach high levels of efficiency, quality and financial performance for a manufacturing organization, it is necessary to exploit all the resources made available by the current era; in the Industry 4.0 context, this means utilizing new technologies to minimize accidents and injuries and to maximize the well-being of employees. The aim of this study was to summarize the current state of the art about the integration of OHS with Industry 4.0 tools. A systematic review of the literature has been conducted, with the examination of a total of 29 papers published on journals from various sectors or resulting from conference proceedings in the period 2019-2024. Results shows that different technologies can enhance occupational health and safety, both directly, reducing accidents, hazardous situations and risky/deteriorating conditions (i.e. increasing safety performance), and indirectly, helping in finding accident causes to remove them, predicting potential dangers, and developing safety policies and procedures (i.e. improving safety management systems). According to the reviewed literature, the most useful tools to increase safety performance are Collaborative Robots, Exoskeletons and smart wearable devices, which can physically protect workers, guarantee the ergonomics of operations and detect risks and hazards to alert the employee; to improve safety management system, Internet of Things, Cloud and Big Data are pointed as the most helpful technologies, as they allow to collect, store, manage and analyze a large amount of data to identify cause-effect relationships and areas of improvement. As a limited number of studies focused on the integration of Industry 4.0 in OHS, and technology trends change frequently, future research should continue to analyze the application of new tools for safety improvement with case studies and original proposals, in order to increase the awareness about the impact of technology on OHS and of OHS on the success of the firm.

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