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Exploring Industry 4.0 technologies to improve manufacturing enterprise safety management: A TOPSIS-based decision support system and real case study

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ABSTRACT

Industry 4.0 is changing the traditional manufacturing context, increasing digitalization towards smart production. Safety is one of the most critical issues and companies are approaching its digital transformation from technological and management perspectives. The main criticalities in this transition are due to the different benefits deriving from the impact of each Industry 4.0 technology applied and therefore to the choice of the most appropriate technologies for the specific production system for safety management. In this scenario, the aim of this study is to assist practitioners in the choice of the most appropriate technologies according to the benefits to be obtained and to the constraints dictated by the characteristics of the production system. For this purpose, a Systematic Literature Review has been performed, to gain a comprehensive overview of current or potential application of Industry 4.0 technologies in safety management, identifying the most impactful technologies and defining the key parameters to consider. Based on the obtained results, a Decision Support System (DSS) has been designed, consisting of a flowchart and a TOPSIS-based tool, to identify the best Industry 4.0 technologies and quantify their suitability for safety management, respectively. Finally, the proposed methodology was applied and validated in a real case study of a large food company. According to the final ranking suggested by the DSS, it is possible to consider Cloud as the most impactful Industry 4.0 technology for the safety management system within the specific company, followed by IoT. This result is consistent with data collected from the experts, confirming the effectiveness of the theoretical DSS to investigate the best Industry 4.0 technology adoption.

1. Introduction

Industry 4.0 represents one of the most emerging areas for scholars, practitioners, and policymakers worldwide. Through a technology-driven paradigm, Industry 4.0 entails transformation of the conventional factory in a hyperconnected manufacturing ecosystem, whereby all is connected, from machines, devices, and operators to products and customers (Bragança et al., 2019). The integration of physical and digital systems is achieved by means of technologies such as *Artificial Intelligence*, *Cloud computing*, *Internet of Things* (IoT), *Cyber-physical Systems* (CPS), *Augmented Reality*, *Big Data*, and *Additive Manufacturing* (Liu et al., 2020). These technologies are defined as "disruptive" because of their potential to redefine and significantly reshape manufacturing operations (Benitez et al., 2020), imposing a change of employers work and performances (Sharma et al., 2021). The resulting *smart factory* addresses a specific and complex set of challenges (Moktadir et al., 2018), into an enhanced environment where service robots and automated machines have to be well controlled and monitored (Qin et al., 2016). The revolution in technology raises new opportunities to improve efficiency, profitability, customization, and innovation, as well as for process safety and environmental protection (Gobbo et al., 2018). Indeed, in addition to direct advantages offered by facility sensors and wearable technology that enable workers to take preventive measures to reduce accident rates, the digitalization of operations also creates many opportunities for automating safety processes (Liu et al., 2020). On the other hand, changes introduced by Industry 4.0 technologies can be also harmful to

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the worker, e.g., the chemical risk due to the gases generated by the various materials used in Additive Manufacturing or the stress due to information overload introduced by Augmented Reality (Zorzenon et al., 2022). Thus, new technologies are imposing relevant changes in workers and managers' responsibilities in the safety area, as well as in culture and management. Industry 4.0 is able to improve worker safety and factory safety only through appropriate *safety management* actions (Liu et al., 2020), including a more effective communication and involvement of employees (Zorzenon et al., 2022). These assumptions are even more relevant for Industry 4.0 where the development of a collaborative culture is required for companies' survival (Camarinha-Matos et al., 2017), to which is required to promptly identify new collaborative needs to address. In this case, a proper safety management will be reached when managers are able to identify most important technologies for different sectors to improve safety, as well as the possible combinations of technologies which are reinforced by each other (Zorzenon et al., 2022).

Generally, safety management plays a fundamental role since high levels of safety are essential for the well-being of operators in a smart factory. Safety management is an organized approach to manage and improve safety, including the necessary organizational structures, accountabilities, policies, and procedures ("International Civil Aviation Organization, 2006). This approach is also useful to promote a strong safety culture, which is crucial to achieve good safety performance (International Nuclear Safety Advisory Group, 1999), and it is related to decision-making, planning, organizing and control activities to achieve safety objectives. All of this results in the analysis of various unsafe factors, in order to adopt effective measures in terms of technology, organization and management, to solve and eliminate these factors and to prevent incidents. Safety management includes safety policies and safety training (Amyotte et al., 2007; Robson et al., 2007). Safety policies involve safety resources and responsibilities, risk identification and mitigation, standards, and human factors-based system design. Safety training concerns safety performance control, incidents reporting and investigation, auditing, and continuous improvement projects and challenges. These two aspects must be properly integrated, to positively affect safety performance, increasing competitiveness and economic performance (Fernández-Muñiz et al., 2009).

Technologies introduced by Industry 4.0 have a great impact on safety management which must be redesigned to use them effectively and to create a safer environment. Indeed, some of these technologies have a great potential to benefit safety performance and recent literature reveals several applications and insights. In detail, the intelligent manufacturing could use real-time wireless communication to identify hazards and dangers effectively (Swuste et al., 2020) and robots can be equipped with remote sensors to both recognize actions that could cause injury to operators and understand the intentions of operators in their proximity (Beetz et al., 2015). IoT sensors installed in machinery make inspection and auditing of standards easier (Barata and da Cunha, 2019) and, combined with Big Data analytics, contribute to a healthier and safer work environment. Indeed, Big Data increases the capacity to examine human behavior and predict errors, favoring safety (Mattsson et al., 2016). Additive Manufacturing can reduce the contact with toxic substances during manufacturing processes (Zorzenon et al., 2022). Data analytics can be accomplished with the Cloud computing favoring safety management, permitting to obtain real-time incident reports (Pistolesi and Lazzerini, 2020). Augmented Reality can improve operator safety, enabling remote operator support to solve complex problems (Calzavara et al., 2020), and assisting maintenance operators performing their activities in safety (Compare et al., 2018). Furthermore, through the analysis of data provided by machine sensors or user emotion bio signals, Augmented Reality allows the estimation of well-being and workability indexes (Gualtieri et al., 2020) and generally an improvement of the mental health of employers in the factory (Madhavi et al., 2020). Finally, Simulation underlines safety and security flaws (Caruana and Francalanza, 2023), as well as the assessment and the comparison of work scenarios (Mattsson et al., 2016).

Even if many recent studies are focused on new single technologies in Industry 4.0, research that integrates all the possibilities offered by Industry 4.0 enabling technologies for safety management are not available. So far, only a few papers have provided insight into the integration between safety management and Industry 4.0. In detail, Badri et al. (2018) examine worker safety in smart factories and further explore regulatory framework and safety management systems in Industry 4.0 context, while Jaradat et al. (2017) propose a modular assurance approach that is able to address some of safety challenges generated by Industry 4.0. In 2020, this gap has been also rose by Liu et al. (2020), highlighting how safety management in Industry 4.0 does not attract considerable attention in academia because of Industry 4.0 is still a new concept and few researchers are paying attention to the integration and interactions of new technologies with safety management. However, their study, focused on opportunities and challenges for safety management in an Industry 4.0 environment, identifies three strategies for its evolution according to safety principles, technologies, and modes.

This paper aims to take a substantial step further in this direction, specifically focusing on the real possibilities of applying Industry 4.0 technologies in this area, also considering the related constraints and criticalities. The contribution offered by these new technologies is able to support traditional safety management methods, which have not been taken into account in the present research as they have already been extensively studied in the literature. The aims of this study are developed through the following points:

1) Performing a *Systematic Literature Review* (SLR) to gain a comprehensive overview of current or potential application of Industry 4.0 technologies in safety management, including criticalities and specific needs related to the application.
2) Identifying the key parameters and criticalities related to the application of 4.0 technologies to improve *safety management*.
3) Designing a *decision support system* made of a *flowchart* and a *TOPSIS-based tool* which interact with each other to identify best Industry 4.0 technologies for safety applications and quantify their suitability for safety management. To this end, a semi-structured interview with experts has been developed and acquired.
4) Demonstrating and validating the method's effectiveness through a real case study in the food company.

2. Method

The research path is presented in Fig. 1. First, a *Systematic Literature Review* (SLR) was performed to establish the most impactful Industry 4.0 technology for safety management, as well as key parameters to design the *Decision Support System* (DSS) framework. The DSS is structured in a *flowchart* with the logical architecture of the decision-making pathway supported by a *TOPSIS-based* tool to quantify choices. In addition, a semi-structured interview was held with 12 experts from a large food company, with at least five years of experience (see Table 6 profile). The aim of the interviews is twofold: to confirm and validate the outcomes from the literature review, assisting the design of the DSS *flowchart*; and to rank the identified set of *alternatives* and *criteria* used in the TOPSIS-based tool for quantifying the choice made.

2.1. The SLR procedure

To better understand what the main advantages are associated with the implementation of Industry 4.0 technologies for safety management, a *Systematic Literature Review* (SLR) was conducted, evaluating different points of view and players involved, to answer the following research question:

- *Which are the most suitable Industry 4.0 technologies for safety management?*

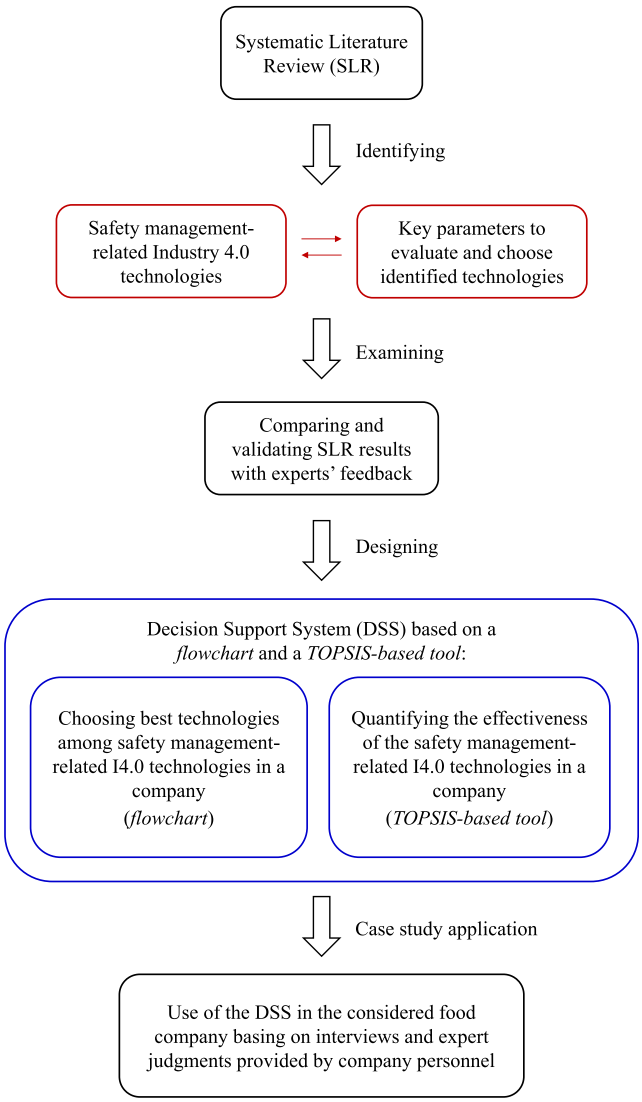

Fig. 1. Research architecture and methodology.

2.1.1. *Data source and analysis method*

The SLR is widely considered as a powerful methodology to investigate the current knowledge related to a specific research question. The difference between SLR and traditional review is that SLR is always conducted through a replicable, scientific, and transparent process (Tranfield et al., 2003), eliminating the risk of introduction of bias or non-critical evaluations (Kitchenham, 2004). In particular, SLR is performed following a methodology able to identify what is known and unknown for the given question (Briner and Denyer, 2012). Such methodology consists in the following steps: 1) formulation of the research question; 2) the examination of literature review according to identified key themes; 3) inclusion of only those papers that meet research criteria and research purposes; 4) design of a database where papers and findings are assessed and sorted; 5) synthesis phase in which results are extracted from database and discussed.

The performed analysis was acquired from Scopus database (*scopus.com*) and only peer reviewed journal and international conferences have been included. The literature exploration was made through several research strings combined with each other with the Boolean operator < AND >. Research strings and the selection process is shown in Table 1. They include the string "industry 4.0" and "safety" in addition to each of the nine technologies of Industry 4.0, which are Industrial Internet of Things (IIoT), Big Data, and Analytics, Horizontal and vertical system integration, Simulation, Cloud computing, Augmented Reality (AR), Autonomous Robots, Additive manufacturing, and Cyber Security. As mentioned before, selected articles were summarized in a database, in order to characterize and assess studies according to the SLR question.

The process for the inclusion of articles was first based on the screening of article titles, keywords, abstract and the final accurate review of the full text (Moher et al., 2009). In the first phase, a paper is included if the title concerns the research topic/questions. In particular, all the papers related to safety management, safety decision making, and risk assessment were included, as well as studies describing Industry 4.0 technologies and their applicability, installation criticalities, and operator skills were selected for the next in-depth analysis. As a second phase, the abstract of selected paper was read independently by co-authors. Each has expressed a judgment on the relevance to the objectives of the SLR and could judge the relevance *adequate*, *inadequate*, or *partially adequate*. Papers deemed inadequate by at least two authors were excluded from the subsequent phases of analysis. Articles that passed the selection phase, focusing on SLR question, were deeply analyzed. In particular, the papers considered unanimously relevant were read by each author, who highlighted the key points. In the case of discordant judgments, the full text of the paper was read by all the authors and the final judgment on the paper was expressed collectively at the end of a discussion.

2.2. *DSS design*

The SLR aims to investigate how Industry 4.0 technologies affect heterogeneous areas of safety management and guarantee adequate effectiveness only if applied appropriately. For this reason, a DSS has been designed to choose the best I4.0 technologies, according to the specific needs and results to be obtained. The DSS considers the outcomes identified from the SLR process, which includes key technologies to enable safety management, as well as specific parameters and metrics to assess them. As aforementioned, the DSS is made of two parts (Fig. 1): a *flowchart* (DSS flowchart) representing the logical architecture of the decision-making pathway and a *TOPSIS-based* architecture (DSS TOPSIS-based tool) to quantify and rank the effectiveness of the considered technology. Therefore, the *TOPSIS-based* tool is particularly useful when there is more than one possible solution in terms of the possibility of applying technologies. Once the decision to implement an industry 4.0 technology for safety purposes is made, the selection of best technologies will be guided using the flowchart, according to the specific characteristics and constraints of the considered production system, then simplifying the decision-making process. As it is possible to see, a single technology, or a group of technologies, can be identified by a step-by-step approach. The decision steps (*diamonds*) collect the most effective decisions and actions to be taken by practitioners, while process steps (*rectangular boxes*) represent the technologies to choose.

For the TOPSIS-based matrix, a total of 5 criteria were identified in order to evaluate the peculiarities of each technology (Table 5). The proposed DSS plans to evaluate each criterium in a 5-points scale, according on the specific case. The DSS is structured to simultaneously exploit the advantages deriving from the flowchart and the TOPSIS model. In detail, the application of the TOPSIS model is able to refine and validate at the same time the outcomes deriving from the flowchart, obtaining a consistent result, focused on the specific production system analyzed.

2.3. *TOPSIS data analysis*

In this paragraph, the TOPSIS-based decision-making tool is described. DSSs are used to support the management process in making decisions. The key aspect of a DSS can be identified in being a decision-oriented, flexible, and adaptive tool, controllable by the user (Sprague, 1980). DSSs have numerous applications in different industrial fields, from manufacturing system (Bertolini et al., 2020; Mathew et al., 2020)

Table 1
Systematic Literature Review (SLR) procedure.

Step 1 *Formulation of the research question*	**Research Question** Which are the most suitable Industry 4.0 technologies for safety management?
Step 2 and **Step 3** *Locating, selecting, and evaluating articles*	**Electronic databases**- Scopus (scopus.com) **Inclusion Criteria** - Papers that developed or investigated safety management tasks in Industry 4.0 context - Peer reviewed journal, reviews, and international conferences - Paper title **Search Strings** - “industry 4.0” AND “safety” - “safety” AND “…” *(each industry 4.0 technology)* **Exclusion Criteria** - Papers in languages that differ from “*English*” - First selection after reading the paper title- Second selection after reading the paper abstract (and full text)
Step 4 *Assessment of findings*	**Analysis phase** - Iterative compilation of the database
Step 5 *Reporting of findings*	**Synthesis phase** - Emerged aspects and results are extraction from database and discussion

to safety problems (Wu et al., 2016; Yazdi, 2018). The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is one of multiple criteria decision making method that was first introduced by Yoon and Hwan (Hwang and Yoon, 1981). TOPSIS method derived from the concept that the selected alternative should have the minimum geometric distance from the positive ideal solution and the maximum distance from the negative ideal solution (Assari et al., 2012). TOPSIS process steps are provided in Appendix B.

3. Results

The obtained results are presented and discussed under the following headings:

- SLR Results;
- DSS Results; and
- Application of the DSS in the case study.

3.1. SLR results

According to the selection criteria summarized in Table 1, the selection process was carried out on 447 documents. After the selection process described above, the sample was reduced to 65 documents (29 articles and 36 conference papers) collected in a database, which is the Appendix A of this study.

3.1.1. Descriptive analysis

By analyzing the SLR outputs, it was possible to obtain preliminary results to provide a global vision of the research topic in terms of diffusion and interest of the scientific community.

In Table 2 the number of documents for each combination of research strings is shown, resulting from the selection process. As can be noted, IoT, Cloud Computing and Augmented Reality are the most applied technologies and have been identified in over 85% of the analyzed documents. This is not surprising, considering that the greatest innovations for safety management concern the possibility of connecting *personal protective equipment* (PPE) to the network, in addition to remote data management and monitoring.

In Fig. 2 the temporal distribution of papers is shown and, as it is possible to see, the global trend is growing and there is a significant increase in published documents since 2018. Further information can be gained by analyzing the country of origin of the first author and the Journals where the greatest number of articles has been published. In Fig. 3, the countries of origin of the first author of the selected documents are shown. China, with 22 articles, is the country with the largest

Table 2
Relative number of papers for considered research strings and research phase.

Research strings	After reading paper's title n	After reading paper's Abstract n	After reading full paper n
“Industry 4.0” AND “Safety”	34	19	5
“Internet of Things” AND “Safety”	143	36	25
“Big Data” AND “Safety”	17	4	2
“Cloud” AND “Safety”	159	35	15
“Horizontal integration” AND “Vertical integration” AND “Safety”	0	0	0
“Advanced Manufacturing” AND “Safety”	2	2	0
“Additive Manufacturing” AND “Safety”	7	3	1
“Augmented Reality” AND “Safety”	55	22	15
“Autonomous robots” AND “Safety”	3	1	1
“Simulation” AND “Safety”	4	1	1
“Cyber Security” AND “Safety”	32	14	2
Total	449	135	67
Total (without duplicates)	**447**	**133**	**65**

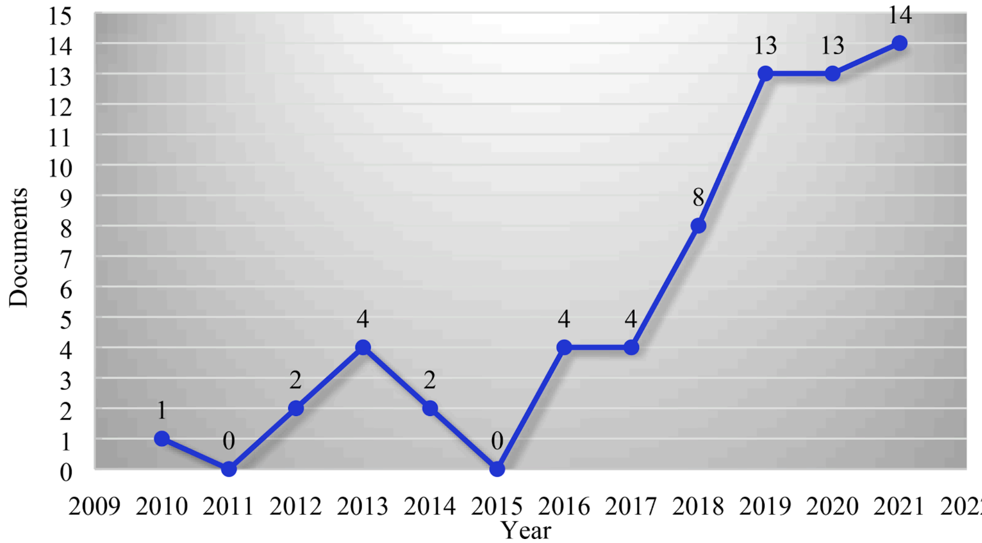

Fig. 2. Temporal distribution of documents.

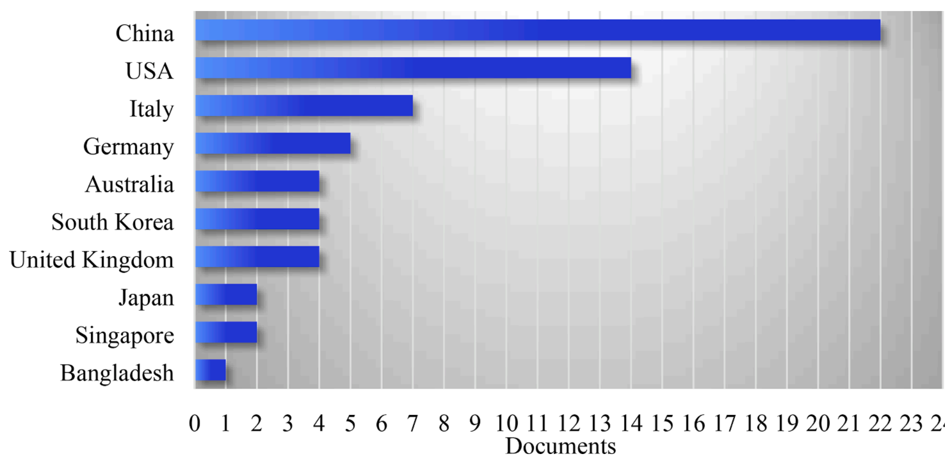

Fig. 3. Countries of origin of the first author of the selected papers.

Table 3
Sources of selected documents.

Journal	n	%
Advances In Intelligent Systems And Computing	4	6.15%
Automation In Construction	4	6.15%
Safety Science	2	3.08%
Sensors Switzerland	2	3.08%
OTHERS	53	81.54%

number of documents, followed by USA (13 documents). It is also significant that the number of countries of origin for authors reached a total of 10, reflecting the geographical spread of the analyzed research topics. On the other hand, the analysis of sources shows that the journals with the highest number of documents are “Advances in Intelligent Systems and Computing” e “Automation in Construction” (with 4 articles out of 65). The total number of journals in the database is 47 and in only 4 of then there is more than 1 document published (Table 3). Most of the collected papers consist in case studies (52.2%) and framework (34.3%) applications (Fig. 4). The remaining of the papers concerns review (9%) and interview (4.5%). Case studies include a validation of theoretical models through empirical applications and generally have been performed by scholars or R&D organizations and industrial companies.

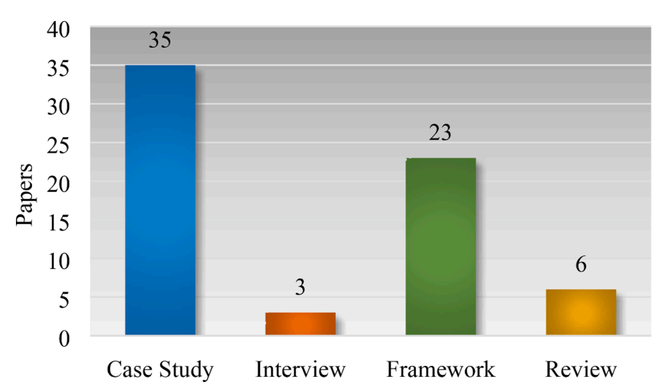

Fig. 4. Distribution based on research typology.

3.1.2. *Content analysis*

The SLR has investigated the most suitable Industry 4.0 technologies and their integration in safety management. As mentioned in the Introduction section, some of these technologies have a greater potential to benefit safety performance than others. Recent literature reveals that all the Industry 4.0 technologies can potentially affect safety management. In detail, the SLR results show how four technologies have a significant and direct integration with safety management, which are: *Internet of Things*, *Cloud*, *Augmented Reality*, and *Big Data analytics*. This finding also emerged in (Forcina and Falcone, 2021), where several examples of this integration have been analyzed with widely recognized benefits for the safety management. In particular, according to the authors, the most used enabling technologies for safety management are Industrial Internet of Things (IIoT) and Clouds, representing over 80% of the employed technologies in safety management. On the other hand, this SLR revealed how Augmented Reality and Big Data analytics have a key role in safety management enabling the use of intelligent devices, advanced monitoring and processing of a large amount of data to check patterns and predict maintenance or replacement of items, preventing accidents.

Internet of things. The most versatile technology is the Internet of things, especially through the use of data reception sensors for security.

More specifically, in underground construction sites or mines, Liang and Liu (2022) explain how IoT technology is combined with BIM (Building Information Modeling) technology in an early warning system for underground engineering construction safety, with the main purpose of reducing the occurrence of accidents and ensuring the safe progress of projects. The research shows how managers can record data transmitted by sensors and through the IoT network equipment, which are then automatically saved in the BIM management platform.

In the same context, Zhou and Ding (2017) propose an IoT-based safety barrier alarm system for underground constructions, to monitor, prevent accidents and improve safety management. This system provides greater guarantees in terms of safety in underground construction, including faster tracking of workers and equipment (more than 200 moving targets simultaneously), more accurate positioning information (1 m above the ground and 1.5 m underground) and faster response speed which allows automatic sending of pre-alarm signals (less than 1 s).

Another important application is proposed by Zhong et al. (2014) through the development safety management system for a tower crane group (SMS-TC) that combines a wireless sensor network (WSN) and IoT in the construction industry. The three main components of the SMS-TC can be classified into the three layers of the IoT: perception layer, network layer and application layer. Furthermore, in addition to the typical three-layered architecture of the IoT, the SMS-TC has a fourth layer (the support layer), which can perform the tasks of thinking, identifying, and deciding as a functional brain of the IoT.

In the study of Zheng et al. (2019) an IoT-based Integrated Security Management System (ISMS) (UIOTE) for smart pumped-storage power stations is introduced. The integrated safety management system includes a central control module and five functional modules. The central control module refers to the safety monitoring and emergency command module. Functional modules include access control and personnel tracking module, security and video monitoring module, emergency broadcast and communication module, geological warning module, and fall protection module.

According to Song et al. (2021), early and effective real-time warning of highway construction sites is the key to ensuring safety. The authors propose a real-time early warning model for highway construction safety based on the Internet of Things, able of monitoring, diagnosing, and pre-checking accidents. Furthermore, the authors suggest that the proposed model can be combined with wireless tracking technology to improve accuracy.

A further study from Shostak et al. (2020) aims to develop methodological tools and technologies to identify the physical condition of the driver, with the subsequent use of the information, received from the IoT objects. A mobile application for real-time monitoring and recognition of driver fatigue is developed thanks to a technology for recognizing the face and its parts, such as eyes and mouth used as fatigue indicators. The developed prototype is intended for managers of logistics companies involved in the transportation of goods by road, as well as drivers in general with the purpose of individually checking their physical condition in real time while driving.

Cloud. Cloud is used for information management and remote accessibility in real time with particular attention given to safety in maritime transport and port areas.

Mohaimenuzzaman et al. (2016) focus on the development of a new transport model, based on IoT and Cloud, which transforms unsafe waterways into a safer, more reliable, and sustainable network. In the proposed model, the moving vehicle is equipped with an ECU and a set of machine-to-machine (M2M) devices. The control unit consists of a special M2M device (called collector), a display unit and a 3G module for wireless communication. The system stores the received data and other related information in the database.

In the research of Jo and Khan (2017), the safety of underground mines were evaluated, studying their interdependencies and integrating separately identifiable IoT-based systems to build a comprehensive monitoring and safety system specifically for underground mines. Technologies such as standard monitoring, intelligent event detection and identification, miner tracking, and real-time information sharing are integrated into this study. The system uses an Arduino-based network to measure five parameters, which are temperature, humidity, CO2, CO and CH4 at different points of the underground mine, with more than 95% accuracy and more than 99% efficiency.

From the integration of Cloud and IoT (Zeng et al., 2022), monitoring platforms for safety in coal mines are developed. The Cloud is used to connect traditional wireless personal networks to the Internet and carry out intelligent safety monitoring, also ensuring faster transmission of information via GPRS.

Regarding safety in construction sites, in the study of Golovina et al. (2021) safety alert systems are used collaboratively and the data are analyzed and combined in a cloud-based solution. A sensor and data communication network for the reporting and analysis process is developed and tested. An autonomous detection and warning system has been complemented by an operator display, an accident detector, a positioning sensor and software for recording, reporting and analyzing data.

With reference to safety related to electrical equipment, in the work of Chernov et al. (2021) an intelligent monitoring system is proposed through the application of the IoT and the Cloud. Intelligent Cloud monitoring systems allow to receive information about the status of dangerous electrical equipment and the microclimate of power plant rooms. With the use of computer vision, it is possible to recognize the presence of personal protective equipment among the employees of the enterprise to allow access to power facilities and remotely monitor the work schedule.

Big Data. Big data analytics are adopted for the analysis of data acquired over time by the company, guaranteeing security management based on efficient information.

In the study of Ajayi et al. (2020), a robust and efficient technique is proposed to find complex patterns, establish statistical cohesion of patterns, and reduce the number of uncorrelated attributes in Big Data analytics for safety decision making in electrical infrastructure. To obtain a reliable prediction model for the anticipation of occupational accidents, a particle swarm optimization (PSO) technique is used.

Liu et al. (2020) focus on the opportunities and challenges of safety management in the Industry 4.0 era. In particular, three phases are identified for the evolution of safety management, considering principles, technologies, and methods. A theoretical framework is also proposed, to integrate Safety 3.0 and Industry 4.0 and to automate safety management processes. Big data-driven safety monitoring and compliance processes require broader team involvement, and safety managers should be supported by IT experts to produce a more comprehensive safety strategy and a smarter safety system.

Augmented Reality. Augmented Reality applications are based on the use of wearable accessories, such as glasses, which allow you to keep your hands free and also provide useful information for safety.

For workers in hazardous areas such as highways, Sabeti et al. (2021) propose a new framework which incorporates the benefits of AR to

Table 4
Relative number of papers for considered research strings and research phase.

Technology	Devices	Areas of application
Internet of Things	Sensors for hazard detection Monitoring sensors Wearable sensors Vehicle sensors	Underground construction site, mine Construction site Manufacturing industry Electric infrastructure Transport vehicle, highway Port, maritime sector
Cloud	Monitoring systems Safety Management systems Data transmission systems	Underground construction site, mine Construction site Manufacturing industry Electric infrastructure Port, maritime sector
Augmented Reality	Wearable displays Wearable sensors Communication systems	Manufacturing industry Transport vehicles, highways Port, maritime sector
Big Data analytics	Safety Management systems Data analysis systems	Underground construction site, mine Manufacturing industry Electric infrastructure

Table 5
TOPSIS-based matrix of the alternatives.

		Alternatives			
		A_1	A_2	A_3	A_4
Criteria		Internet of Things	Cloud	Augmented Reality	Big Data analytics
C_1	*Multi-sector applicability*	–	–	–	–
C_2	*Ease of installation*	–	–	–	–
C_3	*Need for specialized personnel*	–	–	–	–
C_4	*Scope of action*	–	–	–	–
C_5	*Tangible results*	–	–	–	–

improve the situational awareness of highway workers by providing a communication infrastructure in time real. The proposed framework has three main pillars: AR UI design for multimodal notification, real-time deep learning for vehicle detection/classification, and real-time wireless communication between hardware components. Applications can be multiple in highway work areas.

Rowen et al. (2019) evaluate the impacts of the use of wearable augmented reality displays (WARDs) on operator performance, situational awareness (SA), and communication in the safety–critical system of the maritime transport. The study found that the use of WARDs has a positive impact on operator performance, but has a mixed effect on communication, increasing closed circuit communication while decreasing operator responsiveness. At the same time, WARDs improve tracking, good seamanship practice and operator situational awareness.

3.1.3. Documents classification and key points definition

For each technology, the main applications and the main areas have been identified, extrapolating the results from the analysis of the database. Results are summarized in Table 4.

As shown above, IoT, Cloud and augmented Reality represent almost all applications. IoT technology is mainly used to equip PPE or to set up sensors in work environments and on machines. This technology allows to obtain advantages in terms of risk prevention and reduction of alarm times. The use of Cloud Computing is instead linked to the ability to remotely manage and control data for safety. Often the applications analyzed are based on the integration of Cloud computing and IoT, where Cloud Computing represents the management system of networked safety devices.

Big Data applications refer above all to the management and analysis of historical data, bringing fantasies in terms of risk reduction and operator training. Augmented reality is also used for training or to simulate risk events. The main areas of application are the construction sector, the manufacturing industry, logistics and work environments with high risk for workers, such as mines, tunnels, or sewers.

3.2. DSS results

According to the DSS design described in Section 2.2, the SLR provides a set of alternatives (most impactful Industry 4.0 technologies for safety management) and criteria for the application of the DSS. The identified criteria are detailed below:

- Multi-sector applicability (C1)
- Ease of installation (C2)
- Need for specialized personnel (C3)
- Scope of action (C4)
- Tangible results (C5)

The *"Multi-sector applicability"* criterion has been chosen to evaluate whether the technology is usable in different sectors of the industry or is exclusive to only one sector. Therefore, a grade of 1 indicates that the technology is specific to a particular sector, while a score of 5 indicates that it can be adopted in many industrial fields.

Table 6
Study participants and experience.

Role	Company experience (years)
Director	*11*
Site engineer	*5*
Project manager	*6*
Consultant	*5*
Site engineer	*8*
Site engineer	*7*
Safety engineer	*9*
Safety team leader	*9*
Safety engineer	*5*
Technical engineer	*6*
Head of Engineering	*6*
Safety engineer	*7*

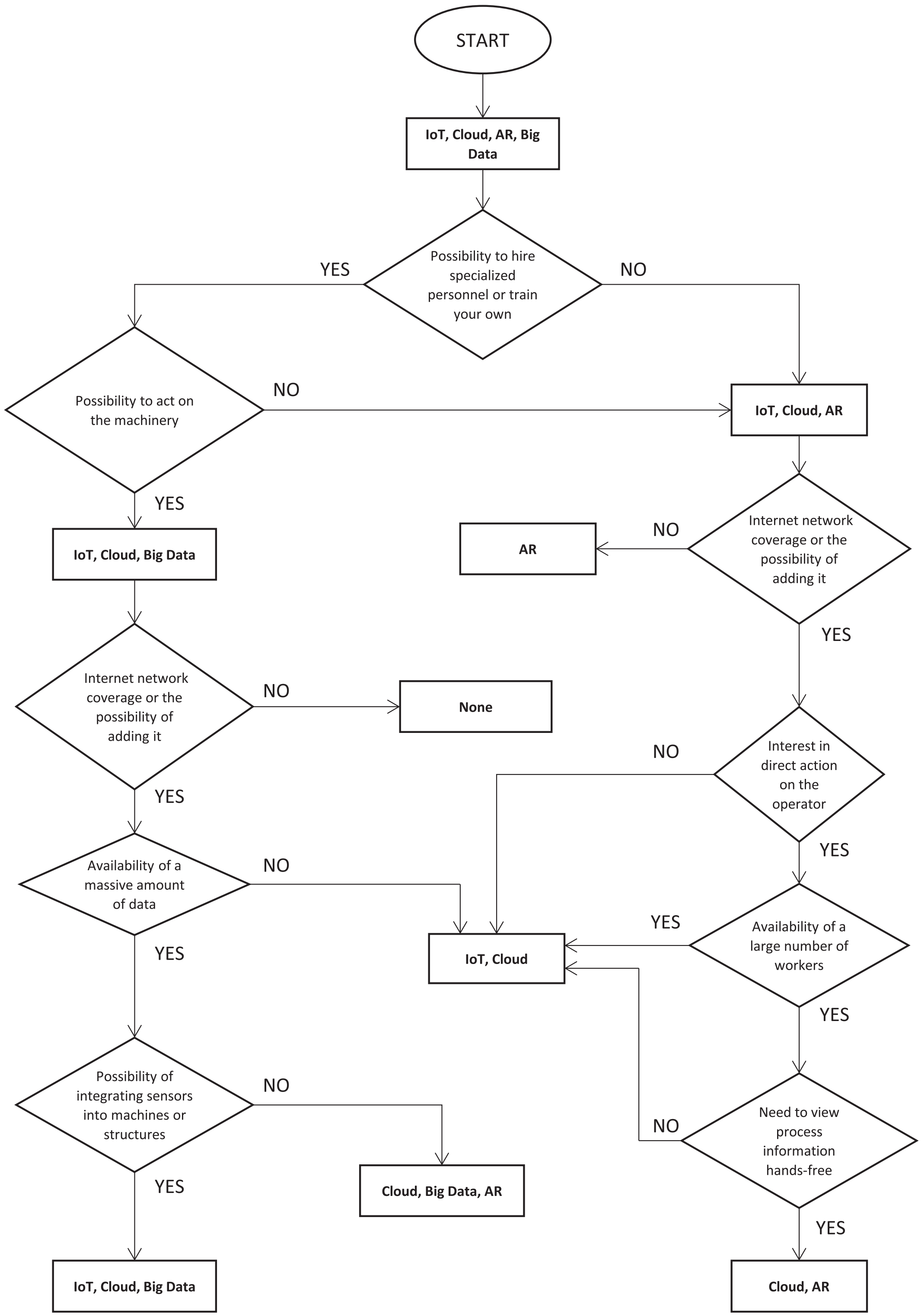

Fig. 5. The flowchart step of the designed DSS, representing the logical architecture of the decision-making pathway.

"Ease of installation" criterion refers to the possibility of applying the technology without need of major changes to the company structure or system; therefore, if the technology is compatible with pre-existing systems. A score of 1 means that the plant requires radical changes to install the technology, while 5 is equivalent to an integration of the technology without any change in the system.

"Need for specialized personnel" criterion measures the need to hire experts or train existing personnel in order to use the technology. A score equal to 1 is for completely user-friendly technologies, while 5 indicates that the technology must be supported by a highly qualified expert.

The *"Scope of action"* criterion evaluates whether the technology makes the machine safe or directly the operator. A score of 1 indicates that the technology predominantly affects the machine, while 5 means that it directly affects the worker.

The *"Tangible results"* criterion evaluates how much technology has brought concrete improvements in safety. With grade 1 the technology is

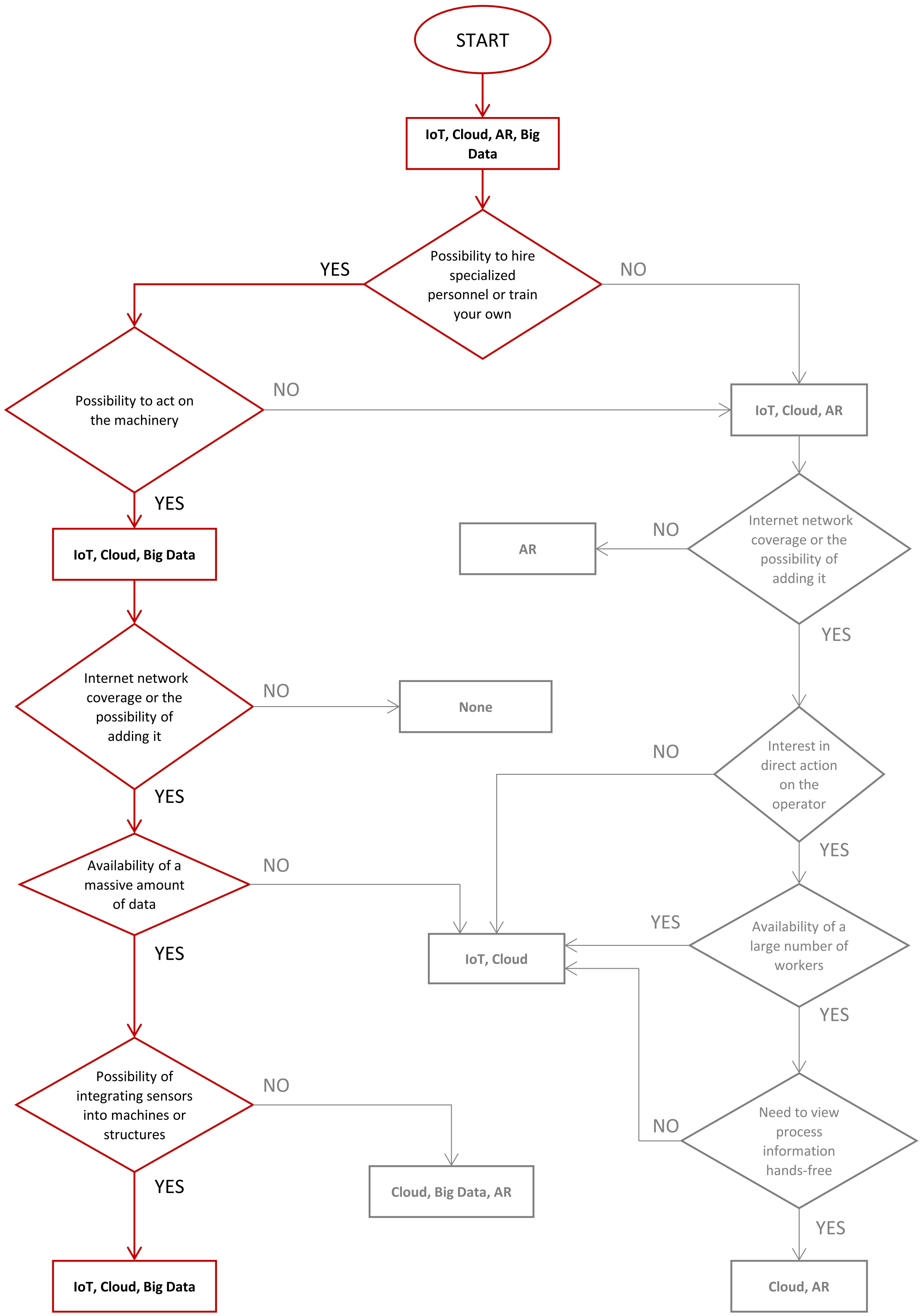

Fig. 6. Pathway chosen by experts for the specific case study.

not yet developed and effective enough to improve safety, while with grade 5 it has a positive impact on safety.

On the other hand, the identified technologies, or *alternatives*, are:

- Internet of Things (A1)
- Cloud (A2)
- Augmented Reality (A3)
- Big Data analytics (A4)

According to the structure of the TOPSIS model, the ideal solution would correspond to a technology evaluated with a score of 5 for all the chosen criteria, with a corresponding value of 1 in the ranking. Conversely, a ranking value of 0 corresponds to all scores equal to 1 for the selected criteria (worst-case solution).

The flowchart contents (Fig. 5) directly derive from outcomes of the SLR and feedback provided by experts. In particular, these outcomes include, in addition to the most suitable Industry 4.0 technologies for safety management (IoT, Cloud, AR, and Big Data), the common barriers and enablers to implement them in companies, which can be represented by the integration of technologies already present in the company, operations, and number of involved workers.

3.3. DSS application: Case study

The study was carried out in a division of a large food processing and service company based in Italy and has over two-hundred employees. Main operations within the unit include the procurement of raw materials, industrial food processing, and logistics. In particular, the company has one main facility where the food is processed and packed for delivery in canteens and restaurants. Part of the products are sold in few stores and supermarkets located in Italian metropolis. A team of experts have been asked to review and validate the framework for content and applicability. A detailed description of employers involved in the survey has been provided in Table 6. During last five years, the company has gradually adopted Industry 4.0 technology in its production activities. In fact, the application of these technologies involves different areas such as intelligent manufacturing, food safety, quality control, food traceability system, training, marketing, and customized orders. In particular, the company has implemented Big Data analytics to predict and inform customers of the delivery time, in that way avoiding disruption in the food chain, as well as helping to understand consumer demand. The IoT technology is employed in food distribution through the use of temperature and humidity sensors on trucks transporting products. The information from sensors are monitored in real-time and recorded. Furthermore, the monitoring of body data has been implemented to improve the health and safety of operators involved in most dangerous activities. Finally, data flow across the process value are systematically sent to a cloud computing system through a standardized communication protocol.

To understand technologies and actions to be taken to enhance the safety management, the designed step-by-step DSS (Fig. 6) has been tested for the considered case study. According to the data from experts' interviews, it has been possible to identify the specific pathway within the DSS flowchart and highlighted in Fig. 6. As it is possible to see, the results lead to three Industry 4.0 technologies suitable for the safety management scope in the considered food company, which are IoT, Cloud, and Big Data analytics. These results are strictly dependent on the specific case study and even if the flowchart has general characteristics, it leads to the identification of different technologies, according to the production system to be analyzed. Indeed, results fit with the features of the company, which can store and handle a large amount of data more effectively, as well as machines and vehicles can be equipped by sensors for parameters monitoring and management of both humans and machines.

As aforementioned, the company has already implemented Big Data, IoT technology and Cloud for non-safety purposes and this confirms the DSS results, being the *Ease of installation* (C_2) and *Need for specialized personnel* (C3) predominant factors. Furthermore, Big Data and Cloud can be effectively used to give numerous solutions for safety, such as providing the operator with accurate information to improve health and well-being during food processing and other factory environments. From a larger perspective, the possibility offered by Big Data and Cloud computing to analyze human behavior and anticipate errors can favor safety. Smart sensors and IoT can timely detect fire hazards or other accidents and can automatically shut off some machines and alert local authorities to make necessary actions. Finally, Cloud computing can also provide any information to the operator without requiring him/her to be physically close to the computer service, enhancing safety especially for delivery workers and porters.

As a final phase of the decision-making process, practitioners gave, adopting a 5-point rating scale (Low, 1988), a rank for each of the technologies and criteria described in Section 3.1.

Table 7
Case study decision matrix.

		Alternatives															
		A1				A2				A3				A4			
Criteria		**Internet of Things**				**Cloud**				**Augmented Reality**				**Big Data analytics**			
		Mean	Mode	Sigma	Rank	Mean	Mode	Sigma	Rank	Mean	Mode	Sigma	Rank	Mean	Mode	Sigma	Rank
C1	**Multi-sector applicability**	4.67	5.00	0.89	**5**	4.67	5.00	0.89	**5**	4.25	4.00	0.87	**4**	3.33	4.00	0.78	**3**
C2	**Ease of installation**	3.01	3.08	0.95	**3**	3.52	4.00	0.69	**4**	3.82	4.00	0.83	**4**	3.55	3.29	0.89	**4**
C3	**Need for specialized personnel**	3.35	3.00	0.98	**3**	3.37	3.21	0.88	**3**	2.44	2.13	0.99	**2**	4.17	4.04	0.94	**4**
C4	**Scope of action**	3.51	3.04	1.08	**3**	3.43	3.00	0.66	**3**	3.63	3.79	0.64	**4**	1.76	2.00	0.76	**2**
C5	**Tangible results**	4.64	5.00	0.48	**5**	4.54	4.75	0.50	**5**	4.54	5.00	0.89	**5**	4.06	4.00	0.53	**4**

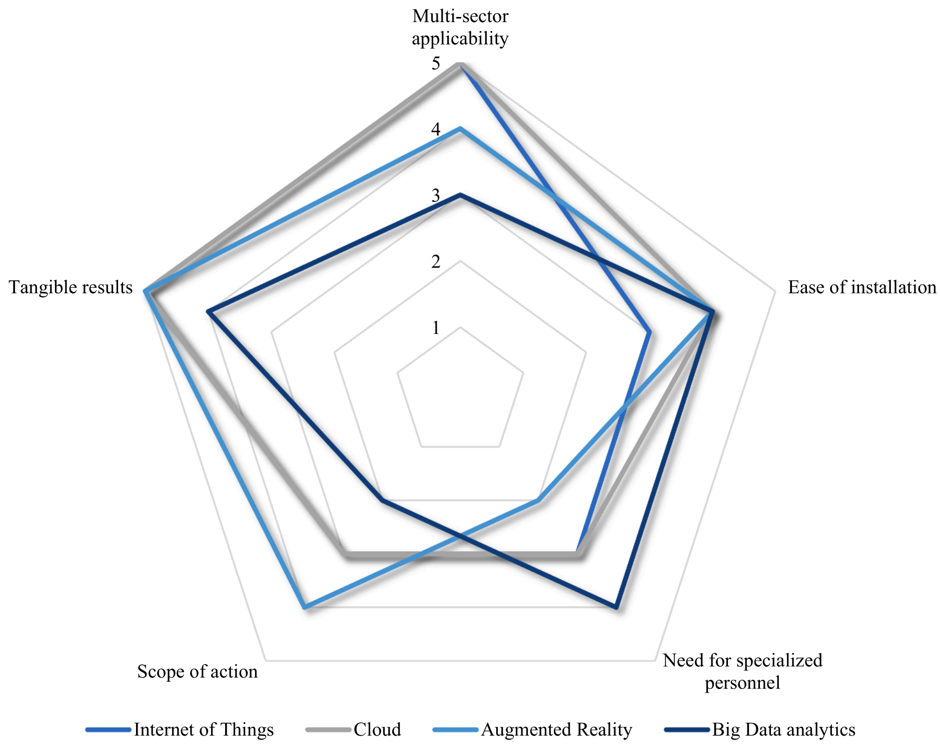

Fig. 7. Technologies evaluation in a 5-point scores scale.

Table 8
Calculation of the separation measures from the positive ideal solution and the negative ideal solution.

	d_w	d_b
A1	0.074722684	0.090710951
A2	0.073972614	0.091323646
A3	0.107825752	0.108464111
A4	0.117048811	0.105144791

Table 9
The ranking of the A_i alternatives.

	s_w
A1	0.548322298
A2	0.552484648
A3	0.501475701
A4	0.473212505

Table 10
The final ranking of the Industry 4.0 technologies.

Technology	Ranking
Cloud	1
Internet of Things	2
Augmented Reality	3
Big Data analytics	4

In particular, according to the decision matrix was evaluated by the TOPSIS-based architecture. To resume, the eligible technologies, or *alternatives*, to enhance the safety management are:

A_1 = *Internet of Things.*
A_2 = *Cloud.*
A_3 = *Augmented Reality.*
A_4 = *Big Data analytics.*

While parameters, or *criteria*, to assess each technology are:
C_1 = *Multi-sector applicability.*
C_2 = *Ease of installation.*
C_3 = *Need for specialized personnel.*
C_4 = *Scope of action.*
C_5 = *Tangible results.*

Each alternative was evaluated on the basis of the identified criteria, through interviews and expert judgments provided by company personnel (Table 6). In particular, experts were explicitly asked to rate the technologies with a score between 1 and 5, instead of using a semantic scale. According to the designed decision matrix (Table 5), the participants gave a rank for each combination of alternative and criterion. The final rank used in the DSS is the arithmetic average of all the scores gave by the participants for the same combination, rounded to the nearest integer. The resulting decision matrix, made of 5-point scores, is shown in Table 7, as well as mean, modal values, and standard deviation, while a graphical representation is shown in Fig. 7.

The *normalized decision matrix* and the *weighted normalized decision matrix* are shown in matrixes (*R*) and (*W*), respectively.

$$R = \begin{bmatrix} 0.577350269 & 0.397359707 & 0.486664263 & 0.486664263 & 0.524142418 \\ 0.577350269 & 0.529812943 & 0.486664263 & 0.486664263 & 0.524142418 \\ 0.461880215 & 0.529812943 & 0.324442842 & 0.648885685 & 0.524142418 \\ 0.346410162 & 0.529812943 & 0.648885685 & 0.324442842 & 0.419313935 \end{bmatrix}$$

$$W = \begin{bmatrix} 0.130623272 & 0.031682588 & 0.156919612 & 0.156919612 & 0.025757821 \\ 0.130623272 & 0.042243451 & 0.156919612 & 0.156919612 & 0.025757821 \\ 0.104498618 & 0.042243451 & 0.104613074 & 0.209226149 & 0.025757821 \\ 0.078373963 & 0.042243451 & 0.209226149 & 0.104613074 & 0.020606257 \end{bmatrix}$$

The calculation of d_w and d_b distances of weighted normalized matrix in respect to the ideal solution is shown in Table 8.

The ranking (s_{iw}) of the preference order is shown in Table 9. The selected technology is the alternative closest to 1. It is important to note that all the alternatives are close to each other in terms of distance from the ideal solution. In cases like this, the application of a mathematical model such as TOPSIS is particularly effective since the alternatives are almost equivalent.

According to the final ranking (Table 10), it is possible to consider Cloud as the most impactful Industry 4.0 technology for the safety management system within the specific company, followed by IoT, Augmented Reality, and Big Data.

The case study is particularly explanatory of how the DSS works. In detail, the application of TOPSIS allows to validate the results of the flowchart and, at the same time, to define a ranking of technologies by identifying those whose impact on safety management is greater. It is clear that implementing all the technologies at the same time would be the ideal solution, however the ranking defined by the DSS allows priorities to be established when it is not economically or technically possible to implement all the technologies simultaneously. Indeed, the flowchart and the TOPSIS model complement each other, reducing the possibility of inconsistent results. In the analyzed case, results from the TOPSIS-based tool add the implementation of AR, even if this option was not included by the previous flowchart step. In fact, according to the designed flowchart, the AR pathway is the only solution when there is no sufficient "*Possibility of integrating sensors into machines or structures*" (Fig. 6). However, in this specific case, the company has already implemented a strong and well-coordinated maintenance strategy and is not interested in taking advantages from AR for safety purposes yet, then wireless communication is limited only to integrate sensors of IoT applications.

4. Discussion

The results of this research provide numerous topics for discussion. The SLR conducted showed how only some of the I 4.0 technologies are able to bring real advantages in safety management (IoT, Big Data, AR, and Cloud), confirming what was supported by previous studies such as Zorzenon et al. (2022). This is because the application of technologies related to the Industry 4.0 paradigm is designed to be oriented towards the improvement of production or the provision of services. Attention to the worker and his safety therefore ends up being a collateral benefit, since the application of some technologies can improve safety.

On the other hand, the analysis of the literature has shown that the implementation of I 4.0 technologies can collide with constraints linked to the peculiarities of the specific production system.

In this scenario, the results emerging from the application of the proposed DSS to the case study show that a correct application of the aforementioned technologies requires a synergistic interaction between the company's experts and technicians with specific skills on the technologies to be implemented. This interaction makes it possible to optimize the advantages in relation to the specificities, constraints and characteristics of the production system and workers, taking into account economic as well as technological needs.

For these reasons, decision support systems, and more generally decision making methodologies, prove to be a valid support when involved people, constraints and selection criteria to be take into account are multiple and so heterogeneous, as already highlighted by He et al. (2023). In this regard, it is important to underline that the criteria chosen for the TOPSIS model are generic and have no dependence on the production system. In the same way, the flowchart is based on characteristics common to each production system. For this reason, the case study has an exemplifying aim and the designed DSS can be applied to the most diverse production systems.

5. Conclusion

Factories that follow Industry 4.0 principles address different and complex sets of challenges and potential opportunities. The increasing presence of a hyper connected environment, where a large amount of data from sensor networks provides continuous information on the behavior and performance of the factory, has to be well controlled and monitored. In this context, safety management can take advantages of Industry 4.0 technologies, enhancing safety in manufacturing processes through a more precise and real-time analysis, evaluation, measure, early warning, and control.

The preliminary aim of this study was to determine, by means of a systematic review, the state-of-art of current or potential application of Industry 4.0 technologies to improve safety management, as well as establishing key parameters to assess their specific impact. A total of 65 papers, published between 2010 and 2021, have been examined. During the research, information from each paper were summarized in a comprehensive database, useful for the further analysis. Part of this database is shown in Appendix A, where authors are listed by year highlighting the main technologies they investigated. In a late stage, a DSS has been designed to select the best technology for safety management according to specific enterprise domain. The resulting flowchart has been successfully tested by experts from a food company, confirming the suitability of the DSS architecture, as well as the consistency with current and future company plans. Finally, a TOPSIS-based tool has been integrated in the DSS to quantify and rank the suitability of the identified technology derived from the flowchart step. This tool resulted to be particularly useful when more than one possible solution come from a specific flowchart pathway and then to choose the most impactful technology.

The DSS were applied in a real case study of a food company. It was determined that the proposed approach allows to determine Cloud as the most useful technology for the safety management system within the specific company environment, followed by IoT, Augmented Reality, and Big Data. This result is strongly consistent with the experts' interview, confirming the suitability of this theoretical DSS to investigate the best Industry 4.0 technology adoption.

An important limitation of the proposed model concerns the need for interaction with company experts to be implemented effectively. for this reason, the future developments of the present research consist in the integration of artificial intelligence with the proposed model, in order to obtain a self-sufficient and easier to use tool.

CRediT authorship contribution statement

Antonio Forcina: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Luca Silvestri:** Writing - review & editing, Writing - original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Fabio De Felice:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Domenico Falcone:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. . Systematic literature review database

Year	Document title	Technology	Authors
2022	Early warning and real-time control of construction safety risk of underground engineering based on building information modeling and internet of things	IoT	(Liang and Liu, 2022)
2021	Towards autonomous cloud-based close call data management for construction equipment safety	Cloud	(Golovina et al., 2021)
2021	Toward AI-enabled augmented reality to enhance the safety of highway work zones: Feasibility, requirements, and challenges	AR, AI	(Sabeti et al., 2021)
2021	Assessing the Feasibility of a Commercially Available Wireless Internet of Things System to Improve Conveyor Safety	IoT	(Jacksha and Raj, 2021)
2021	Continuous Monitoring of Work Area Safety at Energy Enterprises by Online Cloud Monitoring and Computer Vision	Cloud	(Chernov et al., 2021)
2021	Requirements for Augmented Reality Solutions for Safety-Critical Services – The Case of Water Depth Management in a Maritime Logistics Hub	AR	(Osterbrink et al., 2021)
2021	Artificial Intelligence (AI) Coupled with the Internet of Things (IoT) for the Enhancement of Occupational Health and Safety in the Construction Industry	IoT, AI	(Palaniappan et al., 2021)
2021	Development of ARMSS: Augmented reality maintenance and safety system	AR	(Moreland et al., 2021)
2021	Internet of Things (IoT) based Smart Vehicle Security and Safety System	IoT	(Sabri et al., 2021)
2021	Design of mine safety dynamic diagnosis system based on cloud computing and internet of things technology	IoT, Cloud	(Weiqi et al., 2021)
2021	The role of Industry 4.0 enabling technologies for safety management: A systematic literature review	All	(Forcina and Falcone, 2021)
2021	Real-Time Warning Model of Highway Engineering Construction Safety Based on Internet of Things	IoT	(Song et al., 2021)
2021	A vehicle safety monitoring system based on the Internet of things and the identification of physiological characteristics	IoT	(Wang et al., 2021)
2020	A paradigm of safety management in Industry 4.0	All	(Liu et al., 2020)
2020	Using Internet of Things Technologies to Ensure Cargo Transportation Safety	IoT	(Shostak et al., 2020)
2020	Optimised Big Data analytics for health and safety hazards prediction in power infrastructure operations	Big Data	(Ajayi et al., 2020)
2020	Practice of cloud computing in coal mine safety production	Cloud, IoT	(Wang, 2020)
2020	Bi-directional navigation intent communication using spatial augmented reality and eye-tracking glasses for improved safety in human–robot interaction	AR	(Chadalavada et al., 2020)
2020	Assessing the Feasibility of Integrating the Internet of Things into Safety Management Systems: A Focus on Wearable Sensing Devices	IoT	(Okpala et al., 2020)
2020	Augmented Reality Smart Glasses in the Workplace: Safety and Security in the Fourth Industrial Revolution Era	AR	(Pierdicca et al., 2020)
2020	Safety in industry 4.0: The multi-purpose applications of augmented reality in digital factories	AR	(Damiani et al., 2020)
2020	Safety management of assembled construction site based on internet of things technology	IoT	(Li, 2020)
2020	Design of Safety Production Supervision and Data Management System Based on Cloud Platform	Cloud	(Xu and Fan, 2019)
2020	Research and Application of Substation Safety Control Technology Based on Internet of Things Technology	IoT	(T. Wang et al., 2019)
2019	Improving process safety: What roles for digitalization and industry 4.0?	Tutte	(Lee et al., 2019)
2019	Impacts of Wearable Augmented Reality Displays on operator performance, Situation Awareness, and communication in safety–critical systems	AR	(Rowen et al., 2019)
2019	An integrated safety management system based on ubiquitous internet of things in electricity for smart pumped-storage power stations	IoT	(Zheng et al., 2019)
2019	A dynamic information platform for underground coal mine safety based on internet of things	IoT, Big Data, Cloud	(Wu et al., 2019)
2019	Toward the improvement of safety planning for construction activities performed at high elevation by using augmented reality	AR	(Limsupreeyarat et al., 2010)
2019	Enhancing Construction Safety Monitoring through the Application of Internet of Things and Wearable Sensing Devices: A Review	IoT	(Awolusi et al., 2019)
2019	Optimize safety and profitability by use of the ISO 14224 standard and big data analytics	Big Data	(Ciliberti et al., 2019)
2019	Network optimisation for improving security and safety level of dangerous goods transportation based on cloud computing	Cloud	Wang et al., 2019a
2019	An internet-of-things (IoT) network system for connected safety and health monitoring applications	IoT, Cloud	(Wu et al., 2018)
2019	Augmented Reality for Health and Safety Training Program Among Healthcare Workers: An Attempt at a Critical Review of the Literature	AR	(Corvino et al., 2018)
2018	A Conceptual Framework for the Selection of an 'Industry 4.0′ Application to Enhance the Operators' Safety: The Case of an Aseptic Bottling Line	Tutte	(Rosi et al., 2018)
2018	Design and testing of an augmented reality solution to enhance operator safety in the food industry	AR	(Vignali et al., 2018)
2018	A critical review of virtual and augmented reality (VR/AR) applications in construction safety	AR	(Li et al., 2018)
2018	Research and application of internet of things technology in field safety and accident prevention and control	IoT	(Wang et al., 2019b)
2018	Technology impact on process safety through the cloud	Cloud	(Srivastava and Patel, 2018)
2018	Using panoramic augmented reality to develop a virtual safety training environment	AR	(Pereira et al., 2018)
2018	A fiber Bragg grating-based condition monitoring and early damage detection system for the structural safety of underground coal mines using the Internet of things	IoT	(Jo et al., 2018)
2017	Safety barrier warning system for underground construction sites using Internet-of-Things technologies	IoT	(Zhou and Ding, 2017)
2017	An event reporting and early-warning safety system based on the internet of things for underground coal mines: A case study	IoT, Cloud	(Jo and Khan, 2017)
2017	The application of augmented reality technologies for the improvement of occupational safety in an industrial environment	AR	(Tatić and Tešić, 2017)
2017	Towards a better industrial risk analysis: A new approach that combines cyber security within safety	Cyber Security	(Abdo et al., 2017)
2016	RFID and PPE: Concerning workers' safety solutions and cloud perspectives a reference to the Port of Bar (Montenegro)	IoT, Cloud	(Bauk and Schmeink, 2016)
2016	SEeS@W: Internet of persons meets internet of things for safety at work	IoT	(Antonini et al., 2016)
2016	Technical framework design of safety production information management platform for chemical industrial parks based on cloud computing and the internet of things	IoT, Big Data, Cloud	(Lele and Lihua, 2016)
2016	Enhancing Safety in Water Transport System Based on Internet of Things for Developing Countries	IoT, Cloud	(Mohaimenuzzaman et al., 2016)
2014	A practical application combining wireless sensor networks and internet of things: Safety management system for tower crane groups	IoT	(Zhong et al., 2014)
2014	Study on safety expert system based on internet of things	IoT	(Wang et al., 2014)
2013	Cyber-security as an attribute of active safety systems and their migration towards vehicle automation	Cyber Security	(Ibarra and Ward, 2013)

(continued on next page)

(*continued*)

Year	Document title	Technology	Authors
2013	The application of internet of things technology to water transport safety	IoT	(Wu and Yang, 2013)
2013	Construction health and safety, BIM and cloud technology: Proper integration can drive benefits for all stakeholders	Cloud	(Bennett and Mahdjoubi, 2013)
2013	Development of a safety education support system for construction sites using augmented reality technique	AR	(Banba et al., 2013)
2012	The application of internet of things (IOT) technology in the safety monitoring system for hoisting machines	IoT	(Zhao et al., 2012)
2012	Applied research on tower crane safety supervising system based on internet of things	IoT	(Bai et al., 2012)
2010	Geospatial Databases and Augmented Reality visualization for improving safety in urban excavation operations	AR	(Talmaki et al., 2010)

Appendix B. . TOPSIS process

TOPSIS process works according to the following steps:

Step 1. Building of the decision matrix and determine the weight of criteria

In a matrix, m alternatives and n criteria are given as $(x_{ij})_{mxn}$.

Step 2. Calculation of the normalized decision matrix

The $R = (x_{ij})_{mxn}$ matrix is normalized by:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^2}}, i = 1, 2, \cdots, m, j = 1, 2, \cdots, n$$

Step 3. Calculation of the weighted normalized decision matrix

$$t_{ij} = r_{ij} \bullet w_j, i = 1, 2, \cdots, m, j = 1, 2, \cdots, n$$

where

$w_j = \frac{W_j}{\sum_{k=1}^{n} W_k}, j = 1, 2, \cdots, n$ such that $\sum_{k=1}^{n} w_i = 1$, and W_j represents the original weight assigned to the indicator $v_j, j = 1, 2, \cdots, n$.

Step 4. Determination of the best alternative (**A_w**) and the worst alternative (**A_b**)

$$A_w = \left\{ \langle \max(t_{ij} | i = 1, 2, \cdots, m) | j \in J_- \rangle, \langle \min(t_{ij} | i = 1, 2, \cdots, m) | j \in J_+ \rangle \right\} \equiv \{ t_{wj} | j = 1, 2, \cdots, n \}$$

$$A_b = \left\{ \langle \min(t_{ij} | i = 1, 2, \cdots, m) | j \in J_+ \rangle, \langle \max(t_{ij} | i = 1, 2, \cdots, m) | j \in J_- \rangle \right\} \equiv \{ t_{bj} | j = 1, 2, \cdots, n \}$$

where

$J_+ = \{ j = 1, 2, \cdots, n | j \}$ is referred to the criteria with positive impact, and.

$J_- = \{ j = 1, 2, \cdots, n | j \}$ is referred to the criteria with negative impact.

Step 5. Calculation of the separation measures from the positive ideal solution and the negative ideal solution

The L^2-distance is computed between the target alternative i and the worst condition A_w

$$d_{iw} = \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_{wj} \right)^2}, i = 1, 2, \cdots, m$$

and the distance between the alternative i and the best condition A_b

$$d_{ib} = \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_{bj} \right)^2}, i = 1, 2, \cdots, m$$

where d_{iw} d_{ib} are L^2-norm between the target alternative i to the worst and the best conditions, respectively.

Step 6. Calculation of the relative closeness to the positive ideal solution

The similarity to the worst condition is given by:

$$s_{iw} = \frac{d_{iw}}{d_{iw} + d_{ib}}, 0 \leq s_{iw} \leq 1, i = 1, 2, \cdots, m$$

$s_{iw} = 1$ if and only if the alternative solution has the best condition, and $s_{iw} = 0$ if and only if the alternative solution has the worst condition.

Step 7. Ranking of the preference order or selecting the alternative closest to 1

Finally, the ranking of the alternatives is performed by the descending order according to $s_{iw}(i = 1, 2, \cdots, m)$.

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