Synergy of industry 4.0 technologies in the operational safety management system for integration into enterprise management

Sinergia de tecnologías de la industria 4.0 en el sistema de gestión de seguridad operacional para su integración en la gestión empresarial

Sinergia das tecnologias da Indústria 4.0 no sistema de gestão da segurança operacional para sua integração à gestão empresarial

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Abstract

Introduction: This paper presents research on the integration of Industry 4.0 technologies into Safety Management Systems (SMS) across various industrial sectors, conducted between 2024 and 2025. The study examines how emerging technologies enhance SMS by improving operational efficiency, risk management, and decision-making in regulated industries such as aerospace, maritime, and energy.

Problem: The integration of Industry 4.0 technologies into SMS poses a challenge in business management. Despite technological advancements, the relationship between these digital tools and safety management processes remains underexplored in the literature, limiting their adoption in strategic sectors such as naval, aerospace, mining-energy, nuclear, hydrocarbons, and other key industries.

Objective: This study aims to identify the synergy between Industry 4.0 technologies and Safety Management Systems (SMS) to evaluate their integration into business management across various industrial sectors. It seeks to assess how these technologies can enhance operational efficiency, improve information traceability, and optimize data-driven decision-making.

Methodology: The research follows a theoretical approach based on a systematic review of scientific and technical literature. An empirical analysis was conducted in industrial sectors where SMS applications are subject to strict regulations and access restrictions due to confidentiality and patent protection. The study considers recognized regulatory frameworks and methodologies, including Integrated Management Systems (IMS), Six Sigma, 5S and 6S methodologies, ISO 9001, and additional strategies related to continuous improvement and industrial process optimization.

Conclusion: The findings indicate that the convergence of Industry 4.0 technologies with SMS presents significant opportunities for process optimization, data-driven decision-making, and operational risk mitigation. However, the lack of previous studies on this synergy, coupled with restrictions imposed by patents and industrial confidentiality, highlights the need for further research into its applicability across different sectors.

Originality: Industry 4.0 technologies are still emerging in the field of safety management, resulting in limited availability of technical literature. This challenge is further compounded by confidentiality restrictions on industrial processes and data protection measures within organizations. This study provides a novel perspective by analyzing the inherent synergy between these technologies and SMS, enabling the exploration of new methodologies for risk management optimization, data-driven decision-making, and operational efficiency in strategic sectors.

Limitations: The analysis is constrained by limited access to technical and operational data due to patent protection and industrial confidentiality in various organizations' processes. Therefore, the study is conducted at a theoretical level, relying on a literature review of specialized sources without direct access to real-world industrial implementations.

Keywords: Industry 4.0, Communication Protocols, Safety Management System, Hazard and Operability, Layer of Protection Analysis, Hazard Identification.

Resumen

Introducción: Este artículo es el resultado de una investigación sobre la integración de las tecnologías de la Industria 4.0 en los sistemas de gestión de seguridad (SMS) en varios sectores industriales, desarrollada en 2024-2025. El estudio explora cómo las tecnologías emergentes mejoran los SMS al mejorar la eficiencia operativa, la gestión de riesgos y la toma de decisiones en industrias reguladas como la aeroespacial, la marítima y la energética, entre otras.

Problema: La integración de las tecnologías asociadas a la Industria 4.0 en los sistemas de gestión de seguridad operacional (Safety Management System - SMS) representa un desafío en el ámbito de la gestión empresarial. A pesar de los avances tecnológicos, la relación entre estas herramientas digitales y los procesos de seguridad operacional no ha sido suficientemente abordada en la literatura, lo que limita su adopción en sectores estratégicos como el naval, aeronáutico, minero-energético, nuclear, hidrocarburos, entre otros sectores industriales estratégicos.

Objetivo: Identificar la sinergia entre las tecnologías de la Industria 4.0 y los sistemas de gestión de seguridad operacional (SMS), con el propósito de evaluar su integración en la gestión empresarial dentro de distintos sectores industriales, en la búsqueda inherente de la implementación de estas tecnologías puede mejorar la eficiencia operativa, fortalecer la trazabilidad de la información y optimizar la toma de decisiones basada en datos.

Metodología: El estudio se desarrolló a partir de un enfoque teórico basado en una revisión sistemática de la literatura científica y técnica. Se realizó un análisis empírico en sectores industriales donde la aplicación de sistemas de gestión de seguridad operacional está sujeta a regulaciones estrictas y a restricciones de acceso a información por motivos de confidencialidad como de protección de patentes. Se consideraron marcos normativos y metodologías reconocidas, tales como los Sistemas Integrados de Gestión (SIG), SIX SIGMA, metodologías 5S, 6S, la norma ISO 9001, entre otras, así como otras estrategias asociadas a la mejora continua y la optimización de procesos industriales.

Conclusión: El estudio evidencia que la convergencia de las tecnologías emergentes de la industria 4.0 con los sistemas de gestión de seguridad operacional ofrece oportunidades significativas para la optimización de procesos, la mejora en la toma de decisiones basada en datos y la mitigación de riesgos operacionales. Sin embargo, la escasez de estudios previos sobre esta sinergia, junto con las restricciones impuestas por patentes, la confidencialidad industrial, refuerza la necesidad de continuar explorando su aplicabilidad y desarrollo en distintos sectores.

Originalidad: Las tecnologías asociadas a la Industria 4.0 son consideradas emergentes en el ámbito de la seguridad operacional, lo que ha generado una limitada disponibilidad de información en la literatura técnica. Esta situación se ve acentuada por las restricciones impuestas por la confidencialidad de los procesos industriales y la protección de datos dentro de las organizaciones. En este contexto, la presente investigación aporta un enfoque novedoso al analizar la sinergia inherente entre estas tecnologías y los sistemas de gestión de seguridad operacional (SMS). Su desarrollo permite explorar nuevas metodologías para la optimización de la gestión del riesgo, la toma de decisiones basada en datos y la eficiencia operativa en sectores estratégicos.

Limitaciones: El análisis se ve condicionado por la disponibilidad restringida de información técnica y operativa, debido a la protección de patentes industriales y la confidencialidad en los procesos de diversas organizaciones. Por esta razón, el estudio se enmarca en un nivel teórico basado en la revisión de literatura especializada, sin acceso a datos específicos sobre implementaciones reales en entornos industriales.

Palabras clave: Industria 4.0, Protocolos de Comunicaciones, Seguridad Operacional, Hazard and Operability, Layer of Protection Analysis, Hazard Identification.

Resumo

Introdução: Este artigo é resultado de um projeto de pesquisa sobre a integração de tecnologias da Indústria 4.0 em sistemas de gestão da segurança (SGS) em diversos setores industriais, conduzido entre 2024 e 2025. O estudo explora como as tecnologias emergentes aprimoram os SGS, melhorando a eficiência operacional, a gestão de riscos e a tomada de decisões em setores regulamentados, como aeroespacial, marítimo e de energia, entre outros.

Problema: A integração de tecnologias da Indústria 4.0 em sistemas de gestão da segurança (SGS) representa um desafio na área da gestão empresarial. Apesar dos avanços tecnológicos, a relação entre essas ferramentas digitais e os processos de segurança operacional não tem sido suficientemente abordada na literatura, o que limita sua adoção em setores estratégicos como naval, aeronáutico, mineração e energia, nuclear e hidrocarbonetos, entre outros setores industriais estratégicos. Objetivo: Identificar a sinergia entre tecnologias da Indústria 4.0 e sistemas de gestão da segurança (SGS), com o objetivo de avaliar sua integração na gestão empresarial em diferentes setores industriais. O objetivo inerente à implementação dessas tecnologias é melhorar a eficiência operacional, fortalecer a rastreabilidade das informações e otimizar a tomada de decisões baseada em dados.

Metodologia: O estudo foi desenvolvido a partir de uma abordagem teórica baseada em revisão sistemática da literatura científica e técnica. Foi realizada uma análise empírica em setores industriais onde a aplicação de sistemas de gestão da segurança está sujeita a regulamentações rigorosas e restrições de acesso à informação devido à confidencialidade e proteção de patentes. Foram considerados marcos regulatórios e metodologias reconhecidos, como Sistemas de Gestão Integrados (SGI), metodologias SIX SIGMA, 5S, 6S, a norma ISO 9001, entre outras, bem como outras estratégias associadas à melhoria contínua e otimização de processos industriais. Conclusão: O estudo demonstra que a convergência de tecnologias emergentes da Indústria 4.0 com sistemas de gestão da segurança oferece oportunidades significativas para otimização de processos, melhor tomada de decisão baseada em dados e mitigação de riscos operacionais. No entanto, a escassez de estudos prévios sobre essa sinergia, aliada às restrições impostas por patentes e confidencialidade industrial, reforça a necessidade de continuar explorando sua aplicabilidade e desenvolvimento em diferentes setores.

Originalidade: As tecnologias associadas à Indústria 4.0 são consideradas emergentes na área de segurança operacional, o que tem levado à disponibilidade limitada de informações na literatura técnica. Essa situação é acentuada pelas restrições impostas pela confidencialidade dos processos industriais e pela proteção de dados dentro das organizações. Nesse contexto, esta pesquisa oferece uma abordagem inovadora ao analisar a sinergia inerente entre essas tecnologias e os sistemas de gestão da segurança (SGS). Seu desenvolvimento permite a exploração de novas metodologias para otimizar a gestão de riscos, a tomada de decisões baseada em dados e a eficiência operacional em setores estratégicos.

Limitações: A análise é limitada pela disponibilidade limitada de informações técnicas e operacionais devido à proteção de patentes industriais e à confidencialidade dos processos de diversas organizações. Por esse motivo, o estudo se baseia em uma abordagem teórica baseada na revisão de literatura especializada, sem acesso a dados específicos sobre implementações reais em ambientes industriais.

Palavras-chave: Indústria 4.0, Protocolos de Comunicação, Segurança Operacional, Perigo e Operabilidade, Análise de Camadas de Proteção, Identificação de Perigos.

1. INTRODUCTION

The transition to Industry 4.0 has revolutionized industrial environments through the adoption of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), 5G connectivity, and digital twins. In this context, Safety Management Systems (SMS) play a crucial role in ensuring both efficiency and safety in industrial operations.

IoT enables the interconnection of devices and systems, facilitating real-time data collection and analysis, which allows for the prediction and prevention of failures. AI, in turn, enhances analytical and decision-making capabilities, optimizing processes and mitigating risks through machine learning and the processing of large data volumes. 5G connectivity strengthens communication between devices and systems, providing the low latency required for critical operations. Digital twins—virtual representations of physical systems—enable simulations and testing in controlled environments, helping to identify potential issues before they occur in real-world operations. This integration supports proactive safety management and rapid incident response.

Incorporating these technologies into SMS not only improves industrial efficiency but also enhances resilience against operational risks. The convergence of Industry 4.0 technologies redefines safety and efficiency standards in industrial management by fostering a more data-driven, automated, and interconnected approach.

Data science serves as a key tool for decision-making, leveraging the capabilities of these technologies to ensure information traceability through inputs from both internal and external stakeholders. This includes activities related to HAZOP (Hazard and Operability Analysis), LOPA (Layer of Protection Analysis), HAZID (Hazard Identification), and other quality assurance processes, applicable across all industrial sectors. Furthermore, compliance with models such as SHELL, SHELL+C, ISO 9001, ISO 45001, and others facilitates the integration of standardized policies and methodologies across various industries and economic sectors.

SMS, therefore, serves as a dynamic framework for continuous improvement and the identification of opportunities within industries that implement it, regardless of their sector or business focus. Consequently, the integration of technology—whether at the software or hardware level—must align with the specific needs of companies, providing essential support for automation, industrial control, and enhanced safety management within organizations.

2. METHODOLOGY

Given the diverse methodologies within Integrated Management Systems (IMS) and various frameworks such as Six Sigma, 5S, 6S, ISO 9001, and related quality management standards, this study applies a theoretical methodology based on empirical review within an industrial sector that increasingly demands verifiable sources due to patent restrictions and confidentiality concerns. Since Industry 4.0 technologies are still emerging, this research focuses on analyzing recent advancements, identifying opportunities for their application across different industrial sectors. A key emphasis is placed on data traceability, recognized as one of the foundational pillars of Industry 4.0, along with the technologies supporting these domains.

This study follows an applied approach, assessing how Industry 4.0 technologies shape organizational characteristics and decision-making processes. Data science plays a crucial role, as the ability to process large volumes of information can enhance incident prevention, risk identification, and overall safety management. The research considers both hardware and software assets managed by organizations, which define the type of data required for operational, managerial, and developmental activities. Additionally, proper data handling protocols and the necessary work environment requirements—for both normal and abnormal conditions—are examined. Ensuring compliance with operational standards requires a decentralized and distributed information system that facilitates communication between various organizational levels.

In this context, communication technologies play a fundamental role in transmitting critical information. Whether through 5G telecommunications, wireless networks, or other specified systems, the operations manual and task complexity dictate the most suitable communication method. However, redundancy measures must always be in place to prevent data loss and ensure information security. Identifying threats in the work environment—where SMS implementation occurs across organizations of varying industrial sectors and maturity levels—is essential. Safety management extends beyond the physical environment to include operational considerations, whether in services or product manufacturing. This also encompasses the participation of clients in business processes, reinforcing situational awareness linked to occupational health and safety systems across industries such as nuclear, mining, steel, oil, and gas. By mitigating deficiencies in task execution, organizations can preserve assets and optimize asset management across departments such as human resources, maintenance, logistics, and warehousing.

The integration of processes at all corporate levels ensures synergy among departments, fostering result traceability, process reliability, and continuous improvement. Industry 4.0 technologies enable organizations to capture vast amounts of data, monitoring both dependent and independent variables throughout production. The implementation of digital twin models enhances interoperability within software ecosystems, depending on the digital tools designated by the organization, workforce, or external consultants. This integration between physical and digital workspaces allows personnel to analyze hazards, risks, time and motion studies, workplace ergonomics, and other operational parameters within simulated environments. Consequently, organizations can incorporate a virtually unlimited number of variables and constants, tailored to their specific needs and workforce expertise.

The collected data integrates with fields such as data science, chain of custody, document management, and information security, reinforcing compliance with standards such as ISO 27001, ISO 55001, ISO 45001, ISO 9001, Six Sigma, 5S, 6S, SHELL, SHELL+C, HAZOP, LOPA, and HAZID (hereafter referred to as standardized processes). While this list is extensive, the application of these frameworks depends on each organization's maturity, industry requirements, and strategic objectives.

Through a review of existing literature, this study highlights that various engineering disciplines establish a direct relationship between standardization and organizational management systems, which evolve based on sector-specific needs over time. This review demonstrates that these methodologies can be adapted to globally recognized industrial standards and seamlessly incorporated into Industry 4.0 frameworks.

Thus, the empirical methodology employed in this study underscores the intrinsic link between Industry 4.0, hardware, and software, supporting the integration of existing industrial processes with modern Safety Management Systems (SMS). This approach facilitates the adoption of emerging technologies by industrial sectors seeking to enhance operational efficiency, safety, and regulatory compliance.

3. JUSTIFICATION

The integration of Industry 4.0 technologies—specifically 5G, wireless networks, digital twins, IoT, and AI—into Safety Management Systems (SMS) is essential for ensuring business continuity. The implementation of AI will be tailored to the stakeholders' needs and developed according to organizational requirements. Figure 1 presents the fundamental characteristics of these technologies, while Figure 2 illustrates their integration into SMS within organizations [6]. While additional technologies exist beyond these five, they serve as a preliminary foundation for SMS implementation, whether fully or partially, depending on identified needs. This integration supports data-driven decision-making, fostering a corporate safety culture and enhancing compliance with standardized processes, both existing and forthcoming, within organizations [7].

Maintaining asset management, as discussed in [4], [5], requires the identification of operational hazards across different corporate levels, a key function of SMS. The coexistence of SMS with various standardized processes generates large volumes of data [6], enabling the incorporation of Industry 4.0 technologies into safety management frameworks (See Figure 1). These data streams facilitate automated statistical compilation and storage, as outlined in [7], enhancing decision-making, continuous improvement [8], and enabling SMS deployment across various platforms—whether open-source or proprietary—while ensuring security at all operational stages.

Integrating Industry 4.0 technologies into SMS not only enables automation and process optimization but also fosters the development of a data-driven organizational culture. The real-time collection and analysis of operational data through IoT, AI, digital twins, and related tools support early anomaly detection and the implementation of proactive risk mitigation strategies. This results in a significant reduction in costs associated with failures, incidents, or accidents, ultimately enhancing operational efficiency and ensuring business sustainability.

Furthermore, interoperability between different management systems and standardized communication protocols strengthens information traceability and regulatory compliance, both of which are critical in highly regulated sectors. The scalability of these technologies allows for their progressive implementation, adapting to the specific needs of organizations regardless of size or industry. This approach not only enhances data-driven decision-making but also reinforces the integration of management models such as ISO 45001, HAZOP, LOPA, among others. As a result, organizations achieve greater resilience in the face of the challenges posed by digital transformation.

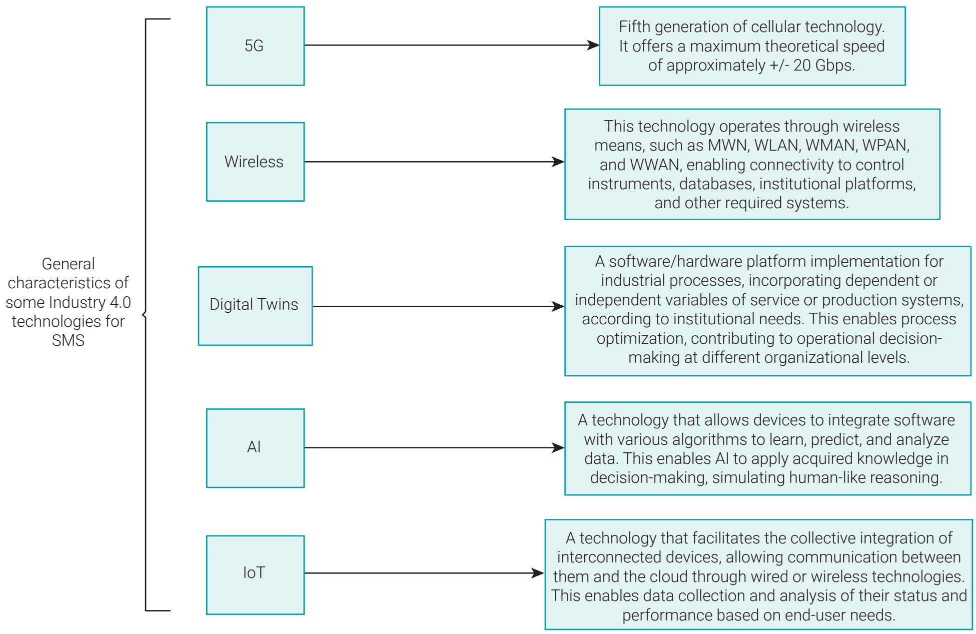

Figure 1. General Characteristics of Some Industry 4.0 Technologies for SMS
Source: Author's own work.

Industry 4.0 technologies are highly applicable to Safety Management Systems (SMS), as they are inherently data-driven, enabling data acquisition and transmission for organizational databases. This facilitates result analysis, helping to identify organizational strengths and weaknesses, while also linking project management with SMS. Such integration allows senior management to strategically plan improvements [8]. Operational data across various levels can be validated and incorporated into SMS, ensuring traceability, mitigating operational risks, and supporting business continuity [6] [9]. Additionally, SMS can seamlessly integrate with other standardized processes, whether currently implemented or introduced later, further enhancing organizational performance when leveraging Industry 4.0 technologies.

As highlighted by various authors [6] [9] [41] [47] [51], Industry 4.0 technologies enable interoperability through diverse communication protocols, facilitating data compilation and utilization. These large data volumes serve as a foundation for informed decision-making, supporting the adoption of hardware and software solutions tailored to an organization's specific sector or industrial needs. Consequently, compatibility and scalability are seamlessly integrated into existing management systems, ensuring efficient adaptation within different industries.

While Safety Management Systems (SMS) **are commonly applied in the** naval and aeronautical industries**, their** versatility **allows them to** adapt **to the needs of various** industrial sectors **while maintaining** compatibility with standardized processes **[10]. This adaptability enhances** organizational culture **and strengthens** situational safety**, regardless of** organizational size or industry type**.**

The integration of Industry 4.0 technologies **further** optimizes processes **and** enhances productivity **by ensuring** operation traceability **through** data generation**. This enables the** compilation, control, evaluation, and monitoring **of** measurable information**, facilitating** audits and targeted interventions **as needed. By transforming** measurable environments into controllable ones**, Industry 4.0 technologies establish a** foundation for data acquisition**, particularly through** digital twins**. These** virtual representations **provide** real-time or scheduled data **for** process control **[11] [12] [13], enabling** operational improvements **and** enhancements in service provision **or** production activities**.**

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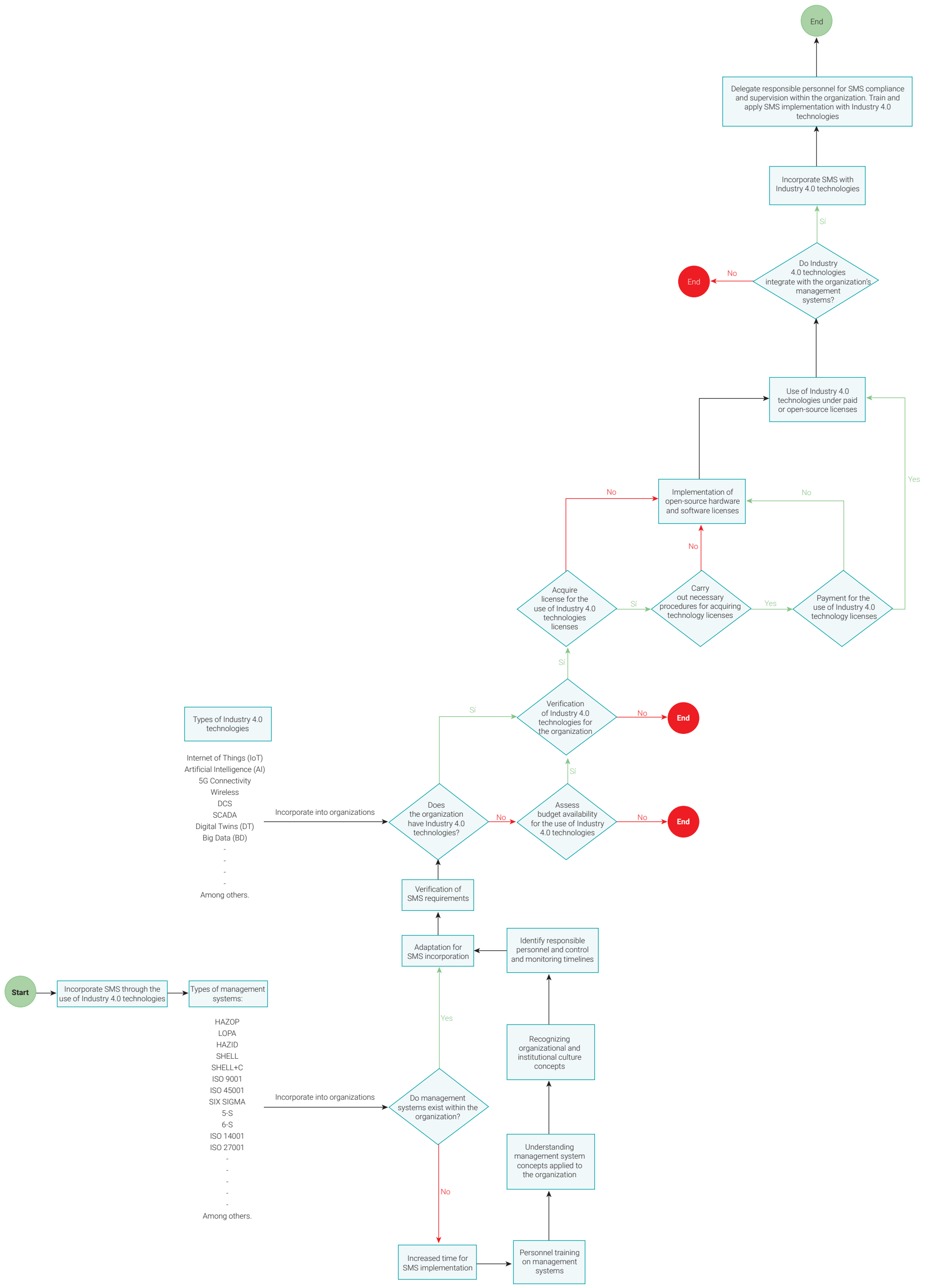

Figure 2. Pathway for Incorporating Industry 4.0 Technologies into Business Management Systems for Operational Safety
Source: Author's own creation.

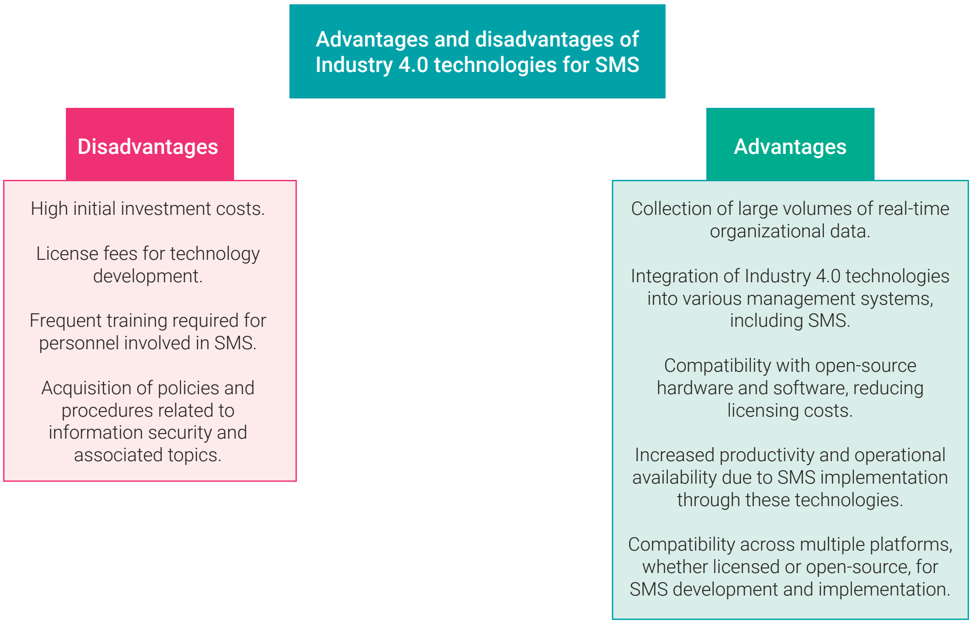

Figure 3. Advantages and Disadvantages of Industry 4.0 Technologies for SMS
Source: Author's own creation.

Organizations have the flexibility to choose **application frameworks** and **implementation levels**, with **digital twins** adapting to **departmental needs** based on **organizational maturity** [17] or **specific process requirements**. Information transmission via **5G**, **wireless networks**, **data compilation**, **automation**, and **industrial control systems** (whether **software or hardware**) can be customized accordingly. These systems include **sensors, actuators, PLCs** (Programmable Logic Controllers), **PID controllers** (Proportional-Integral-Derivative), **DCS** (Distributed Control Systems), **SCADA** (Supervisory Control and Data Acquisition), **MES** (Manufacturing Execution Systems), **ERP** (Enterprise Resource Planning) systems (both **horizontal** and **vertical**), etc., depending on the **specific needs** and **business objectives** of the organization.

Industries such as **oil**, **logistics**, **nuclear**, **aeronautical**, **naval**, and **steel** require specialized systems, including **hydraulic, pneumatic, electro-pneumatic**, and **oleo-pneumatic systems**, tailored to **general** or **industry-specific processes** [19].

The **development and adaptation** of **Industry 4.0 technologies** depend on the **established needs** or **evaluation levels**, utilizing either **licensed** or **open-source software/platforms** [17]. **Information technology** plays a key role in **data collection**, forming the foundation for **data science**, which supports **data compilation**, **storage**, and **traceability**. This aligns with **SMS principles** for systematic application [20] in **operational**, **financial**, **managerial**, and other industrial areas. It encompasses both

service provision and **product manufacturing**, involving both **internal and external clients** to enable **continuous improvement** in **decision-making**.

Compiled **SMS data** supports **operational continuity**, ensures **process safety**, and enhances **task execution integrity** in **work environments**. Despite SMS's origins in **high-risk sectors**, its **versatility**, strengthened by **Industry 4.0 technologies** or **standardized processes**, can be adapted to meet **specific needs** and **infrastructures**, leveraging **existing systems** or transitioning as necessary. This adaptation fosters an **organizational culture** that promotes the identification of **workplace hazards and risks**, traces **incident origins**, mitigates **incidents and accidents**, and ensures **institutional quality** [7].

Furthermore, this integration increases **inter-departmental interoperability**, enabling SMS to align with the **Quality Management System (QMS)** as needed. It facilitates **decision-making** through **real-time data**, contributing to organizational improvement via **training and retraining processes**, while utilizing **Industry 4.0 technologies** for enhanced **service delivery** and **product manufacturing** [21].

Introduction to the Opportunities of Industry 4.0 Technologies

The opportunities presented by various **Industry 4.0 technologies** include **continuous improvement**, which serves as a foundation for integration with **international standards** such as those from the **International Organization for Standardization (ISO)**, **American Society for Nondestructive Testing (ASNT)**, **The American Society of Mechanical Engineers (ASME)**, **Institute of Asset Management (IAM)**, and the **Society for Maintenance & Reliability Professionals (SMRP)**, among others. This integration also extends to **programming protocols**, **telecommunications** [22] [2], and **data networks** like those from **CISCO**, the **TCP/IP protocol suite**, including **Ethernet/IP**, **Modbus**, **PROFINET**, **PROFIBUS**, **Serial ATA (SATA)**, **Serial Attached SCSI (SAS)**, **EtherCAT**, **BACnet**, and **CANOpen**, among others that organizations may choose to implement [2] [23], depending on their **organizational maturity** or the **industrial sector** they belong to.

In this context, both **dependent** and **independent variables** in system and process data analysis [23] [24], included in organizational tasks and industrial developments [22] [33], must be carefully considered. This requires defining **process protocols** that organizations adopt for work tasks, alongside the **security protocols** set for **SMS adoption**. These protocols, which may vary based on **priorities** and the **security needs** of each organization, include different **firewalls** or **firmware** required for the operation of embedded control devices across various industrial sectors. These protocols are essential for the **transmission**, **processing**, and **analysis** of information signals [8] [25] [26], enabling the **scalability** of different technologies based on the specific needs of the organization.

Communication Protocols and Technological Integration

Communication protocols for integrating various **Industry 4.0 technologies** should be classified into **wired** and **wireless** categories [26] [27] to determine their operation at different organizational levels [28] [32]. This integration will align with globally accepted industrial standards, as previously mentioned, and ultimately be incorporated into the organization's **SMS**, enabling continuous improvement and quality processes [7] [14] [23] at various organizational levels. The synergy between different **Industry 4.0 technologies** in **enterprise management systems** for operational safety is illustrated in **Figure 4** (Synergy of Operational Safety Management System with Industry 4.0 Technologies).

These protocols facilitate process **standardization**, which serves as the foundation for **traceability**—an essential element for implementing one or more of the aforementioned management systems, regardless of the type of organization or industrial sector. This process also supports **database monitoring** and **information management** at the **information security level** for decision-making. Depending on the organization's needs, decision-making may occur in **real-time** or at a later stage.

The considerations outlined above help to understand the **scalability** of the necessary technologies based on industry-specific variables, such as **budgets**, **personnel availability**, **training**, and other factors external to **Industry 4.0 technologies** [41] [47] [49] [50]. This information, derived from both direct and indirect variables, creates an **operational synergy** within management systems across various organizational areas such as **asset management**, **maintenance**, **quality**, and more.

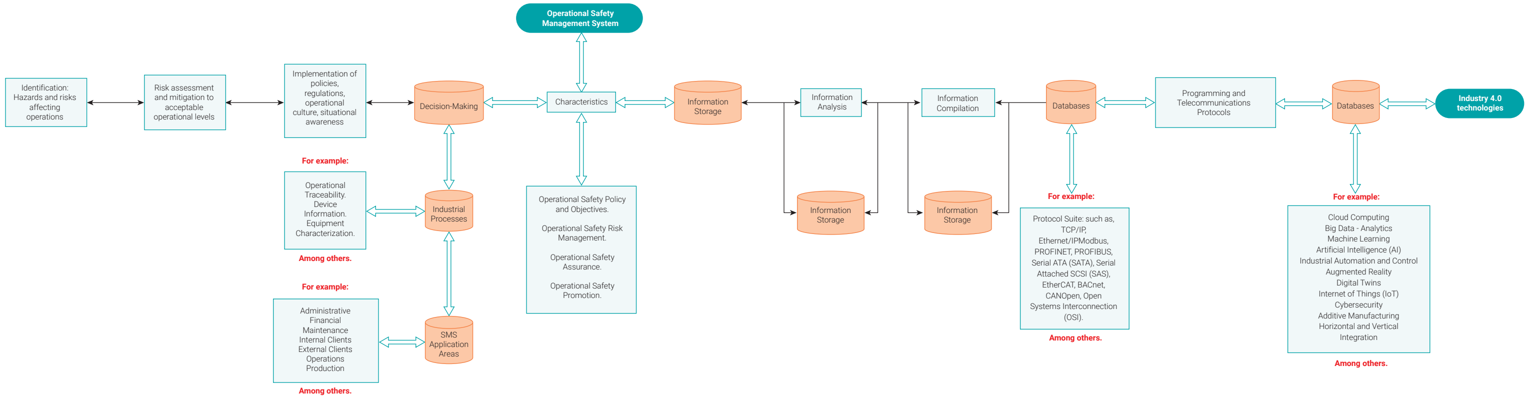

Figure 4. Synergy of Operational Safety Management System with Industry 4.0 Technologies.
Source: Author's own work.

Compatibility, Data Science and Operational Management Actions

The compatibility of various **Industry 4.0 technologies** will empower the **data science department** and different organizational levels to gather data for industrial activities. Technology acts as a key component in integrating management systems with applications across areas such as **automation**, **maintenance**, **training**, **occupational health and safety**, **hazard identification**, and **risk assessment** in work environments [29] [33], facilitating **SMS integration** across various industrial sectors.

In the context of **SMS** within enterprise management, it is essential to emphasize the **traceability** of work activities and devices. This traceability enables the collection of indicators that inform decision-making at different organizational levels [29] [30]. To effectively implement this, organizations must train all stakeholders—both internal and external clients—ensuring they integrate **operational culture** and **situational awareness** into various organizational processes.

Additionally, this training facilitates **data acquisition** for compilation, analysis, and task execution according to company needs [1] [6] [30]. The data collected from various devices during industrial processes is consolidated within the **data science department**, regardless of the industrial sector, with the aim of improving the **workplace climate** within companies.

Critical State Identification and Asset Management

The **compatibility of Industry 4.0 technologies** with **SMS** facilitates the identification of critical process states, hazards, and risks, and integrates these with **asset management** [32], **maintenance tasks**, and the reduction of bottlenecks in redundant activities. This improves **device availability** and enhances value generation throughout the asset lifecycle [5][6][31], from product manufacturing to service delivery.

Moreover, internal control, involving various internal clients within the organization [34], enables the continuous monitoring and evolution of **SMS** across different work areas. This includes tracking data provided by devices or adjusting their programming [8][15] as needed to align with organizational processes. **Internal control** is also closely tied to **enterprise management** [34] and the integration of existing or desired management systems and standards within the company.

Technologies of Industry 4.0 in SMS Integration

As illustrated in **Figures 2**, **3**, and **4**, various **Industry 4.0 technologies** can be seamlessly integrated into **enterprise management systems** within the **SMS**, based on the specific needs of the organization. This integration promotes a stronger **operational culture**, enhances **situational awareness**, ensures adherence to **occupational health and safety policies**, and provides **component traceability**, among other benefits. These technologies can also coexist with other industry standards, such as **ASNT**, **ASME**, **SMRP**, **IAM**, **ISO 27001**, **55001**, **45001**, **9001**, **SIX SIGMA**, **5S**, **6S**, **SHELL**, **SHELL+C**, **HAZOP**, **LOPA**, **HAZID**, and others, depending on the company's maturity level or specific needs.

Industry 4.0 technologies can be integrated with a variety of devices across industrial units [16] [35] [36], generating data at each process stage [9] [36] to ensure **operational safety**. Participation from all company members is crucial, creating opportunities for improving **asset availability** [37] and fostering **continuous process improvement** within the organization. This facilitates the **data compilation** across various **Industry 4.0 devices** [38] [39], ensuring that personnel involved in process stages are equipped with the **necessary recurrent training** [38] for data analysis and operations using **data science**. This ensures that information is accurately delivered to the relevant work areas.

Training and Continuous Improvement

Various **Industry 4.0 technologies** must be carefully analyzed to determine the most suitable ones for implementation in organizations, based on their specific needs. Regardless of the selected technologies, it is essential to train the involved personnel [39] on the processes associated with each technology and the **SMS**. This ensures that data acquired from various control devices is effectively analyzed by the **data science departments** [40], which then feed the information into the SMS to identify **hazards**, **risks**, and other relevant **SMS-related policies** [1][2].

The principles of **automation**, **industrial networks**, and **control systems** must adhere to the communication standards set by the devices [40] or, if necessary, follow the manufacturer's recommendations. This guarantees that data can be stored, incorporated into the SMS, and integrated with **asset management** [41], providing valuable feedback to both **SMS managers** and **internal or external clients** of the organization [41][43]. This feedback process involves all work areas, aiming to generate **financial dividends** [42] while delivering **sustainable improvements** and mitigating rework throughout the **asset lifecycle**.

Furthermore, training personnel [43] on the technologies is crucial for understanding and analyzing the data that contribute to decision-making within the SMS and organizational maturity. This also ensures compatibility with other standards that companies may have or wish to incorporate.

Finally, the evaluation of the **SMS** relies on the **types of data** [10][12] collected, which are analyzed by **data science teams** to support decision-making. The SMS adapts to **QMS** and integrates Industry 4.0 technologies and standardized processes, involving all organizational members, regardless of the organization's capital type (public, private, or mixed). Continuous training for employees involved in **Industry 4.0 technologies** is vital for **continuous improvement** [43][44], reducing or mitigating incidents, accidents, or mishaps in organizational processes.

This requires **SMS managers** to effectively integrate these technologies into their work processes, ensuring alignment with various standards [45], as previously discussed. These technologies and communication protocols represent a **global reality** [46] across different industrial sectors, and their adoption enhances **institutional competitiveness**. Implementing these technologies ultimately improves areas like **finance**, **maintenance**, and **overall asset management** [47], leading to enhanced **service delivery**, greater **stability**, and increased **production**.

Ongoing training for personnel, incorporating updates on industrial trends and technologies [45][48], is essential for efficient management of operations throughout the **asset lifecycle** [46]. It ensures that data can be collected, stored, processed, and integrated into the company's **SMS**. **Data science** becomes a fundamental pillar for data analysis [49], supporting informed decision-making that aligns with **SMS policies** across organizational levels. As the data remains traceable, it can be seamlessly integrated into various standards [50][51], facilitating continuous updates and improvements, and positioning **personnel** as one of the most valuable assets for the organization. They are the key source of information, helping to identify issues at each process stage [50], regardless of the industrial sector in which the organization operates.

4. CONCLUSIONS

It has been demonstrated that the **Safety Management System (SMS)** is compatible with various existing management systems, allowing for its adaptation and application across organizations. Since SMS relies on data acquired during operations, this data forms the foundation for **data science** and **big data**, enabling the integration of **Industry 4.0 technologies**.

Some weaknesses were identified in creating a symbiosis between SMS and Industry 4.0 technologies, particularly regarding the costs of technology licenses. However, open-access license alternatives are available, making these technologies more accessible and affordable for organizations. This facilitates their adjustment and seamless integration into the organizational culture of institutions.

While SMS originated in high-risk sectors like the naval and aeronautical industries, it has been shown to be compatible with companies across all sectors, provided that there is active participation from all organizational members.

The empirical methodology implemented aligns with the current state of research for integration with management systems, as well as with various globally accepted industrial standards. This integration establishes a synergy between the **Safety Management System (SMS)** and **Industry 4.0 technologies**, making it applicable to organizations in any sector or industrial field.

For SMS, data plays a crucial role. Given the large volumes of data generated, compiling and analyzing this data is essential for informed decision-making. This process enables the implementation of Industry 4.0 technologies, which help streamline and standardize operations, making them more homogeneous and better integrated into the overall management system. This integration enhances organizational operations at all levels within the company.

5. RECOMMENDATIONS

Interested parties are encouraged to incorporate **Industry 4.0 technologies** into integrated management systems to reduce costs over time. The longer an organization waits to adopt these technologies, the higher the cost of integration will be, making the financial investment more significant. The greatest economic value from implementation will be realized in the near future.

It is crucial to involve all members of the organization in the implementation and use of **Safety Management Systems (SMS)**. Their active participation ensures compliance and continuous improvement, leading to better outcomes and a reduction in operational risks.

Operational safety is an inherent benefit of **Industry 4.0 technologies**. Continuous training will enhance situational awareness across various processes, such as industrial safety, maintenance, and asset management. These technologies should not be viewed as a cost but as an investment that increases competitiveness and helps organizations become world-class leaders in their fields.

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