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OCCUPATIONAL SAFETY IN INDUSTRY 5.0 – TECHNICAL ASPECTS OF SHAPING SAFE HUMAN–MACHINE INTERACTION

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Purpose: The aim of the work is to define guidelines for selecting technical solutions that ensure safe cooperation between employees and machine equipment. Their application improves the operation of machine equipment in Industry 5.0 enterprises, reducing the scale of potential burdens and losses.
Design/methodology/approach: The study was prepared based on subject literature and legal documents related to the analysed issue. A synthesis of available scientific publications and legal regulations was conducted, in particular the Machinery Regulation (EU) 2023/1230.
Findings: The conducted analysis indicated that ensuring the efficient implementation of activities in Industry 5.0 requires taking into account the limitations of individuals working alongside technical equipment. For this purpose, the implicational requirements of Industry 5.0 and the guidelines specified in applicable legal regulations (e.g., Machinery Regulation (EU) 2023/1230) should be considered. This makes it possible to increase usability during operation while eliminating an unacceptable level of risk.
Research limitations/implications: The results of the study indicate that effective improvement of human interaction with technical equipment requires the implementation of solutions that eliminate potential incompatibilities. Due to the limited number of available information sources, the study should be considered complex and preliminary. The effectiveness of the applied solutions should be verified through their practical implementation and assessment of their impact on work comfort and safety.
Originality/value: The study linked the technical aspects of Industry 5.0 operation with the provisions of the Machinery Regulation (EU) 2023/1230. Attention was drawn to the importance of applying the indicated guidelines to ensure safety during the use of technical equipment. The current lack of detailed knowledge regarding the above relationship justifies the need for further verification in this area, fitting into the research gap associated with the changing machinery requirements.
Keywords: Industry 5.0, technical equipment, operational safety, Machinery Regulation (EU) 2023/1230.
Category of the paper: Research paper, Conceptual paper.

1. Introduction

Ensuring employees' safety during the performance of their work is one of the conditions for the efficient execution of production tasks. This situation is not changed by the introduction of automation and robotization. On the contrary, the technical equipment in use generates new hazards, requiring the implementation of solutions that limit the possibility of accidents and increase the friendliness of the working environment.

Analyses conducted in manufacturing organizations indicate that industrial development does not eliminate the risk of accidents, and that the condition of technical equipment is crucial for employee safety and health, as well as for the efficiency of ongoing operations (Górny, 2024a; 2024b). This highlights the importance of technical requirements in achieving safety in organizations that use technical equipment.

The effectiveness of implemented solutions depends on their adequacy to the nature of the existing hazards and nuisances. Situations that generate risks require the introduction of measures that minimize the negative impact of technical equipment on humans. In Industry 5.0, shaping safety cannot be limited solely to protection against existing hazards. It is necessary to ensure safe and sustainable cooperation between humans and the technical equipment in use (Xu et al., 2021; Trstenjak et al., 2025). Addressing safety issues is particularly important in areas where task execution requires close interaction between humans and technical equipment.

The change in machine requirements resulting from the entry into force of the Machinery Regulation (EU) 2023/1230 on 21 January 2027 creates the need to identify guidelines for selecting technical solutions that mitigate the consequences of machines not being adapted to workers' needs. This issue is becoming particularly significant in the context of the increasing level of mechanization of work processes. At the same time, it is essential to take into account the human-centered aspects of machine design and use. This approach is consistent with the assumptions of the Industry 5.0 concept, which emphasizes the role of humans in an environment of advanced production technologies. The appropriate selection of technical solutions should consider both technological requirements and the needs of users.

The limited knowledge of these relationships justifies the need for research in this area.

2. Fundamental assumptions of Industry 5.0

2.1. Human as a key element of the efficient functioning of Industry 5.0

The concept of Industry 5.0 assumes a shift away from a purely technology-driven approach to enterprise operations toward a human-centered model. At the core of its requirements is human collaboration with advanced technologies, including artificial intelligence (AI),

collaborative robots (cobots), and Internet-based systems (IoT). The implemented solutions analyze acquired data and automatically take actions in real time, with limited human intervention.

Many authors point out that ensuring a technical system's resilience to occurring disturbances is crucial for its functioning (Liu et al., 2014; Simba et al., 2018; Cohen, Singer, 2021). In Industry 5.0, emphasis is placed on safety and ergonomics, shaped within an automated work environment. The role of technology is to support the worker and enhance decision-making efficiency (Górny, 2023). As a result, Industry 5.0 combines technological innovation with concern for employee well-being and the stability of industrial systems, focusing on humans, sustainable development, and system resilience (Gajdzik, 2023; Wolniak, 2023).

The concept of Industry 5.0 is based on the implementation of three fundamental aspects of the development of production activities. These are presented in Table 1. The areas shaping the requirements are characterized by their relation to technical requirements. The indicated guidelines focus on the digital transformation of the economy, assuming the achievement of socio-economic prosperity, sustainable development, and human safety (Grabowska et al., 2024). This concept promotes responsible innovations that enhance the well-being of workers, consumers, society, and the environment (Nahavandi, 2019; Longo et al., 2020; Breque et al., 2021).

Table 1.
Technical requirements characterizing key areas of the conducted activity, in accordance with Industry 5.0 guidelines

Categories of requirements development	Key areas of requirements development
Human-centric	- The role of machines is to collaborate with humans (implemented through the use of cobots, i.e. collaborative robots). - The technology takes into account human limitations (machines are tailored to human needs, not vice versa). - The design of devices considers safety and ergonomics (including human limitations).
Sustainable development	- Production is characterized by reduced environmental and surrounding impact. - The activities carried out minimize the use of raw materials (they are based on the use of previously processed materials and substitute raw materials). - The production process ensures reduced energy consumption.
Resilence	- Production organization takes into account factors that may disrupt its execution. - Enterprises are characterized by autonomy in their operations, adapting to identified needs.

Source: author's own compilation based on (Grabowska et al., 2024; Breque et al., 2021; Dixson-Declève et al., 2021).

In all the areas indicated in Table 1, achieving results requires ensuring effective cooperation among the participants involved in the tasks. The use of solutions aimed at enabling human–machine interaction is one of the key areas shaping Industry 5.0 (Breque et al., 2021; Dixson-Declève et al., 2021). The problems that arise require identifying their causes and determining how to effectively eliminate or mitigate the consequences of events.

The application of proactive monitoring of employee activity in smart factories increases the level of safety, thereby enabling the detection of unusual states and emerging threats (Amade, Nwakanma, 2021).

In Industry 5.0, shaping occupational safety is highly complex due to the close interdependence between humans and technology. It requires consideration of both traditional hazards and issues arising from collaboration with robots and autonomous systems. The effective implementation of requirements is determined by taking into account the results of analyses of complex socio-technical systems, which identify all conditions resulting from human–technology interaction (Adriaensen et al., 2019). It also requires consideration of ethical principles and ergonomics, strengthening the role and position of humans, and providing them with decision-making capabilities and intuitive collaboration interfaces (Panter et al., 2024). In all these areas, humans should be ensured conditions free from hazards and burdens. The growing integration of human–technical object systems makes cybersecurity and the prevention of unauthorized interference a key issue (Cao et al., 2024).

2.2. Guidelines for the selection of technical solutions increasing the efficiency of Industry 5.0

Industry 5.0 represents a departure from the concept based exclusively on automation and robotization, which formed the framework of Industry 4.0. It is based on the application of solutions that support humans rather than replace them. At the same time, production processes are more flexible, sustainable, and resilient to disruptions. The integration of artificial intelligence (AI) into the structure of requirements necessitates consideration of ethical issues.

Technical solutions support the operator in decision-making. Humans are treated as key decision-making elements influencing processes (Sarkar, 2024). The human-centered approach shifts focus from technology development to the working environment and full use of human capabilities. Technology is intended to serve people, meaning that solutions used in production are adapted to the needs and diversity of employees. It is essential to ensure a safe working environment that supports development. Priority should be given to physical and mental health, employee well-being, and the protection of their fundamental rights, including autonomy of functioning.

The applied solutions must ensure operational efficiency, considered in relation to (Lu et al., 2021; Breque et al., 2021):

- The ability to achieve effective communication that enhances the usefulness of the ongoing dialogue, taking into account the nature and context of the transmitted content as well as the characteristics of the human recipient, ensuring the required level of efficiency.

- Ensuring effective cooperation between humans and technical equipment, requiring consideration of the human physical, cognitive, and psychological state, as well as the machine's ability to perceive variability in performed tasks. This can be addressed through solutions that account for dynamic changes in the environment and the role of humans influencing decision-making.

Taking into account human needs and expectations requires reducing the negative impact of technical equipment on their health and safety. Many of these aspects are addressed in the EU Machinery Regulation (2023/1230). It enables the use of technical devices in new industrial areas that utilize automation, computerization, and artificial intelligence. These include (Emma-Ikata, Doyle-Kent, 2022):

- In complex conditions and under time pressure, where the system indicates a possible solution that is ultimately approved by a human.
- Performing actions based on stored algorithms (human-in-the-loop), where a decision previously made by a human can be repeated by the device within defined constraints.
- Making decisions based on the current situation rather than solely on pre-established operating schemes.

Moreover, Industry 5.0 emphasizes workplace friendliness, taking into account human limitations in relation to the technical equipment being used.

3. Characteristics of the research problem and the applied methodology

The aim of the conducted study was to identify guidelines for the selection of technical solutions that influence the effective functioning of humans interacting with technical equipment. The literature analysis indicated that ensuring employee safety requires enabling efficient and intuitive use of technical equipment. Based on these assumptions, a research question was formulated, defining the objective of this study:

Research question (RQ): What characterizes solutions that determine safe interaction between humans and technical equipment used in Industry 5.0?

The answer to the research question is based on identifying key factors that determine the possibility of reducing the negative consequences of human interaction with technical equipment and supporting safe functioning in the work environment. Conditions forming the basis for effective human–technical equipment cooperation were identified. Their characteristics were linked to the essential requirements defined in the Machinery Regulation (EU) 2023/1230. The obtained results constitute a specification of requirements and enable the identification of guidelines for technical solutions.

4. Results of the conducted study

Each element of the human–technical equipment interaction system performs its assigned tasks in accordance with its capabilities. Their effect is the provision of:

- Physical safety (PHS), related to protection against collisions with technical equipment, ergonomic overload, and fatigue. It requires the application of, among others:
  - Guards and barriers protecting against moving machine parts.
  - Emergency stop systems activated when a hazard occurs, as well as sensors preventing the occurrence of hazards.
  - Ergonomic requirements taking into account the individual characteristics of users.
- Psychological safety (PSS), including the reduction of stress as well as excessive information load and time pressure. It requires, among others:
  - The use of intuitive interfaces and clear control panels.
  - Elimination of excessive information reaching users.
  - Implementation of unambiguous operating procedures.
  - Support for teamwork and training to enable efficient operation of technical equipment.
- Digital safety (data security, DS), covering the protection and securing of data monitoring technical equipment. Possible solutions include, among others:
  - Regular software updates.
  - Monitoring system performance and preventing unauthorized access.
- Ethical safety (ES), related to the transparency of applied algorithms and the ability to maintain human control and supervision (human-in-the-loop). In particular, it includes the application of:
  - Transparent decision-making algorithms in the technical equipment used.
  - Systems monitoring the compliance of technical equipment operation with the ethical principles of performed work.
- System resilience (R), including ensuring the ability to operate safely in emergency situations, achieved through, among others:
  - Rapid restoration of proper operation of technical equipment after a failure occurs.
  - Use of software resistant to overloads and operator errors.

The characteristics of the objective of the applied solutions, based on the provisions of the Machinery Regulation (EU) 2023/1230, together with guidelines for their implementation and the achieved effects, are presented in Table 2.

Table 2.
Characteristics of requirements defined in the Machinery Regulation ensuring the safe use of technical equipment, adapting machinery equipment to Industry 5.0 guidelines

Aspects of operational efficiency	Guidelines for the implementation of requirements	Achieved results
Ensuring reliable communication system performance	Effective information flow necessitates the application of appropriate communication systems and properly selected devices for transmitting information, which are regularly tested. It is necessary to ensure monitoring of operating parameters, rapid elimination of detected errors, and maintaining the continuity and reliability of communication	DS ES R
	Examples of required solutions: - Control systems must be designed and constructed in a way that prevents the occurrence of hazardous situations. - The design and construction of control systems must ensure proper supervision of the processes being carried out. - To ensure effective operation, communication means must be visible, clearly identifiable, and quickly accessible.	
Reducing the effects of human-related consequences	It is necessary to take into account the physical and psychological limitations of the operator. It is essential to ensure intuitive operation of technical equipment and to minimize overload, fatigue, and the likelihood of errors	PHS PSS ES R
	Examples of required solutions: - Technical equipment must be designed with the operator's needs in mind. - Operator discomfort, fatigue, and physical and psychological strain must be eliminated or reduced to a minimum.	
Reducing the impact of dynamic changes in the human working environment	Dynamic changes in the working environment require the implementation of solutions that adapt to the current physical and psychological conditions of the employee as well as to work organization	PHS PSS R
	Examples of required solutions: - The design and construction of equipment must take into account the need to verify the correct operation of control elements. - Control systems with self-modifying logic, intended for use at different levels of autonomy, must not generate actions exceeding their assigned tasks or required range of motion. - The design and construction of control elements must ensure that the machine can only be started as a result of an intentional operator action.	
Application of adaptive solutions supporting employees	The application of adaptive measures supporting employees requires the implementation of technologies and work methods tailored to their needs, capabilities, and limitations in conditions where hazards are present	PSS PHS ES R
	Examples of required solutions: - The design and construction of technical equipment must eliminate areas of inconvenience and burden. - The applied technical measures must be consistent with their intended purpose and must not impose excessive workload on employees.	

Source: author's own development based on the Machinery Regulation (EU) 2023/1230.

5. Discussion of results

Industry 5.0 combines the power of precision machines with human creativity and ingenuity, thereby better adapting the technical environment to human needs. The benefits achieved result from the adopted solutions. They are determined by ensuring cooperation

between people and production systems operating at an advanced technological level, which is not free from risks and burden.

The development of Industry 5.0 determines the need to implement solutions in which technology enhances rather than replaces (displaces) humans. Existing studies primarily highlight (Trstenjak et al., 2025; Wang et al., 2021; Sarkar et al., 2024):

- The synergy between the human factor and the technical conditions of task execution.
- The priority role of humans in designing production systems in line with human-centric guidelines.
- Human–robot interaction and ergonomics treated as key elements of safety.
- Ensuring employee well-being that enables maintaining productivity and motivation, which are closely linked to the company's market position.

In these conditions, humans cannot be replaced, but only their advantages can be better utilized. They can be treated as a paradigm that employs adaptive and flexible technological innovations used to support industrial development. It should be noted that the implementation of advanced technologies and tools supporting intelligent manufacturing is crucial for the efficient functioning of technical equipment.

The characteristics of solutions enabling the above benefits are presented in Table 2. The conducted synthesis indicated that their implementation allows to:

- Optimize workloads as a consequence of the rational use of employees' knowledge and skills.
- Reduce burdens generated by accidents caused by human errors during the operation of technical equipment.
- Improve task execution by introducing automation that reduces the scope of human activities and adapts work intensity to human capabilities.
- Reduce the number of failures caused by human error by decreasing human involvement in task execution.

Effective implementation of activities should take into account guidelines related to solutions supporting automation, the use of artificial intelligence, and remote execution of control and supervisory tasks. At the same time, the operating conditions of autonomous systems and their impact on generated risks must be considered.

In an industrial context, this means that applied solutions must be adapted to the needs and diversity of employees, rather than requiring them to continuously adapt to dynamically changing technological solutions (Gualtieri et al., 2021). The employee gains greater opportunities in an environment that becomes more dynamic. These activities should include reducing the impact of risks associated with the use of technical equipment. In Industry 5.0, safety refers to ensuring physical, psychological, and digital protection of the worker in a human–machine collaboration environment, while maintaining human control over the technical equipment used. It encompasses not only technical aspects but also ethical and

organizational ones that support well-being and the safe integration of intelligent production systems. Industry 5.0 enables the use of synergy between humans and autonomous machines, which must be “perceptive” and “aware” of human intentions and desires.

6. Summary

Ensuring occupational safety in Industry 5.0 is a priority. The implementation of solutions that enable safe interaction between workers and machine equipment requires recognizing the protection of humans as a paramount value, for example in relation to productivity. System performance is influenced by the use of intelligent monitoring systems, including those that detect the presence of a worker in the working zone, as well as technical equipment that automatically adapts its operation to the operator’s behavior. An important element in the selection of solutions is also the consideration of ergonomic guidelines for workplace design and the use of technologies that reduce the physical and mental burden on employees. As a result, this improves the operation of machine equipment, enhancing task performance in Industry 5.0 enterprises. These are characteristics whose identification was the objective of the conducted research.

The results of the synthesis indicate that, in order to ensure employee safety and support the development of activities aligned with Industry 5.0 guidelines, solutions provided for in the Machinery Regulation (EU) 2023/1230 may be applied, which establishes the legal framework for the use of technical equipment in the workplace. The identified features define the criteria for selecting technical equipment used in Industry 5.0 enterprises. This, in turn, facilitates and improves the selection of technical equipment by individuals responsible for the development of Industry 5.0 organizations.

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