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Occupational Risk Management for a Sustainable Workplace Using Simulation

Keywords: occupational risk; sustainable workplace; simulation; warehouse work; humanization of work

JEL: C5; D2; J8; M11; Q55

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Abstract

Theoretical background: The article delves into the realm of occupational risk management within the context of supply chain management and enterprise logistics. It emphasizes the importance of ensuring safety and sustainable working conditions in today's dynamic business environment, where supply chains are becoming increasingly globalized and complex.
Purpose of the article: The primary objective of the article is to introduce a novel approach to occupational risk management that leverages advanced digital technologies and simulations. It aims to address the existing research gap by developing a method that considers dynamic environmental factors and individual worker needs. By analyzing the synergy of various hazards, monitoring employee workload, and employing simulations, the article seeks to enhance the accuracy of occupational risk assessment and facilitate more effective corrective actions.
Research methods: The article employs a mixed-method research approach, drawing upon both theoretical analysis and practical application. It begins with a thorough literature review to establish the theoretical framework and identify research gaps. Subsequently, it discusses the proposed solution – a method for managing occupational risks using simulation – by presenting its theoretical description and implementation process. The research methodology involves the development and application of this method to a selected order picking process, followed by simulation to minimize occupational risks. The authors also utilize software tools to simulate work processes and assess health risks to workers.
Main findings: The main findings of the research suggest that occupational risk assessment using simulation has a significant impact on improving work processes in terms of sustainable workplaces. By introducing elements of labor humanization and redesigning work processes, the study demonstrates a reduction in the sources of occupational risk. The innovative approach to risk assessment, based on recursion across different organizational resources, facilitates the identification of improvement action projects. Additionally, the study emphasizes the importance of digitalization and Industry 4.0 technologies in monitoring working conditions, identifying risks, and implementing preventive measures. Overall, the research contributes to shaping new standards for safe and sustainable work environments, thereby enhancing both safety and efficiency within organizations.

Introduction

In today's dynamic business environment, where supply chain management and enterprise logistics play an important role in ensuring competitiveness and operational efficiency, and safety and sustainable working conditions are also becoming an integral part of management strategies. With what is becoming a more globalized and complex supply chain, companies face a number of challenges, including varying risks to employee health and safety.

In the context of supply chain management and, most importantly, enterprises as links in the supply chain, effective occupational risk management is a key element in ensuring operational continuity, reducing costs and building trust with business partners. Employees who experience higher levels of well-being, safety, engagement and job satisfaction are more likely to demonstrate increased productivity and performance (Ateeq et al., 2024; Manuti & Giancaspro, 2019). Work (Al-Refaet et al., 2019; Zumrah et al., 2021) has shown that there is a clear correlation between employee well-being and productivity and efficiency in a company. Therefore, it is important to create conducive work environments that facilitate optimal productivity and employee health and safety, thereby increasing employee motivation and engagement (Pfeffer, 2009). Safe and sustainable workplaces not only affect motivation and efficiency by reducing the risk of accidents, delays in delivery.

Employers are obliged to assess and document occupational risks associated with their work and apply measures that will prevent and reduce the risk of injury or illness. Their duties also include informing employees of the occupational risks that are associated with their work. In addition, employers are obliged to fulfill their duty to ensure occupational health and safety by preventing hazards through proper organization of work, using preventive measures and informing employees about occupational risks. Among the main tasks to prevent accidents and occupational diseases that employers must fulfill are: prevention of hazards, assessment of risks that can be excluded, elimination of hazards at the source, and adaptation of working conditions and processes to the capabilities of employees through appropriate prodesign and organization of workplaces, selection of work tools, machinery and equipment, do selection of production methods and work methods, reduction of monotonous work and work at a set pace, substitution of new technological solutions (Gov.pl, 2024).

The introduction of innovative methods of occupational risk management can therefore contribute to streamlining logistics and optimizing logistics processes, as well as increasing a company's competitiveness in the global market. In the context of occupational risk management, digitalization creates opportunities to monitor working conditions in real time and identify potential risks based on data generated by devices and information systems. Thanks to this, it is possible to effectively monitor and assess the level of employee fatigue or identify areas where there is a high level of risk of hazards. Using simulation will allow you to identify potential hazards and at the same time optimize the spatial layout in such a way as to minimize the risk of accidents. By integrating the data, the company can quickly respond to changing working conditions and make informed decisions on occupational risk management.

After all, logistics processes play an important role to keep the supply chain running smoothly, and warehouse management is one of the most important links in the supply chain. However, the nature of the work environment and the activities involved in the manual transportation of goods make this profession very heterogeneous. The hazards associated with it largely depend on the stored goods and handling conditions. In Poland, as shown by the CSO data (GUS, 2024) from January–September 2023, 4,192 people were injured in the transport and storage sector, of which 20 workers lost their lives and 31 were seriously injured. Taking into account the accident rate, which determines the number of injured in all accidental incidents per 1,000 employees, the sector is in fifth place – 4.48. In addition, the number of victims of occupational accidents translates into 139,156 days of work incapacity, and thus huge costs for medical benefits on the one hand and for companies on the other. Ergonomic hazards, such as occupational musculoskeletal disorders (MSDs), represent a significant burden on the economy (Otto et al., 2017). Therefore, ensuring that employees work safely and in healthy conditions is key to success and minimizing costs. This also translates into a competitive advantage and builds trust in the brand, as increasingly customers want to buy products or services that are ethically produced and employees are protected by the company.

In this context, the development of an occupational risk management model that takes into account dynamic environmental factors and the individual needs of workers is becoming an essential tool for managers and occupational safety specialists. The article presents a novel approach based on the use of advanced digital technologies and simulations that enable comprehensive occupational risk assessment.

The main purpose of the article is to present the method and justify its relevance to management and quality practice and its contribution to the development of sustainable workplaces. By analyzing the synergy of various sources of hazards, monitoring the workload of employees and simulation, the study makes it possible to more accurately determine the level of occupational risk and, at the same time, more effectively take corrective action. This research is making an important contribution to the field of occupational risk management, as it is shaping new standards for safe and, above all, sustainable work, which will contribute not only to improving safety, but also to the company's efficiency.

The text contains a literature analysis and identifies the research gap by identifying research questions. The next section is a discussion of the problem solution using the created model. Then, a description of the implementation of the method is included. The discussion, which refers to the discussion on the important issues of implementing improvement projects, is presented in the next part of the text. The obtained conclusions and identification of further research directions are included after the discussion.

The subject of the study in terms of the literature

A key aspect in this area is to understand the concept of occupational risk management. There are a number of definitions of the term in the scientific literature, as well as in business practice, which highlight its meaning and scope. According to the European Agency for Safety and Health at Work (2024), the very concept of occupational risk refers to the probability and severity of injury or illness resulting from exposure to a hazard. Therefore, the purpose of occupational risk assessment is to protect the health and safety of workers and includes identifying the risk, assessing its severity and deciding whether there is a need to take action to reduce it. On the other hand, the definition according to the International Labour Organization (2024) defines occupational risk management as the process by which an employer or enterprise identifies, analyzes and controls occupational risks associated with the workplace in order to reduce the possibility of accidents and occupational diseases. The goal of occupational risk management is to ensure safe and healthy working conditions for employees and to minimize the risk of hazards (Goetsch, 2018).

Moving in this direction, it is particularly important to prevent both occupational accidents and illnesses resulting from long periods of work in adverse conditions (Folch-Calvo et al., 2019; Brocal et al., 2018a), through appropriate management and assessment methods. In the scientific literature, there are methodologies oriented towards occupational risk management with the use of tools such as: risk assessment based on fuzzy logic having application in the mining industry (Gul & Fatih Ak, 2018), in manufacturing companies (Mur & Demichela, 2009; Brocal et al., 2018b, 2017) the use of an evolutionary algorithm to take into account tasks and their associated risks and the safety of workers (Papazoglou et al., 2017a, 2017b). There are also risk management-oriented methodologies in the scientific literature that apply to people working at sea. The studies use Bayesian networks, or probabilistic models that allow for the analysis of the relationships between different risk factors and their impact on the resulting events (Song et al., 2016). Studies in the literature also appear in connection with risk assessment in the aluminium processing industry for workers using extruders, forklifts, cranes and production (Aneziris et al., 2010). Meanwhile, a study (Papazoglou & Ale, 2007) used flowcharts to identify and assess the risk of falls from escalators. Occupational illnesses and injuries that an employee acquires while working can result in short- and long-term reductions in quality of life (Park et al., 2023).

However, it should be remembered that another technological development is taking place in industry that exploits the potential of Internet-connected machines and equipment. These technologies of Industry 4.0 increase competitiveness in many industries but can, however, cause new types of hazards and risks (Reiman et al., 2021). As an example, automated objects and collaborative robots interacting with humans can cause unintended contacts and collisions between humans and physical objects such as machines and robots, which can also lead to accidents and injuries (Park et al., 2023; Badri et al., 2018; Javed et al., 2021; Gualtieri et al., 2022). In today's economy, which is characterized by highly competitive markets, highly demanding customers in terms of quality, deadlines and prices, legal and regulatory requirements from countries, and difficult-to-control logistics costs, companies are realizing that offering the best product at the lowest price is not only related to functions or activities within the company itself but to the entire supply chain. Such situations lead to an intensification of material flows which results in an acceleration of the pace of work and logistical operators are required to lift, move or transport loads under time pressure. These demands, which are specific to jobs in logistics, result in logistics workers being more likely to suffer accidents than workers in other business sectors (INRS France, 2018; Kudelska & Niedbał, 2020).

Due to changing technologies and approaches to producing products, new types of risks are emerging. This necessitates the development of new approaches to methods relating to ways of managing enterprise risk. The main directions in the development of new methods of occupational risk management are an attempt to use solutions from Industry 4.0 to apply sensors, i.e. to monitor selected risk factors, detect the location of workers (Podgórski et al., 2017; Hu et al., 2013; Bhattacharjee et al., 2012) and generate warnings for workers approaching high-risk zones (Seminatore et al., 2012; Lian et al., 2013).

In the context of occupational risk management, digitalization and Industry 4.0 create unique opportunities to monitor working conditions in real time and identify potential risks based on data generated by devices and information systems. Through the use of advanced sensors, Big Data analytics and artificial intelligence, it is possible to effectively monitor and assess worker fatigue levels, identify high-risk areas and implement appropriate preventive measures.

An element of occupational risk management is the activities that should be carried out in accordance with the procedure to reduce the level of risk. The first stage is first and foremost activities that should result in the avoidance or elimination of risks. Next is the minimization of risks through technical, organizational measures. The use of a digital twin for occupational risk management in terms of sustainable workplace creates added value by creating an environment for the manipulation of information in this regard. It allows observation of conditions and ongoing acquisition and updating of subject information. Maintaining records for the digital twin and their availability in any cross-section is an important asset in the new approach to occupational risk management.

In the literature relating to occupational risk management research, there are also studies on the management of working conditions in the supply chain in terms of "social" sustainability (Tobis & Górny, 2014). These studies focus on analyzing working conditions not only in individual companies, but also in the entire supply chain, taking into account social aspects such as workers' rights, working conditions, safety and social justice. Social sustainability in the context of managing working conditions in the supply chain includes attention to balancing workers' needs with business goals, promoting fair labor relations, minimizing occupational risks, and ensuring fair employment conditions for workers at all stages of the supply chain. This research is key to building a more ethical and sustainable work environment both locally and globally. One link in the supply chain is the warehouse. A significant portion of the work performed by warehouse workers qualifies as manual labor. These works are characterized by a significant level of risk, resulting from overloading the musculoskeletal system, causing musculoskeletal ailments and injuries. Commonly occurring factors of strain are incorrect position adopted during work, excessive weight of handled loads and too high frequency of repetition of performed activities (Tobis & Górny, 2014; Sadłowska-Wrzesińska, 2016). In the context of warehousing, a balanced workstation includes a number of measures aimed at improving working conditions for employees and minimizing the impact of the environment (Bartkowiak & Butlewski, 2023).

Accordingly, the article poses two research questions:

RQ1: Does occupational risk assessment using simulation have a significant impact on improving the work process in terms of a sustainable workplace?

RQ2: Will occupational safety improvement projects in the implementation of elements of humanization of work significantly reduce the energy expenditure of the worker?

Proposal for a solution – theoretical description

The adoption of economic goals by companies as paramount may result in the occurrence of some negligence in the area of improving ergonomics at the workstation, which becomes a source of excessive fatigue that can cause injuries and accidents. Despite the performance of mandatory state occupational risk assessments, some sources of risk are not properly identified. This can be remedied when the work process is modeled in detail and quality standards based on continuous improvement, i.e. the P-D-S-A (plan-do-study-act) cycle, are implemented. Information technologies support such behavior and significantly improve the quality of occupational safety management by creating conditions for the implementation of the sustainable workplace concept.

In their research, the authors set a goal: to develop a method for managing occupational risks in terms of sustainable workplace using simulation. They conducted a research process for a selected order picking process and, through the simulation of a project to improve working conditions, minimized the sources of occupational risk. System relationship designs were created to reduce the high level of employee burden. Following the presented algorithm (Figure 1), the simulation was carried out by introducing elements of labor humanization into the work process, such as employee rotation, enrichment, by changing the equipment of the workplace, and expansion, by additional means of work.

For the occupational risk assessment of warehouse workers, the authors proposed an assessment algorithm that is embedded in the flexible design of actions given the organizational context and resource potential of the organization. For this purpose, the author's software was used to simulate the work process using information about the sources of health risks to workers.

The basis of the presented innovative approach to occupational risk assessment is the recursion of risk assessment across different cross-sections of the organization's resources. The result is the creation of numerous improvement action projects that can be part of an organization's strategy seeking to ensure business continuity in the event of disruption to the work process. The environment of simulation of employees' work activities provides the opportunity to assess the adequacy of the organization's re-sources in relation to the psychophysical needs of employees. Inadequate availability or low quality of these resources is considered a threat. On the other hand, knowledge of the availability of these resources in the context of designed improvement activities gives confidence in the disposition of these resources at an appropriate operational level, which is assessed as a manifestation of safety.

The conditions for initiating actions according to the given algorithm take place in the organization if the safety strategy has a high priority for the company. It then begins with the securing of resources and the appointment of a team responsible for the process of implementing digital risk assessment (K1). Once the necessary paperwork is completed, the data sources are enriched with digital records that characterize the assessment object, as well as with up-to-date information on the occupational risk assessment position. The acquired and systematized data provide guidelines to adequately prepare for the execution of the next 12 steps of the developed method of flexible design of improvement activities in occupational risk management in terms of the human factor using simulation (Figure 1). The selection of people in K1 is

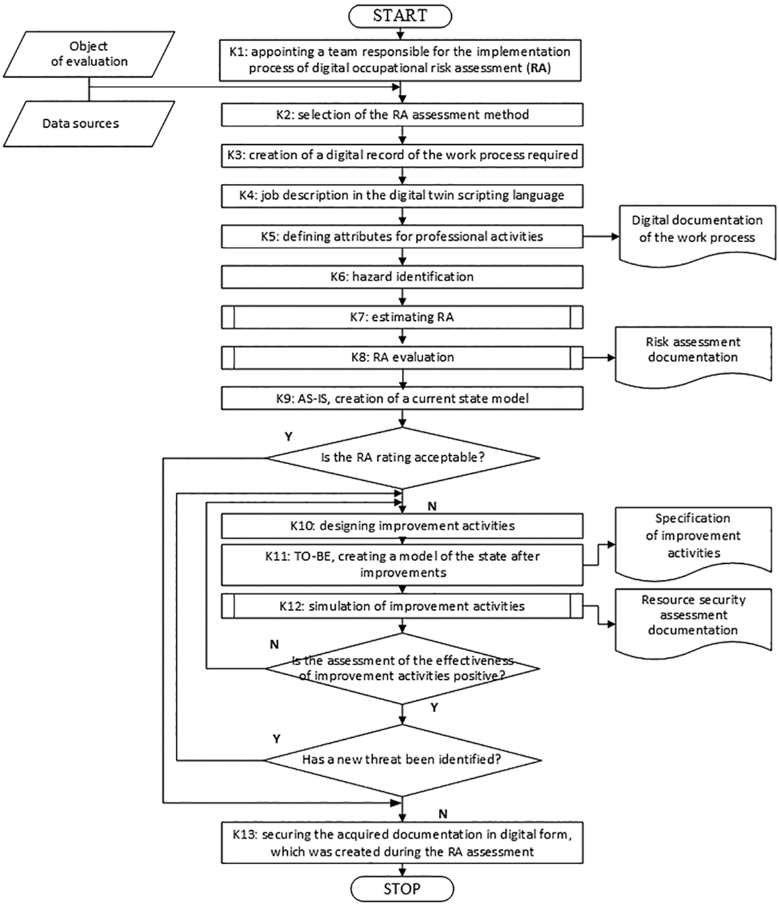


Figure 1. General scheme of occupational risk using simulation

Source: Authors' own study.

very important, as the quality of the entire process depends on their experience and knowledge. The next steps are closely linked to the professional competence of these people. On their decision-making depends the achievement of positive results in the implementation of improvement projects. Their first decision is to choose a specific method of risk assessment, since the scope of improvement of the work process directly follows from its specifics and limitations. In order to gain arguments for management decisions, also in terms of the effectiveness of work improvement, it becomes necessary to use virtual reality. The means to do this is the use of digital recording in step three of the method (K3), through which an opportunity is created to manipulate information on the availability of resources of a particular organization.

For the implementation of digital modelling, the authors used the model of the so-called digital twin in the fourth step of the method (K4), which in a fragment is shown in Figure 2.

Figure 2. View of the analyzed site of the 3D digital twin

Source: Authors' own study.

This is the source of a significant increase in the number of combinations of improvement projects. In step five (K5), the parameters of the occupational risk assessment me-method selected in step two are implemented into the virtual work process model. The digital documentation created in step five is developed with attributes for work activities according to the risk assessment procedure. The information obtained and processed in the previous steps is the basis for conducting hazard identification (K6) and performing occupational risk estimation (K7). Depending on the procedure for carrying out steps K6 and K7, the corresponding values for the identified risks and knowledge are obtained, which forms the basis for decisions in occupational risk management. In the eighth step (K8), digital documentation is created, with which it is possible to selectively, with the application of selection criteria, map the phenomena of interest and effectively design the process of improving occupational safety (Table 1, Table 2). The creation of the digital environment in the ninth step (K9) makes it possible to create a record of the current state model, which, depending on the availability of resources in a given organization, can be freely modified with the entire baggage of normative requirements, which are introduced into the system through attributes defined according to the appropriately selected method of occupational risk assessment (Figure 3). These attributes are:

- – mass,
- – lift height (difference in levels),
- – deposition height (difference in levels),
- – ambient temperature,
- – energy expenditure.

The weight lifted, deposited by the worker, is determined in PFEP (Pawlewski, 2018a) in a database that is an integral part of the digital twin and is automatically shown in graphs as a function of time – Figure 3.

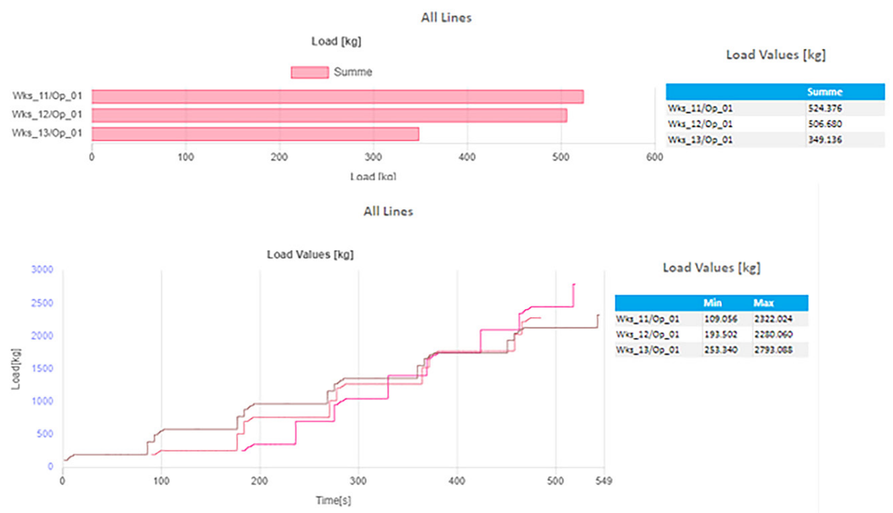
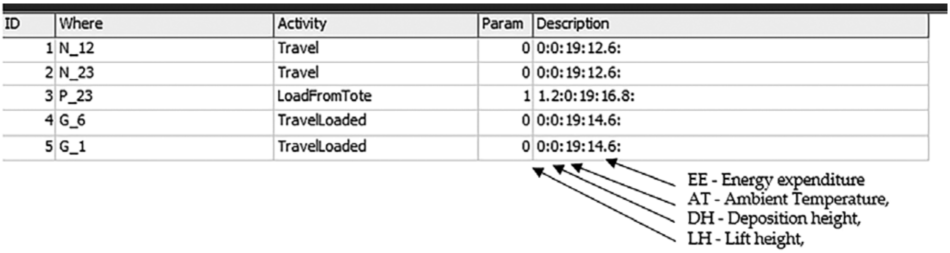


Figure 3. View of the employee weight load analysis chart

Source: Authors' own study.

The remaining attributes are assigned to the instructions of the language of work that is executed by workers. This is a high-level language for defining and assigning value-added attributes – this language is defined in Pawlewski (2018a), and its use in simulation is described in Pawlewski (2019, 2018b). For the purposes of the described research, it is pro- posed to modify this language by introducing the listed attributes (except mass) into the work instructions use for this purpose the Description field used in the in-structure format – LH:DH:AT:EE: where LH – lift height, DH – deposition height, AT – ambient temperature, EE – energy expenditure. An example of the use of the defined attribute format, which is an extension of the work language, is shown in Figure 4. The work cycle consists of transition (Travel) to point N_12, N13, lifting the load (LoadFromTote) from location P_23 and transition with the load (TravelLoaded) to points G_6 and G1.



ID	Where	Activity	Param	Description
1	N_12	Travel	0	0:0:19:12.6:
2	N_23	Travel	0	0:0:19:12.6:
3	P_23	LoadFromTote	1	1.2:0:19:16.8:
4	G_6	TravelLoaded	0	0:0:19:14.6:
5	G_1	TravelLoaded	0	0:0:19:14.6:

Figure 4. View of employee work cycle with proposed format of attributes associated with each work instruction

Source: Authors' own study.

From the tenth to the thirteenth step (K10, K11, K12, K13) in the presented method goes through the simulation of improvement activities and the search for a project due to the resource potential of the organization: situation plans, employee turnover, change of site equipment, addition of new work resources.

Implementation

The risk assessment method is a set of selection criteria for the created improvement action projects. In the presented research, the Manual Handling Assessment Charts (MAC) method was adopted as a suitable tool for assessing the RA of the order picking process under study. Already in step one (K1) of the method presented in the article, the rationale for the selection of the RA assessment tool due to the competence of those taking a methodical approach to the management of safety of a sustainable workplace is included. The authors point to the MAC method as an effective tool for evaluating manual warehouse work. It is a useful tool for studying phenomena when workers are exposed to injuries related to lifting, carrying and lowering loads. The criteria that enable RA to be valued using MAC are:

– lifting and lowering the weight (LH and DH attributes, mass),
– carrying – distance,
– environmental conditions – temperature and energy expenditure.

Load, which consists of the weight, size and shape of the load due to the way it is gripped:

– effort, which consists of the frequency of the activity and the characteristics of how it is performed, i.e. how far the loads are moved, and the height of the location of the loads relative to the worker's body modules,

– contextual working conditions, which include the working space and the quality of the surface during movement.

Consideration of criterion (1) indicated activities during the evaluation of lifting:

– due to the weight of the load, indicated activities for which the risk was de-ter-mined at the medium level. The performance of professional activities should then be corrected. In a cross-sectional search of digital records in an Excel application sheet, a selection criterion (filter) was applied: cargo weight type of pack-aging (Table 1),

– due to the size and shape of the cargo, activities were indicated for which the risk was determined to be medium. A cross-sectional search of digital records used the selection criterion: type of packaging (Table 1).

Table 1. List of worker's activities during which the worker lifts heavy goods and moves with a load (excerpt)

Observation content	Weight good [kg]	Place	Energy expenditure [kJ/min]	Energy expenditure for a given work activity [kJ]	Body position
Lifting pallet 1	25	Pallets outdoors (large temperature difference in summer)	12.6	1.89	lifting
Picking up lettuce from the lettuce pallet from the cold store 3	16	Cold room 3	12.6	0.84	lifting
Putting tomatoes on pallet 1	24	Picking station	25.1	2.51	lifting
Picking apples from a pallet in the warehouse	30	Warehouse	35.1	3.56	lifting
Picking zucchini from a pallet in a cold store	10	Cold room 2	25.1	1.67	lifting
Picking beets from a pallet in the warehouse	10	Warehouse	25.1	2.09	lifting
Picking bananas from a pallet with goods in stock	10	Bananas	25.1	1.67	lifting
Getting cartons of lime (the lime covered the avocado)	20	Cold room 1	40	2.00	lifting
Rearranging lime boxes	20	Cold room 1	40	4.0	lifting
Picking up sauerkraut from the pallet (2 buckets)	10	Pickled	25.1	2.09	lifting

Source: Authors' own study.

When considering criterion (2), activities were indicated in terms of the distance over which loads are moved. In a cross-sectional search of digital records, a selection criterion was used: moving with load (Table 1), for which the risk was determined to be medium. An in-depth study of the course of occupational tasks should then be carried out. When considering criterion (3), activities related to environmental factors were indicated and activities that require staying in a significantly different microclimate environment were indicated. In a cross-sectional search of digital records, the selection criterion used was: ambient temperature with a load for which high risk was determined. An immediate response is needed. A significant proportion of workers may be exposed to the risk of injury.

Discussions

Occupational risk assessment is used specifically to analyze the work process, which aims to detect threats, recognize them and introduce measures to improve and limit the harmful impact of the work process on the employee, and thus improve working conditions. All this leads to increased work efficiency and reduced costs. There is a close relationship between proper working conditions and the final financial result of the company. Reducing the impact of harmful and dangerous factors on the employee increases the quality of work, which translates into its efficiency, and at the same time limits the number of days of inability to work caused by poor environmental conditions (e.g. microclimate) and accidents at work.

In the presented research, the MAC method was adopted as an appropriate tool for assessing occupational risk. The analysis of the sequence of manual transport work activities showed that the load on the employee's musculoskeletal system presented in the tables was too high. Applying improvement activities to the analyzed experimental situations, it is assumed that, among others, the following will be carried out: simulations of the implementation of the following elements of humanization of work.

For a situation in which activities are indicated when assessing the lifting of load weight and specific risk at an average level, it is assumed that a simulation of the use of 2 or 4 transport trolleys will be carried out. It is assumed that situations that may result in the crossing of transport routes will be recognized.

For the situation in which activities are indicated when assessing the size and shape of the load and the specific risk at an average level, it is assumed that a simulation of the use of various types of transport trolleys will be carried out.

Only by simulating the schedule of professional activities in the context of various projects implementing elements of humanization of work can the implementation of the concept of sustainable workplace safety management be optimized.

Practical issues are also an important aspect. The accuracy and reliability of the ergonomic risk assessment are highly dependent on the quality and completeness of the collected data. Therefore, it is important to implement robust data collection protocols, ensure regular calibration of sensors and validate data through cross-checking with manual observations. Employees or management may resist implementing new technologies due to lack of understanding, which is why it is important to provide comprehensive training programs and ongoing support. It is also worth investing in high-performance computing resources for faster data processing, as real-time monitoring may require constant data streaming and fast processing capabilities. Sensors and other monitoring equipment may require regular maintenance and calibration to ensure accuracy, which is also important to establish, for example, a maintenance schedule. The mentioned practical solutions to the identified problems are crucial for the successful implementation and, above all, operation of the proposed ergonomic risk management method. By proactively identifying and mitigating these challenges, companies can increase the effectiveness of their occupational risk management strategies, ensuring a safer and more productive workplace.

Conclusions

Continuous improvement of occupational safety requires estimating the availability of an organization's resources for implementing improvement projects. As a result, the post-improvement issues undertaken by the authors also fit into the area of resource security. The adopted goal of the research was realized and the research questions were positively answered.

The research presented here assumes that the evaluation of the effectiveness of projects to improve occupational safety is crucial. Both the criterion of availability and efficiency of resources requires an environment in which it is possible to simulate these solutions. This environment is the LogABS (www.logabs.com) tool discussed in the article, which allows embedding work operations in the 3D space of the work environment. At the same time, it minimizes the time for model preparation, batch data and solution variant checking phases. The digital twin-considering the approach focused on work operations (and not on object states typical of simulation solutions based on the DES Discrete Events Simulation concept) opens up new directions for the study of workload in the context of potential accident situations. The created environment of the digital twin of the work process may, in the near future, assist in balancing demanding work activities and in managing a sustainable workplace.

The main objective of the article was to develop a new approach to occupational risk management using advanced digital and simulation technologies to ensure a sustainable workplace. This objective was achieved by creating a method that integrates dynamic environmental factors and individual employee needs into the occupational risk assessment process. The research has shown the effectiveness of using simulation tools in embedding work operations in a three-dimensional workspace, thus increasing the accuracy of risk assessment and facilitating the implementation of effective countermeasures. Digital twin technology, which focuses on work operations rather than on the states of objects, has opened up new possibilities for studying workload in potential accident scenarios and has significantly contributed to the development of occupational safety management.

Directions for further research should focus on several key areas: human factor analysis – future research should investigate different human-centered risk assessment methods to better capture the complexity associated with human behavior and decision-making in the workplace; integration with other risk assessment methods – this may include a combination of quantitative and qualitative methods to capture a wider range of risk factors; application of the method across industries – extending the application of the proposed method across industries, particularly high-risk industries such as construction, mining and healthcare, will help confirm its effectiveness and adaptability, and comparative studies across these sectors can provide valuable insights into industry-specific challenges and solutions.

By addressing these areas, future research can further refine and optimise occupational risk management practices, contributing to safer and more sustainable workplaces worldwide

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