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Ergonomic Reengineering of Real-Time Human-Machine Interaction as a Safety Component of Modern Manufacturing Technologies

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Abstract:

Purpose: *The aim of the research presented in the article is to validate the method of ergonomic reengineering (RE) of human-machine interaction in a new environment of real-time data implementation due to the safety of using modern manufacturing technologies. In the research process, a procedure analogous to the cyclical model of the chain reconfiguration of the use of automated devices, which is characteristic of Industry 4.0, was adopted.*
Methodology: *Ergonomic reengineering of human-machine interaction enables the incorporation of knowledge about the symptoms of psychophysical overload into the area of technique design. Modelling the phenomena occurring in the environment of the employee is a source of information on the mechanisms regulating working conditions for maintaining the optimal level of the task load. In difficult and extremely difficult situations, the RE method can be used for system solutions, which consist in providing alternative workflows for performing specific tasks using the resources of the entire organization.*
Findings: *The results of experiments at workplaces confirm the correctness of the research assumption: the evaluation of the employee's functioning in real time with the use of devices monitoring the physiological state can be effectively used in the process of improving the safety of using modern manufacturing technologies.*
Practical Implications: *The conducted experiments with the use of motion sensors and devices monitoring the physiological state of an employee in Industry 4.0 maL16de it possible to observe factors influencing his functioning at work. Among other things, those that potentially threaten human health or life, and result from various nuisance factors. During a shift, an employee, with increasing fatigue, may perform the same learned tasks in a less safe and different way, which is a potential cause of work safety hazards.*
Originality Value: *The added value of implementing ergonomic reengineering with the use of IT products is to obtain, concurrently to the production process without interference and interference, the profile of resource requirements for the optimal load in each workplace.*

Keywords: *Ergonomic engineering, human-machine system, motion capture, production process, work safety.*

JEL Classification: *M2, L16*

Paper type: *Research article.*

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1. Introduction

Ergonomic reengineering (RE) is a method of profound transformation of the process due to the limitations related to the psychophysical abilities of the person participating in it (Tillman *et al.,* 2016). In practice, RE aims to optimize the level of the workload of the employee with the technical elements of the production process. Due to the complexity of modern technological installations, most of them are automated devices. The tasks of a man cooperating with such a technique fundamentally change the nature of executive activities. After introducing the IT system for the operation of production devices, we receive a profile of requirements at the workplace, which only minimally resemble the requirements set in the period preceding the implementation. An employee whose tasks previously focused on monitoring the means of work performs operator tasks and manages information. From a situation of a specific physical stress, one moves on to working conditions that result in a high level of mental and postural stress.

To formalize the process of obtaining and recording data for the modelled work environment of operators of modern production technologies, a cyclical model of the chain of use reconfiguration was proposed (Sławińska, 2019), but modified due to the use of devices monitoring the physiological state of the employee in real time. The recalled model comprises 10 stages, and the modified model - 3 stages. Instead of steps 1 to 4, - 1 was introduced. Previously, the point of modifying the course of the work method was the conclusions from the ergonomic diagnosis and the determined need for radical changes, then creating a record of the course of activities at the position, which was a point for assessing the situational context, then the ergonomic occupational risk factors and on this basis to determine the number of potential overloads.

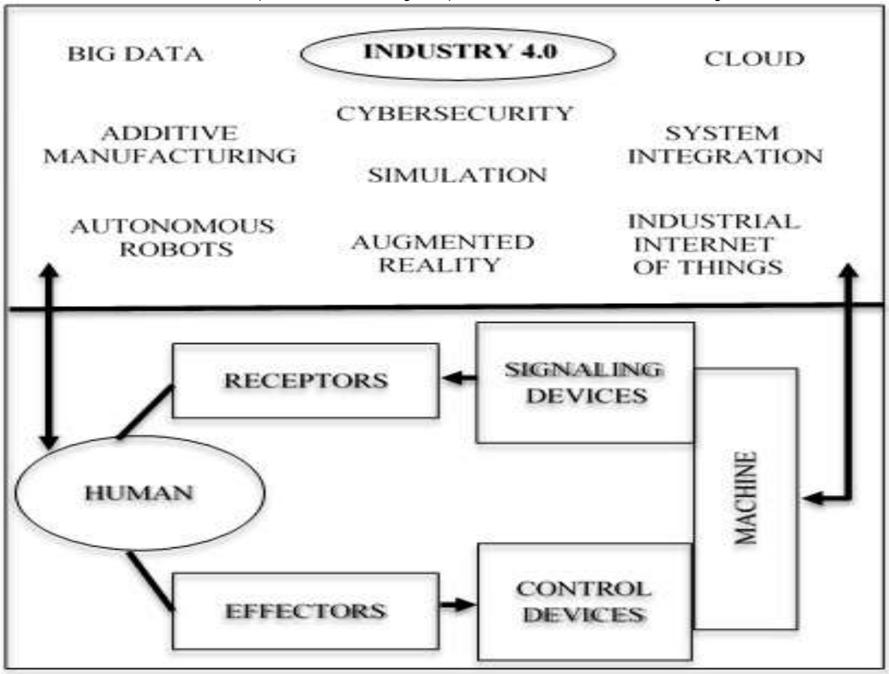
The proposed, modified RE method starts with the current stage 5 - defining indicators and measures to assess the effectiveness and efficiency of target tasks. At stage 2, data is acquired and recorded during task monitoring and the automatic determination of compliance levels for the adopted ergonomic assumptions in the process of improving work safety. Stages 6 and 9 are combined - testing the load level and conformity assessment for ergonomic assumptions in the work system validation process. Stages 7, 8 and 10, which included estimating the costs of the effects of undesirable system operation, assessing optional technical solutions, and defining the goals of ergonomic modification, go down to stage 3. This is done with access to knowledge located in artificial intelligence systems and the automatic decision-making guidance is sought. generated with the use of IT technology based on the organisation's system resources (Sławińska, Derbich, Ewertowski *et al.,* 2019).

The ergonomic approach to designing the work process is consistent with the postulate of individual adaptation of technical means to the employee's abilities. It is assumed that the technical subsystem must be compatible with human performance. Not considering the possibilities of man and his dynamics in creating a new technique, the designers seem to "inscribe" a human error in the created system. The presence of such different factors as machines, people and information in the discussed systems requires finding a coherent, synthetic method of monitoring them. Such opportunities are provided by modern information technologies (Cao *et al.,* 2016; Ma'touq *et al.,* 2018).

2. Man-Machine Interaction in Manufacturing Process

To begin with, it is important to understand the role that man plays in the production process. Industry 4.0 focuses on the use of the latest technological solutions and distracts our thoughts from the topics related to the workload of the employee. Below is a simplified drawing showing the impact of Industry 4.0 on the human-technical system in the working environment (Figure 1).

Figure 1. *Human -machine (technical object) interaction in Industry 4.0.*



Source: *Own study.*

The above figure lists the elements of the modern human-machine system, i.e., large data sets, autonomous robots, simulations, system integration, the Internet of Things, cybersecurity, cloud computing, additive manufacturing, and augmented reality. All these elements are used in a work environment where there is a person receiving signals from devices with receptors and controlling machines with the help of effectors. In addition, the employee is also influenced by material factors of the working environment as well as technical and organizational factors.

Considering all these factors, it is not difficult to conclude that there are too many elements of the work environment that affect the employee. And along with adding more in the closer and more distant environment, due to the specificity of Industry 4.0, the workload of the employee at the workplace increases dynamically. Of course, modern technologies, intelligent machines, efficient communication between machines and humans are needed, but you must take into account both the advantages and disadvantages of introducing new technologies into the work environment.

When writing about the human-technical system interaction in the context of Industry 4.0, we must define specific work safety requirements in this context. Due to the scope of the discussed problem, the authors focused on the issue of using modern technologies for communication between man and machine.

Mental overload when performing operator tasks is a commonly observed phenomenon. During the use of information technology, the nature of most tasks changes dramatically. A feature of the new work environment is low physical effort, the need for constant tension of attention: supervision, tracking, control, correction, high monotony, minor manipulative activities, lack of movement, significant mental and intellectual overload or underload. The basic sources of human psychological burden are information and threat.

Numerous workplaces related to automation require varying degrees of mental effort, conditioned by the inflow of information, its quantity, complexity, variability and accuracy. The more complex and variable information a person perceives, the more effort he has to make decisions, the more complex activities he has to perform in the work process. At the same time, it should be remembered that the load is not a constant property corresponding to the specific abilities of the person performing the task, but rather results from the interaction between:

- requirements included in the task,
- the circumstances in which it is performed,
- skills,
- abilities,
- human perception.

Therefore, it should be assumed that new technologies that are used in the work process require new methods in diagnosing the environment of human-machine system interaction.

3. Safety of Use of Modern Manufacturing Technologies

In the use of modern production technologies, the operator plays a unique role as a "reserve" of the control system, which means that he takes up additional tasks when technical elements fail. In the event of a security threat, it is an element of functional excess in reliability structures (Jaźwiński and Ważyńska-Fiok, 1993). As a result of the above, we can conclude that due to the integration of human and automated devices, the level of ergonomics reflects the level of reliability of the entire system. It is becoming important to adequately define the safety requirements for modern human-machine systems. They must be carried out with reference to the characteristics of the "components" of the operator's operation that occur in the operator's working method and result from the following six situations.

First: when rigid and unambiguous instructions are imposed on a man, then the conditions make his action completely algorithmic. Secondly: creating conditions in which planning of action is excluded and man is forced to work according to landmarks. In such "algorithmic" operation, fatigue quickly develops, and the operator's reliability becomes low due to loss of interest in the work. Thirdly: information about a controlled process is transferred in a form that does not guarantee its development, and sometimes even makes it difficult to predict. This makes it impossible to plan activities, which leads to omissions, errors, and refusals in the operator's work. Fourth: it is allowed to permanently cause information overload and expose the operator to the stress associated with it. Fifthly, information concerning negative slow-changing phenomena and reducing knowledge about them in the context of occurring events is pushed to the background. Sixthly, by imposing on the operator to perform the function of a "backup element" of automation, it is allowed to assume a passive position of an observer for a long time, which leads to the target moving or its "loss". Activities then become chaotic or even stop altogether. The phenomena determine situations that are difficult for humans and require the risk of occupational safety as well as human health and life to reduce the risk of failure (Zwolankiewicz and Czernecka, 2018).

4. Ergonomic Diagnosis

4.1 Monitoring Human-Machine Interactions

The diagnosis of modern manufacturing technologies is focused on the assessment of the degree of adaptation of the work process to the psychophysical abilities of a person, i.e., the way of cooperation with the system via the user interface in a specific workplace. This indirectly relates to the assessment of workplace equipment and the assessment of the employee's functioning space (Sadłowska and Racek, 2021). Comprehensive diagnosis of technical and social systems is made in the context of the forecasted health and life-threatening situation and the anticipated situation of reduced efficiency and effectiveness of the system (Ewertowski and Berlik, 2020). In the diagnosis of the conditions of human cooperation with a technological device via an interface, the subject of research is the executive activities of decision-making processes.

Therefore, decisions to modify the work system are made based on the assessment of the level of perceptual load and postural load. This requires the use of diagnostic tools that make it possible to link design criteria with inference about the effectiveness of reconfiguration of the work system elements in real time (Berlik, Dahlke, and Sławińska, 2018). The tools that justify ergonomic modifications include, first, subjective methods of mental stress and the analysis of human reliability indicators. Diagnostic tools are selected according to the complexity of the work system. If the interface of a technical device is modified, the ergonomic diagnosis can be based on the results of the standard checklists. If the subject of research is a complex technical and social system, then the diagnosis is made using a comprehensive approach appropriate for macro-ergonomics. It should be remembered that in every situation the direction of research is determined by both:

- ergonomic factors,
- the purpose of the system,
- complexity of the operation process,
- the nature of the reliability functional structure of the work system.

Due to the variable nature of the load and to recognize the significant factors of the intensity of the load during the interaction, the following stages were distinguished in modelling the situation of signal detection: 1- the stage of acquiring and processing information; 2 - the decision-making stage; 3 - the stage of performing the activity itself. Ad.1. The stage of obtaining information is based on direct observation of the task and the instruments needed to perform it. In this phase, the main emphasis is on the perception of a variety of visual, auditory, and tactile information and the appropriate response to them. This results in the absorption of certain mental resources, especially memory and attention. The more complex a device is, the more information and knowledge is needed to properly handle it and get the job done correctly. Because human memory has a limited capacity, such a situation may lead to serious mental overload and become a source of threats to human health and life.

Ad.2. The decision-making step is where an operator needs to act with more than one piece of information. In the case of repetitive decisions, which are usually taken quickly, or even instinctively, the mental effort associated with them is not great. However, if the decision to be made is more complex, requires the use of a large amount of information, often incomplete, and is associated with a lot of responsibility, then the mental burden is greater.

Ad.3. In the last phase, which is directly related to the fact of deciding, human effort is mainly physical. Also, at this level there is a load on the nervous system. It depends primarily on the complexity of the work performed, the degree of skill, the typical or unusual nature of the movements, and especially the consequences of their execution.

By shaping the conditions of the work system in terms of ergonomics, decisions are made to redesign the process with detailed knowledge of system goals. The selection of essential criteria for the redesign of operation processes is consistent with the criteria for the performance characteristics, which include, among others:

1. performance criteria, which are adopted to assess the functioning of the components and the operating environment and their impact on the system's ability to function without failure over a specified period of time;
2. the operational criteria by which the situations of improving the efficiency of the operation process are assessed, they are needed to evaluate the operation and the degree of achievement of the intended needs;
3. information criteria, which are adopted to evaluate the organization of the system and information processes flows and the influence of the control system on the operation of the whole;
4. technical criteria against which the quality of the elements and means of operation as well as the effect of the technique on operation are assessed.

The ergonomic aspect in the redesign of the operation processes determines the priorities in categorizing the level of significance of the above criteria (Tytyk and Butlewski, 2011). By examining the time characteristics of the intermediary variable, i.e., the value of the load level with the use of available real-time indicators, the stage of selecting the criteria for optimizing the conditions for the functioning of the system is significantly shortened. The use of modern IT tools to monitor the parameters of the psychophysical state of an employee, we can pay attention to the important phenomena accompanying the increasing level of fatigue, which result in the occurrence of undesirable situations in the workplace (Kubasiński, Piechocki, and Sławińska, 2019).

4.2 Benefits from Real-Time Research

By choosing real-time research, we can achieve better results than using other forms of observation and data logging. Some of the benefits of real-time research are listed below. Investigating nuisance factors in real time can contribute to the prevention of accidents at work. By observing the factors affecting the employee in real time (the presence of a researcher in the workplace most often changes the conditions), we can specify activities that potentially threaten the health or life of the employee (Tobón, 2010). During a shift, the worker, under the influence of increasing fatigue, may perform the same activity differently and less safely, which could potentially cause an accident.

Tests carried out after an accident may prevent another dangerous event but will not reverse an event of loss of health / life of an employee that has already taken place. They are based on data that can be obtained after the accident, which is largely the initial data. Input data - such as the workload of the employee, the way in which he performed activities - may at this stage be no longer available or largely false. The injured employee, as well as other employees, are not able to objectively assess the factors that may have led to the accident event. Moreover, there is a reasonable and considerable risk that the cause of the accident will be determined superficially, without considering the factors contributing to the burden on the injured worker and / or the worker who indirectly led to the hazardous event.

Real-time research allows for faster output generation, additionally, the generated data is much more accurate. For example, we can measure an employee's pulse during an 8-hour shift and based on objectively obtained numbers we can assess the increase or decrease of the heart rate during the performance of given activities or correlate with the working time.

In other forms of research, we usually rely on input data received from the company or employee surveys. We are not able to objectively assess, for example, stressful situations based on measuring the employee's heartbeat in real time. Surveys can often be misrepresented due to various factors, such as the human factor, because the employee is not able to objectively assess the perceived degree of fatigue, the pressure factor, e.g. during the manager's control when conducting research.

Real-time research allows for faster introduction of necessary changes at workplaces. Conducting research in real time enables faster results and drawing conclusions during the research. Faster obtaining the results of an ergonomic diagnosis may be of key importance for employees working in highly stressful positions, it will allow for faster finding of solutions that relieve the employee. In real time, you can propose preventive solutions that do not require major changes and that can prevent potential accidents.

Communication with the management during the audit in real time is much easier, changes can be argued on an ongoing basis (Walkowiak and Sławińska, 2020).

The process of running a study in non-real time usually takes longer, as does obtaining results. A proposal of possible changes at workplaces may be presented only after a thorough reading of the research material. During the analysis of the obtained results, the employee continues to work at the workplace that is onerous for him, during which time the existing nuisances for the employee may intensify or an accident at work related to employee fatigue may occur. Communication with the management is difficult in the case of exchanging e-mails, non-verbal translation, the need to make changes in the workplace (Ewertowski, Berlik, and Sławińska, 2020).

Real-time research allows for a more detailed analysis of factors in the workplace and preferably from synthetic data. The basic element of modern technologies supporting the measurement of human load in the context of Industry 4.0 are motion sensors. The name itself contains a definition - literally translated, these are devices that allow you to capture the changing position of the body during movements (Tarabini *et al.*, 2018a). They allow for real-time analysis of movement by attaching sensors to specific parts of the body. The sensors for measuring the workload of an employee in the work environment, which are used by the authors of the article, are based on the principle of inertia. The measurement is made in inertial measurement units (IMU) - it consists in reading data on linear and angular motion using three elements:

- gyroscope - a device that allows observation of the rotation of the body to which it is attached. Most often it is made as a fast spinning, rigid object suspended in a structure that allows it to rotate freely in relation to the reference system. (https://fizyka.uniedu.pl/);
- accelerometer - a device that converts the vibration energy of an object into an electrical signal proportional to the instantaneous acceleration of the object. It enables the determination of the angle of the measured object from the vertical (https://www.tme.eu/);
- and a magnetometer - used to measure the magnitude, direction and changes of the magnetic field.

They allow for the precise definition of all movements that an employee performs during a shift. Of course, we also need software that allows us to collect data and map the workplace. The sensors presented above are compatible, among others, with the software used in the research conducted by the authors of the article, ViveLab Ergo, picture no. 2, allowing for an accurate mapping of the work process, setting parameters, see, anthropometric parameters, and automatically calculating the load on a given position for a given employee using the OWAS, ISO 11226, EN 1005-4, NASA-OBI and RULA methods.

Therefore, using modern technologies, such as motion sensors and appropriate software for ergonomic analyzes, we can collect large amounts of data on employee loads, which is a very important element in creating interactive human cooperation with the technical elements of the system. In the context of Industry 4.0, we can use this data by creating a system that sends information about employee fatigue to machines. Machines receiving such information can regulate the pace of the technological route. This is because an employee experiences a different level of fatigue during an 8-hour shift, which affects the tasks performed by him and their degree of efficiency. Thus, by tracking the well-being of an employee, we can control the possibility of making mistakes on an ongoing basis, and thus minimize the number of adverse events and, consequently, accidents at work. Fewer accidents at work are associated with the lack of financial and social losses for the company.

Figure 2. *ViveLab Ergo software*

Source: *https://www.enginsoft.com/solutions/vivelab-ergo.html*

Designing workstations in accordance with the most recent knowledge of ergonomics and psychophysical capabilities of the operator significantly contributes to the reduction of the task load and increases its reliability. Often, ergonomics is associated with physical stress, including the prevention of musculoskeletal ailments. At the same time, the issue of mental strain is neglected. The modern approach should aim at the fullest possible perception of a human being in the human-machine-environment system. Modern technologies create opportunities for a wider diagnosis of both factors generating physical and mental stress (Tarabini *et al.*, 2018b).

A characteristic feature of Industry 4.0 is the collection and processing of information in real time. It is important not to limit yourself only to technical objects. Modern technologies also create new possibilities for monitoring operator parameters, which can prove very helpful in process management. The miniaturization of electronic devices as well as the universality and reliability of wireless connections have made it possible to record many physiological parameters of an employee during work. This is an important element of system monitoring, because due to the increasing reliability and continuous improvement of technical facilities in many fields of technology, the key element from the point of view of system reliability is human.

The analysis below focuses on heart rate measurement as one of the parameters, the results of which can be easily and cheaply recorded and interpreted. The heart rate level, or heart rate, increases with increasing physical load and / or stress levels. Monitoring this parameter makes it possible to observe changes in the load to which a person is subjected. (Makarowski, 2010). There are many methods of heart rate measurement, the following are the most useful devices for monitoring changes in the operator during operation:

- pulse oximeter - a device that measures the level of pulse and blood oxygenation. Worn on the finger of the examined person. Its usefulness is small due to the discomfort caused by the compression of soft tissues and difficult performance of activities. It is used in short-term tests that do not require complicated activities with the hand on which the device is mounted;
- heart rate monitor worn on the chest - receives the signal from two electrodes attached to the chest with a special, flexible belt. Provides an accurate measurement of your heart rate without interfering with your work. It can be used for hours, although the test subject may experience slight discomfort. It is characterized by an accurate measurement, sensitive to very short-term changes. Particularly useful during tests on positions where the load changes rapidly;
- wrist heart rate monitor - heart rate monitor in the form of a wristband. It emits light using an LED diode and registers the pulse based on changes in the characteristics of the light reflected from the tissues of the outer side of the hand caused by blood flow in the tissues. Most often, these devices are less accurate than chest pulse monitors or pulse oximeters, but their advantage is the comfort of use. This type of heart rate monitors is more and more often equipped with watches that allow you to measure the heart rate around the clock. A serious disadvantage of these devices is their displacement in relation to the tissues during movements (e.g., twisting or bending the wrist), this may result in distorted results or even a break in the recording;
- smartwatch - an increasingly common device in the form of a wristwatch. However, it is equipped with several functions they enable, among others heart rate and blood pressure approximation, location logging, step count, altitude, daytime activity and sleep quality.

The use of smartwatches allows you to obtain a lot of information about the operator and the factors affecting the safety and quality of work performed by him. At the same time, using an appropriate application, the device can generate tips for the user on leading a more hygienic lifestyle, such as sleeping times and times, increasing physical activity, etc. It can also remind at appropriate times about the need to take appropriate measures to maintain good shape. The disadvantage is the lower quality of the measurement compared to other forms, although it is constantly improving. Like wrist heart rate monitors, it is prone to measurement errors when making sudden movements.

Due to the low sampling frequency, most devices of this type are not suitable for measuring sudden and short-term changes. It is perfect for long-term recording of parameters. Selected models of all the above-mentioned device groups allow you to measure and transfer results in real time, save them on the device memory or on another device, e.g., a smartphone. It should be remembered that individual characteristics play a large role in the interpretation of the results. They should be considered when interpreting the results, and devices should be properly calibrated.

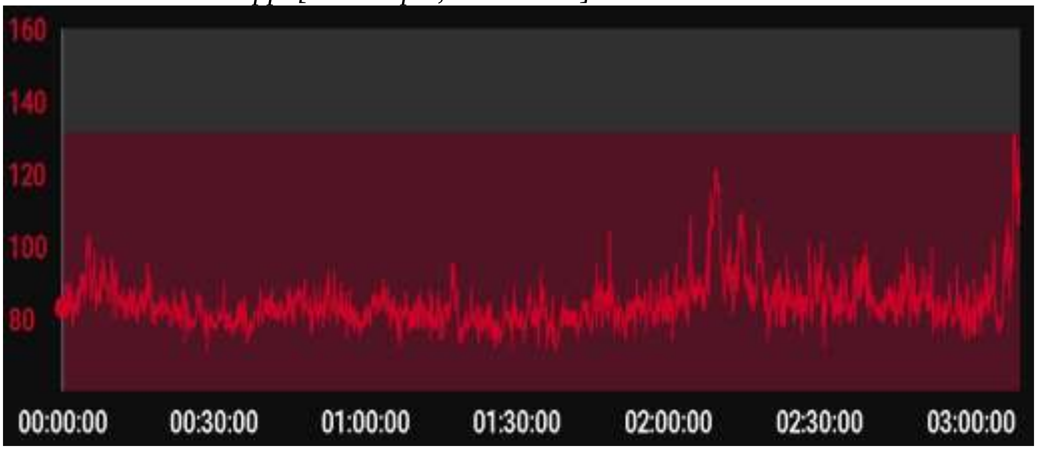
5. Conclusion

Application of the above-mentioned devices and real-time data transmission to the system or control station can bring significant benefits to the functioning of the entire system, its efficiency and, very importantly, human well-being. An example of a graph showing changes in heart rate during work is shown in Figure 3. Several applications are listed below for monitoring the status of an employee's physiological parameters with simple devices:

- adjusting the pace of work - the system by estimating the current level of the employee's heart rate helps to optimize the level of the employee's workload, e.g., by adjusting the work pace to his capabilities. This can be done by changing the number of tasks to be performed at a given time by an employee or redirecting tasks to less busy operators;
- assessment of the load caused by the performance of tasks - by monitoring human parameters, we can estimate the level of load caused by the performance of specific tasks. The collected data can be used for better planning of tasks, so that, for example, more time can be allocated to the performance of tasks that generate more workload, the way the work is performed or another form of relieving the employee;
- capturing positions and tasks generating the greatest load - test results may indicate positions that require an in-depth ergonomic diagnosis and possible corrective actions;
- a diagnostic factor for an occupational medicine physician - it can help in the overall assessment of health condition and facilitate the implementation of appropriate health prophylaxis by the physician, issuing possible recommendations regarding a healthy lifestyle, referral for additional diagnostic tests or consultations with a specialist;
- estimation of energy expenditure - based on the measurement of the pulse, it is possible to estimate the oxygen consumption, which indirectly enables the estimation of the employee's energy expenditure;
- diagnosing difficult and dangerous situations - a sudden increase in heart rate may result from a stressful situation. A high heart rate level can be a warning signal of danger to the operator's supervisor, as well as an increased likelihood of making a mistake;
- indicating people who are overloaded and underloaded with work - based on the interpretation of physiological parameters and other aspects, the person managing the work process may, for example, direct employees to help a person who is particularly burdened at a given time;
- alerting in life-threatening situations - the system can inform the command post about a possible threatening situation in the event of failure to register the employee's pulse, which may indicate, for example, a sudden cardiac arrest;
- intelligent management of breaks at work - the collected data can be the basis for the automatic directing of the operator to a break by the system in the event of a high physical load or inactivity. In industry 4.0, it is possible to modify the course of the process or select a convenient moment so that it is a time that is beneficial both for

the employee and from the point of view of the process flow. The system may suggest a form of taking a break, depending on the way you work (passive rest or physical activity - it is possible to suggest appropriate exercises).

Figure 3. *Graph showing the employee's pulse in beats per minute during work, obtained with the Polar Beat app. [Y axis bpm, X time unit]*



Source: *Own study.*

Despite the benefits of monitoring the condition of an employee, it also entails serious risks. They are related, inter alia, to the protection of privacy of persons subject to monitoring. This may be met with reluctance on the part of employees to submit to monitoring. There are also concerns about the use of such sensitive data. The authors' task is to take appropriate legislative action and use common sense. It is essential to find the right balance between obtaining data that is useful in terms of the process, and maintaining the privacy of people subject to monitoring, which will be a real challenge. This problem will have to be examined by specialists from various fields: engineers, lawyers, but also philosophers, sociologists, and psychologists.

The use of modern technologies in the work environment can bring both benefits and threats. As indicated in this article, testing employee load in the work environment may contribute to the improvement of the quality and safety of use of modern fuel technologies, such as those found in Industry 4.0.

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