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Fatigue Monitoring with IoT-based Ergonomic Approach: Case Study in the Wood Processing Industry

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ABSTRACT

Work fatigue in heavy equipment operators can reduce productivity and increase the risk of work accidents. This study aims to design an Internet of Things (IoT)-based work fatigue monitoring system with an ergonomic approach to monitor the physical condition of operators in real-time in CV. Wana Indoraya Lumajang. This system measures working pulse, oxygen saturation, temperature, humidity, and calorie expenditure using a smartwatch whose data is processed through a cloud server. The research method involved the physiological measurement of the operator over six working days, with two daily measurement sessions. The results showed that the average operator's pulse rate was 149.5 pulses/minute and calorie expenditure reached 598 kcal/min, indicating a heavy workload. In addition, a decrease in oxygen saturation as well as a rise in temperature and a decrease in air humidity in the workspace worsen fatigue conditions. 149IoT monitoring systems are effective in monitoring operator fatigue conditions in real-time, and can help supervisors in taking preventive measures to reduce the risk of accidents due to work fatigue.

Keywords: Work fatigue; internet of things; ergonomics; heavy equipment operator; pulse

INTRODUCTION

The wood processing industry is one of the rapidly growing industrial sectors in Indonesia. This growth has been accelerated due to the ban on the export of raw logs, as stipulated in the Regulation of the Minister of Trade of the Republic of Indonesia No. 20/M-DAG/PER/5/2008 concerning the export provisions of forest industry products. Workers in the wood processing industry operate heavy machinery for both production processes and the transfer of materials from one location to another. According to data from the World Health Organization (WHO) and the International Labour Organization (ILO), a significant portion of accidents involving heavy equipment operators are caused by work fatigue resulting from heavy workloads and long working hours.

The work climate is a combination of temperature and humidity, as well as the body's heat radiation, involving the interaction between temperature, humidity, air movement speed, and radiation heat with the body's heat dissipation levels. A hot environment increases body temperature, causing sweat to be secreted onto the skin's surface. Sweat contains sodium chloride electrolytes, which reduce the muscles' ability to contract, leading to fatigue(Asyulia et al. n.d.).

Work fatigue can be identified through various indicators, with the most commonly used being the increase in heart rate. According to Nurmianto (2008), if the increase in a worker's heart rate is still ≤ 30%, it indicates no fatigue. If the increase is between 30% and 60%, the worker is slightly fatigued. If the increase is between 60% and 80%, the worker is moderately fatigued. An increase of 80% to 100% signifies severe fatigue, and if it exceeds 100%, the worker has reached an extreme level of fatigue. Workload can be determined by measuring the heart rate (Nurmianto 2008). research found that a normal workload is indicated by a heart rate ranging from 100 to 125 beats per minute. If the heart rate is between 125 and 150 beats per minute, the workload is categorized as heavy, and if it exceeds 150 beats per minute, it is considered an extreme workload.

Based on global data from the WHO and ILO, in 2016 there were approximately 1.9 million deaths related to occupational risk factors worldwide. Of that total, 19% were caused by workplace injuries, while 81% resulted from occupational diseases, such as chronic obstructive pulmonary disease and ischemic heart disease. The primary factor contributing to work-related deaths is long working hours, which accounted for about 745,000 deaths due to stroke and heart disease. Additionally, data from various countries show that fatal workplace accidents occur at different rates. For example, in the United States, the fatal accident rate in 2018 was 5.2 per 100,000 workers, while in countries like South Korea, it reached 4.3 per 100,000 workers in 2021. The agricultural and industrial sectors tend to have higher fatal accident rates compared to the service sector. Globally, Southeast Asia and the Western Pacific regions have higher work-related death rates than the global average, with Southeast Asia recording 45 deaths per 100,000 working-age population (World Health Organization 2024).

The workflow of this monitoring system begins with data collected using Bluetooth Low Energy (BLE) technology, which wirelessly transmits the data to a cloud server. The data is then processed and displayed on a user interface based on the database using "node-js." As outlined in the problem above, work fatigue and workload can affect productivity. The higher the fatigue and workload, the lower the productivity. Therefore, a system is needed to monitor levels of work fatigue and workload. This research aims to design a work fatigue and workload monitoring system model with an ergonomics approach based on the Internet of Things (IoT).

The design of this monitoring model focuses on integrating IoT technology with ergonomic principles to create a system capable of collecting real-time data on the physical conditions of heavy equipment operators in the wood industry. Data processing is carried out using an algorithm designed to detect work fatigue. This system provides real-time information on the fatigue levels of heavy equipment operators to both the safety officer and the operators themselves. With this system, safety officers can remotely monitor the condition of heavy equipment operators, even as they move from place to place. Additionally, operators can better understand their own conditions, enabling them to prevent workplace accidents earlier.

WORK FATIGUE

Work fatigue is a major issue frequently faced by workers (Izzati & Ardyanto 2019). In this context, workers in the wood industry are subject to heavy workloads over long periods, which leads to work fatigue. Work fatigue is a condition that can result in decreased work efficiency, reduced productivity and work capacity, as well as a decline in health and physical endurance, which can lead to workplace accidents (Innah et al. 2021). Several factors contribute to work fatigue, including workload, working hours, and the work environment. Workload refers to the series of tasks that must be completed by an individual or group within a specific time frame. Factors such as commuting conditions and the duration of travel from home to work also affect general occupational health and specifically contribute to work fatigue (Riyadi 2021).

Work fatigue is a condition of physical, emotional, and mental exhaustion caused by excessive workload or continuously demanding work conditions. This fatigue is often associated with prolonged work stress, such as high job demands and insufficient rest time(Prinasti 2018) Work fatigue can manifest as physical tiredness, decreased motivation, as well as feelings of frustration and loss of interest in the job. This phenomenon is frequently studied in the context of work environments involving variables like noise intensity, ambient temperature, and shift schedules. Research shows that non-ideal working conditions, such as high noise levels and elevated temperatures, can accelerate the onset of fatigue in workers (Ramdan et al. n.d.)

WORKLOAD

The definition of workload in the context of work generally refers to the number of tasks, responsibilities, and demands that an individual must complete within a certain period. Workload can encompass both physical and mental demands, each relating to physical activities as well as cognitive or emotional requirements during work (Yudatama et al. n.d.). A high workload can lead to fatigue and stress, especially if it is not balanced with the individual's capacity or ability. Research shows that subjective perceptions of workload are often related to an individual's perception of the difficulty or intensity of the tasks faced. Excessive workload can negatively impact both mental and physical health, making it crucial to maintain a balance between job demands and individual capacity to preserve well-being. Excessive physical and mental workload can increase the risk of workplace accidents. This shows that the workload has a considerable negative impact and cannot be used to improve employee performance. hence the importance of proper workload management in reducing accidents (Irbayuni 2024).

IoT SYSTEM

The use of IoT in real-time data collection from connected devices provides insights that can assist in strategic decision-making. Data gathered from various sensors and tools enables organizations to analyze patterns and trends, allowing them to make faster, data-driven decisions, which improves efficiency and responsiveness to changes in market or operational conditions (Burhan et al. 2018). This IoT system still has several weaknesses, such as external factors not being considered. The system only measures the operator's physiological data without accounting for external factors that could affect fatigue, such as psychological stress, sleep patterns, or eating habits.

This study explores the design of an IoT-based fatigue monitoring system with an ergonomic approach to address these challenges. The following are the limitations and proposed improvements for the IoT-based fatigue monitoring system: Limited testing period, Integration of fatigue prediction systems, Expansion of sensor coverage,Inclusion of environmental data, Automated notification systems, Ergonomic integration.

Limited testing period: The testing was conducted over six working days, which does not reflect long-term variations, including seasonal workloads or cumulative fatigue patterns.

Limited environmental factors: In addition to temperature and humidity, other factors such as noise, vibration, and lighting, which also affect fatigue, have not been considered in the system.

To address these weaknesses, the IoT system can be enhanced into a more comprehensive and integrated solution for monitoring and preventing work fatigue:

Integration of fatigue prediction system: Use machine learning algorithms to predict fatigue risks based on historical data, allowing supervisors to take preventive actions early.

Expansion of sensor coverage: Incorporate more parameters, including sleep monitoring, heart rate variability (HRV), and operator stress levels to provide a more complete picture of the operator's condition.

Integration of environmental data: In addition to temperature and humidity, add sensors to measure noise, vibration, and lighting, which can influence operator fatigue. This offers a more holistic view of the work environment.

Automated notification system: Provide early warnings to supervisors and operators through automated notifications if fatigue levels approach dangerous thresholds. The system can also recommend mitigation actions, such as short breaks or workload adjustments.

ERGONOMIC INTEGRATION

The integration of ergonomics in design aims to adjust tools, environments, and work methods to human abilities and limitations, creating efficiency and comfort in activities. In the context of ergonomics, integration involves applying ergonomic principles to various aspects of design, whether in the design of workplaces, public spaces, or other facilities, to ensure that all elements support user comfort and health. Ergonomics is a key factor in enhancing design quality, as it ensures that job demands align with worker capacity, ultimately improving performance and productivity. In ergonomic integration, attention must be paid to factors such as lighting, room temperature, noise, as well as human posture and movement to minimize the risk of fatigue and injury (Sri & Utomo n.d.)

Additionally, in specific contexts like emergency housing design, ergonomic criteria must still be applied, even if the housing is temporary, because it is still used by humans with specific needs, including people with disabilities who require special accessibility.

METHODOLOGY

STUDY DESIGN

This study uses an experimental design with an Internet of Things (IoT)-based ergonomic approach to monitor the work fatigue of heavy equipment operators in real-time. The independent variables measured included pulse rate at work (DNK) and pulse rate at rest (DNI), while the bound variable was the level of work fatigue. After the variable calculation was carried out, the results of the weight percentage of each variable related to its effect on work fatigue for rules in the IoT system were obtained. The monitoring system is designed to process physiological data automatically through IoT technology, which is then analyzed to determine fatigue categories based on changes in pulse, oxygen saturation, temperature, humidity, and calorie expenditure.

SUBJECT AND DATA COLLECTION

The subject of this study is heavy equipment operators in CV. Wana Indoraya Lumajang, who works in the production and material handling. Operator physiological data is measured using smartwatches that collect information related to pulse, oxygen saturation, air temperature, air humidity, and calorie expenditure. Measurements are carried out for six consecutive working days, starting from 08.00–12.00 and 13.00–16.00, Measurements are carried out at 08.00–12.00 and 13.00–16.00 because these two time ranges represent work activities that are in accordance with standard working hours. The hours of 08.00–12.00 reflect the morning period when workers start activities with relatively high energy levels, but fatigue can begin to appear towards the end of this period. Meanwhile, the hours of 13.00–16.00 include the time after lunch, often referred to as the post-lunch dip, when the worker's energy tends to decline due to physiological processes. Measurements in both periods are important for identifying fatigue patterns throughout the day, evaluating the effectiveness of rest time, and detecting critical work hours with a higher risk of fatigue. The data is processed in real-time through a cloud-based system and analyzed to assess fatigue levels.

Data collection is carried out by direct observation and using sensors connected to the IoT monitoring system. These variables are integrated into the system to monitor and analyze the fatigue conditions of the operators on a daily basis. In addition to physiological measurements, work environment data such as temperature and humidity are also recorded to get a comprehensive picture of the factors that affect work fatigue. The data obtained is used as the basis for analysis to evaluate the physical condition of the operator during working hours.

FIGURE 1. Work fatigue measuring

The image above shows the process of measuring work fatigue using a smart watch on a forklift operator on a wood processing industry which is carried out from 08:00 to 12:00. The DHT20 sensor has the advantage of being very accurate in measuring temperature and humidity, energy efficient and long-term stable, suitable for battery-based devices. The ESP32-C has complete wireless communication capabilities, namely supporting Wi-Fi and Bluetooth Low Energy (BLE). This capability is ideal for IoT applications and embedded systems, as well as saving power for battery-based devices. The K56Pro Smartwatch has the advantage of being able to monitor health, such as heart rate, blood oxygen and sleep quality, as well as providing message, call and application notifications directly on the wrist. The Raspberry Pi Zero WH is a small, inexpensive version of the Raspberry Pi that can run Linux and a variety of applications, perfect for robotics, home automation, IoT and education on a budget.To get the value of the change in the working pulse is calculated by the following Equation (1):

$$HRR = \frac{DK - DI}{DM - DI} \times 100\% \tag{1}$$

Description:
HRR = Heart Rate Reserve (%)
DK = Working Heart Rate (BPM)
DM = Resting Heart Rate (BPM)
DM = Maximum Heart Rate (DM for Male = 220 – Age, DM for Female = 200 – Age).

For calorie expenditure is calculated using the following Equation (2):

$$KK = (CJK) + (CBB \times BB) + (CBT \times TB) - (CU \times U) \tag{2}$$

Description:
KK = Working Calories (calories/day)
CJK = Constanta Gender
CBB = Weight Loss
BB = Weight (kg)
CTB = Height Constanta
BB = Height (cm)
CU = Age Constatanta
U = Age (years)

FRAME WORK OF FATIGUE AND WORKLOAD MONITORING SYSTEM

The workflow of this monitoring system begins with data taken from the Smart Watch used by the operator as a data logger, then the data in the smart watch is transferred using a wireless Bluetooth Low Energy (BLE) system, which is then processed on the cloud server and then displayed in the user interface according to the database using node js. Displays of scores and colors that can indicate operator fatigue and workload. Besides that, the display is also in the form of a sound as a warning tone that the operator is already at a level of fatigue and excessive workload. That way supervisors can take appropriate security measures.

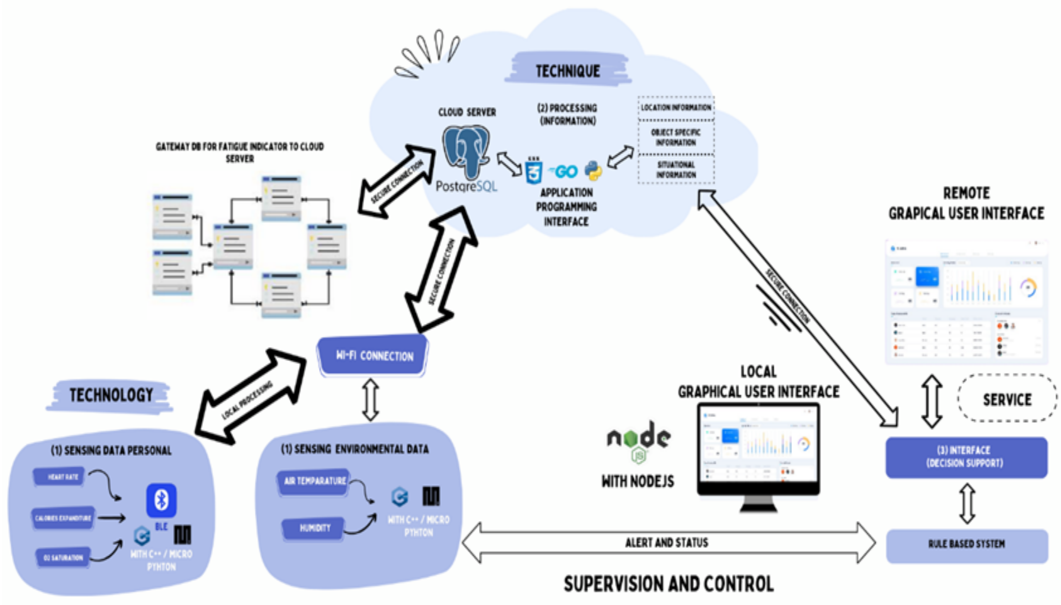

FIGURE 2. Frame Work Design IoT

DIAGRAM MONITORING DEVICE

The diagram of the monitoring device shows measurements of pulse, oxygen saturation, air temperature, and air humidity. From the pulse rate data, it will be known expenditure calories. From the 5 types of parameters, the level of fatigue is obtained. The level of fatigue can be known by the color and sound indicators displayed on the user face. In more detail it is shown as in Figure 2

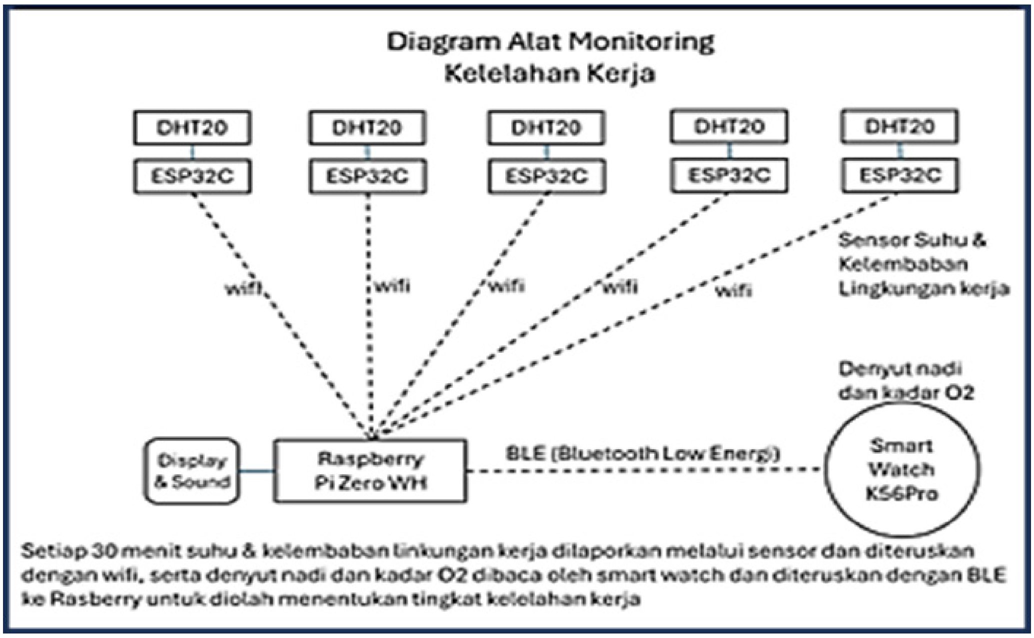

FIGURE 3. Diagram Monitoring Device

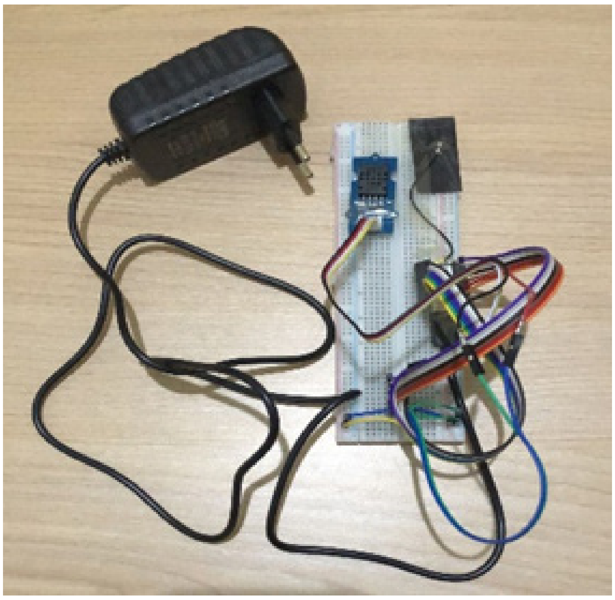

FIGURE 4. Temperature and humidity sensor

The DHT20 sensor measures temperature and humidity periodically, and the ESP32C module sends this data via Wi-Fi to the Raspberry Pi Zero WH. With data collected every 30 minutes, the system can provide early warnings if the temperature or humidity reaches levels that could potentially cause fatigue.

FIGURE 5. Smartwatch K56Pro

The K56Pro smartwatch automatically collects the worker's pulse rate and oxygen levels. Each time data is gathered, the smartwatch sends it via BLE to the Raspberry Pi. If there are significant changes, such as an abnormal increase in pulse rate or a drop in oxygen levels, the system can identify potential. fatigue and issue alerts accordingly.

FIGURE 6. Raspberry Pi Zero WH

The Raspberry Pi Zero WH collects data from two sources: Wi-Fi (for environmental data) and BLE (for physiological data). Using this data, it performs an analysis to monitor workers' conditions and determine fatigue levels. The system operates automatically, ensuring workers receive timely alerts when there is a risk of fatigue or unfavorable environmental conditions

DISPLAY AND SOUND SYSTEM

When the Raspberry Pi Zero WH identifies signs of fatigue or hazardous environmental conditions, it activates the display or sound system to notify workers. These notifications enable them to take preventive measures to avoid health risks or reduced productivity.

RESULTS AND DISCUSSION

RESULT

The subjective and objective assessment results for factors influencing work fatigue were gathered using measurement tools that had been calibrated following proper procedures:

TABLE 1. The subjective and objective assessment results

Parameter	Respondent					
	1	2	3	4	5	6
Heart_Rate_Change (%)	64.1	62.1	60.5	63.6	60.6	65.6
Heart_Rate_Workload (bpm)	149.9	149.9	149.9	149.9	149.8	149.6
Calories_Expenditure (kcal)	5.17	5.50	5.83	6.00	06.08	6.17
Oxygen_Saturation (%)	97.2	97.1	97.2	97.1	97.1	97.0
Temperature (°C)	24	25	26	28	28	28
Humidity (%)	45	46	44	45	43	46
Self_Rating_Score	2.47	2.48	2.49	2.50	2.47	2.48

Upon inputting the data and performing a multiple regression analysis, the SPSS output generates several key tables, including the Model Summary and Coefficients tables. Six-day working pulse (DNK) measurements showed an average DNK of 149.5 beats/minute, which puts the operator's workload in the heavy category (Nurmianto 2008). A significant increase in pulse rate occurred at 09.30-11.30 and 14.00-15.30, indicating that the operator was experiencing high physical fatigue during this time range. In addition, the operator's caloric expenditure was also observed to be high, with an average of 598 kcal/minute, which strengthened the heavy workload category.

In addition to Hearth rate Workload and calorie expenditure, oxygen saturation, air temperature, and air humidity also play an important role in fatigue measurement. The results of oxygen saturation measurements showed a significant decrease at 09.30-11.30 and 14.00-15.30, indicating that the physical condition of the operator was deteriorating due to the increased workload. Increased air temperatures and decreased air humidity in the workspace also worsened the physical condition of the operators, causing work fatigue to be felt even more at these times.

This study highlights the relationship between increased pulse rate and calorie expenditure with heavy workload. An increase in pulse rate above 30% corresponds to the fatigue category according to the Industrial Fatigue Research Committee (IFRC), which shows that operators often experience moderate to severe fatigue. The decrease in oxygen saturation further reinforces the presence of physical fatigue, especially during critical work hours when work activity and physical load reach their peak. The flowchart of this system is as follows:

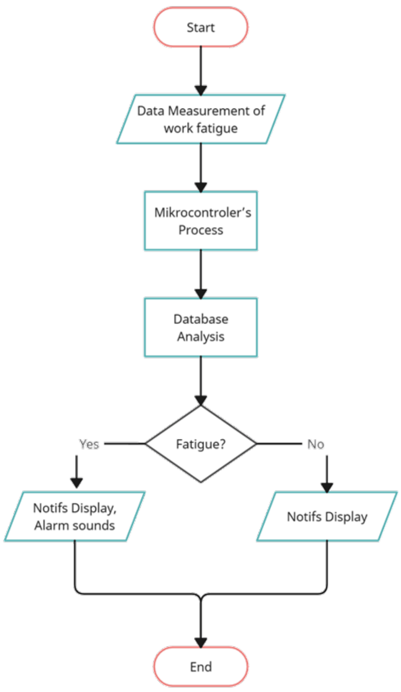

FIGURE 7. System Flowchart

The purpose of the tool's testing is to determine the level of fatigue experienced by each worker. The IoT system provides output in the form of color indicators on the monitoring device. The color green indicates "not fatigued," yellow indicates "mild fatigue," orange indicates "moderate fatigue," red indicates "severe fatigue," and black indicates "extreme fatigue."

TABLE 2. Level of fatigue experienced results

NIP	Name	Working period (Years)	Designation	Level of fatigue (%)	Indicator
2401	Iwan	20	Operator Forklift Barecore	31.00	MILD FATIGUE
2402	Basori	20	Operator Forklift Barecore	101.00	EXTREME FATIGUE
2403	Hendrik	20	Operator Forklift Blockboard	60.50	MODERATE FATIGUE
2404	Saiful Anam	20	Operator Forklift Blockboard	61.00	MODERATE FATIGUE
2405	M. Rizki	20	Operator Forklift Rotary	29.00	NOT FATIGUE
2406	Jamaludin	20	Operator Forklift Rotary	65.62	MODERATE FATIGUE

DISCUSSION

The results show that the Internet of Things (IoT)-based fatigue monitoring system is able to detect the fatigue condition of heavy equipment operators in real-time. Significant increases in working pulse occurred at certain times, especially at 09.30–11.30 and 14.00–15.30, indicating that operators experienced heavy workloads during these periods. This increase in pulse rate is in line with the theory of the Industrial Fatigue Research Committee (IFRC), where an increase in pulse rate of more than 30% indicates significant fatigue. In addition, the results of measuring calorie expenditure of 598 kcal/minute show that the physical workload experienced by the operator is quite heavy. Work environment factors such as temperature and air humidity also play an important role in the fatigue experienced by operators. The decrease in air humidity in the workspace, especially during critical working hours, causes operators to work in suboptimal conditions. The significantly increased air temperature in the Rotary and Spindle workspaces further worsened the physical condition of the operators, leading to increased pulse rate and work fatigue. The combination of high physical loads and unfavorable environmental conditions increases the risk of severe fatigue in the operator.

This research integrates the Internet of Things (IoT) with ergonomic principles, enabling real-time monitoring of worker fatigue levels. The novelty lies in the application of IoT technology specifically in the furniture wood industry, which has rarely been discussed in previous studies. This model is designed so that safety officers can monitor workers' conditions from a distance, an important feature considering the vast work areas in the industry. This remote monitoring is an effective solution for fatigue management and quick decision-making to prevent accidents. The system automatically issues warning signals if workers' conditions reach a certain level of fatigue. This allows for quicker preventive actions compared to manual approaches. Previous studies (Innah et al. 2021 and Izzati & Ardyanto, 2019) focused on subjective fatigue analysis through questionnaires and observations of work posture, without utilizing advanced technology.

On the other hand, this research introduces IoT sensors and data analytics as tools for objective monitoring, updating traditional approaches with cutting-edge technology. Some earlier studies relied on simple indicators such as work posture or the number of working hours (Izzati & Ardyanto, 2019). Your research is more advanced by measuring heart rate, body temperature, and calorie consumption, providing stronger objective indicators of fatigue levels. Most previous research has not addressed the development of a digital user interface and cloud-based access that can be accessed from anywhere. This system utilizes a cloud-based interface, facilitating information access and decision-making.

The implications of this study show the importance of continuously monitoring operator fatigue conditions using IoT technology. The system is designed to provide accurate information to supervisors regarding fatigue levels and workloads, so that preventive measures can be taken early. Additionally, improvements in work environment conditions such as temperature control and air humidity can help reduce the risk of work fatigue. The implementation of this system is expected to improve work safety and operator productivity in the future.

CONCLUSION

This study designed a heavy equipment operator fatigue monitoring system with an Internet of Things (IoT)-based ergonomic approach that focuses on measuring pulse as the main indicator of fatigue. The system is capable of collecting and analyzing pulse data in real-time using smartwatches and Cardio Vascular Load (CVL) formulas to determine operator fatigue levels. Most operators are in the "Moderately Tired" to "Severely Tired" category, especially during critical working hours such as 09.30–11.30 and 14.00–15.30, which indicates that the system accurately detects the physical condition of workers, allowing precautions to be taken before fatigue affects occupational safety. In addition to pulse, other factors such as temperature, humidity, oxygen saturation, and calorie expenditure are also monitored as they contribute to operator fatigue. An increase in temperature and a decrease in humidity in the workspace, as well as a high level of calories expended, indicate a heavy workload. This data is integrated into IoT systems to provide comprehensive analysis of fatigue and workload in real-time, thereby assisting companies in maintaining operator health and safety and increasing work productivity by reducing the risk of accidents due to fatigue.

Future research can develop this work fatigue monitoring system by expanding the scope of the variables measured. In addition to pulse, calorie expenditure, temperature, and humidity, future research may include other physiological indicators such as heart rate variability, blood pressure, as well as operator sleep patterns to provide a more comprehensive picture of health conditions and work fatigue. This will improve the accuracy of fatigue level prediction and help in the prevention of work accidents more effectively.

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DECLARATION OF COMPETING INTEREST

None.

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