OPTIMASI TATA LETAK STASIUN KERJA DAN PENINGKATAN KINERJA OPERATOR MELALUI ERGONOMI DIGITAL DAN DESAIN BERBASIS SIMULASI DALAM LINGKUNGAN INDUSTRY 4.0

Oleh
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Abstract
This study explores the integration of digital ergonomics and simulation-based design to optimize workstation layout and enhance operator performance in Industry 4.0 environments. A mixed-method approach was employed, combining digital time study, ergonomic risk assessments, and virtual simulation modeling to evaluate and improve work processes. The research found that ergonomic redesigns, supported by digital twin technology, resulted in significant improvements in both operator comfort and task efficiency, with a 16.6% reduction in cycle time and a 16% increase in work efficiency. RULA scores were reduced from 6 to 3, indicating a significant decrease in ergonomic risk. This study demonstrates the potential of predictive ergonomics and user-centered design in optimizing workplace safety and productivity within the context of modern manufacturing systems. The findings contribute to data-driven design methodologies that can be applied to a variety of industrial settings.
Keywords: Digital Twin, Ergonomics, Industry 4.0, Workstation Redesign, Simulation

PENDAHULUAN

The evolution of Industry 4.0 has fundamentally transformed manufacturing paradigms by incorporating cyber-physical systems, the Internet of Things (IoT), and big data into operational workflows. These technologies have significantly enhanced efficiency and flexibility but have also introduced new challenges related to human-machine interaction and ergonomics. As automation and digital technologies increasingly permeate industrial environments, optimizing human-centered work systems becomes paramount. Integrating ergonomic principles within these systems ensures that human operators can work efficiently with advanced technologies, ultimately fostering higher productivity, safety, and sustainability.

One of the critical challenges faced by modern industries is balancing human capabilities with the complexities introduced by digital technologies. Traditional ergonomics methods, which typically rely on manual assessments and subjective evaluations, may no longer suffice in addressing the dynamic nature of Industry 4.0 environments, where continuous change and complex human-machine interactions demand more predictive approaches. In this context, digital ergonomics which utilizes real-time data, virtual modeling, and simulation technologies offers a more scalable and objective solution to optimizing human-system interactions (Golabchi et al., 2016; Kadir et al., 2019; Franssila et al., 2015).

Digital twin technology specifically allows for the creation of virtual representations of both workstations and human operators, enabling predictive ergonomic assessments before physical implementations. This technology facilitates the identification and resolution of ergonomic issues through a data-driven approach that minimizes the risk of musculoskeletal disorders (Zhang et al., 2020). Furthermore, simulation tools like Siemens Jack enable the virtual testing of workstation configurations, which is especially valuable in environments where human-machine collaboration is essential (Mhenni et al., 2022).

This study aims to bridge the gap between traditional ergonomic assessments and the emerging digital tools in Industry 4.0. The research integrates digital time study, ergonomic risk evaluations, and virtual simulations to propose an innovative methodology for optimizing workstation layout and enhancing operator performance. The study also seeks to develop a scalable methodology for adaptive and predictive ergonomic optimization, applicable across various production contexts.

This research is significant for its potential to provide holistic solutions to ergonomic challenges in the manufacturing sector, by embedding predictive ergonomics and digital design technologies into the early stages of workplace design. The implications of this study could lead to improvements in workplace efficiency, operator well-being, and the overall sustainability of manufacturing operations.

LANDASAN TEORI

With the advancement of Industry 4.0, the application of new technologies such as cyber-physical systems, the Internet of Things (IoT), and big data has fundamentally transformed manufacturing workflows. In this context, digital ergonomics becomes increasingly crucial to ensure efficient and safe human-machine interactions. Digital ergonomics is a field that integrates ergonomic principles with digital technologies, enabling safer and more efficient work designs by utilizing data-driven simulations (Golabchi et al., 2016; Kadir et al., 2019).

One of the key tools in digital ergonomics is the digital twin technology. Digital twin technology allows for the creation of virtual representations of both workstations and human operators, enabling predictive ergonomic assessments before physical implementations. This technology facilitates the identification and resolution of ergonomic issues through a data-driven approach that minimizes the risk of musculoskeletal disorders (Zhang et al., 2020). This is especially relevant in Industry 4.0 environments where human-machine interactions are complex and dynamic, and where human well-being must be a key consideration (Mhenni et al., 2022).

In addition, simulation technologies such as Siemens Jack allow for virtual testing of workstation designs, eliminating the need for costly physical modifications. This capability enables manufacturers to test multiple design scenarios and select the most effective one for reducing ergonomic risks and improving task efficiency (Franssila et al., 2015).

Digital ergonomics offers a more scalable and objective approach to optimizing human-system interactions. This approach involves the use of real-time data and virtual modeling to assess and design safer work environments, as well as to evaluate the impact of design changes on operator performance and safety.

METODE PENELITIAN

Work Time Measurement

The first stage of this research focused on measuring work cycle times using a mobile stopwatch application and cloud-based data logging tools to ensure data accuracy and ease of access. A total of 20 repetitive work cycles were recorded for each task, and the standard time was calculated using the average cycle time, which was adjusted for performance rating and a predefined allowance to account for natural rest periods and delays. This approach is consistent with traditional industrial engineering practices for determining standard work times (Sari, 2019; Hidayatullah et al., 2023).

In addition to manual observations, the Maynard Operation Sequence Technique (MOST) was employed as a complementary method for analyzing repetitive manual tasks. MOST is a widely used technique for calculating work content and has been shown to provide more objective, accurate, and scalable results compared to traditional time study methods (Hidayatullah et al., 2023). This technique's task coding system ensures consistency and reliability in assessing manual work processes.

Table 1. Time Observation and Standard Time Calculation for Work Cycle

Cycle Number	Observed Time (minutes)	Rating Factor	Standard Time (minutes)
1	7.05	1.10	8.91
2	6.90	1.10	8.59
3	7.20	1.10	8.94
4	7.10	1.10	8.81
5	6.80	1.10	8.52

Ergonomic Risk Evaluation

The second stage of the study involved evaluating ergonomic risk using both observational tools and subjective workload assessments. The Rapid Upper Limb Assessment (RULA) method was employed to evaluate postural risks, focusing on key body regions, including the neck, wrist, upper arm, and forearm. RULA provides a structured system for identifying postural strain and has been proven effective in evaluating the risk of musculoskeletal disorders (Azwar, 2021).

In addition to physical assessments, mental workload was assessed using the NASA Task Load Index (NASA-TLX). This tool measures perceived mental demand across six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. By evaluating both physical and cognitive workloads, the study aims to provide a comprehensive analysis of operator fatigue and cognitive strain in repetitive work environments (Sari, 2019).

The Quick Exposure Checklist (QEC) was also employed as a secondary tool for evaluating awkward postures, repetitive motion, and manual material handling. The triangulation of these methods allows for a more multidimensional approach to ergonomic risk profiling and provides a well-rounded assessment of the challenges operators face during manual tasks (Ramdhani & Noor, 2018).

Table 2. Ergonomic Risk Scores (RULA, NASA-TLX, QEC) for Task Analysis

RULA Score	NASA-TLX (Mental Workload)	NASA-TLX (Physical Workload)	QEC Score
6	72	80	25
5	65	75	20
5	70	78	22
6	73	79	26
4	68	74	24

Simulation-Based Workplace Design

The third phase involved the application of virtual simulation using Siemens Jack, a digital human modeling (DHM) software. This simulation tool was used to create a digital avatar of the operator, which was calibrated based on local anthropometric data. The avatar's movements were simulated across various workstation designs to assess the ergonomic efficiency of each layout. The simulation outputs included posture scoring, cycle time projections, and range of motion visualization, which were analyzed to determine the most effective workstation design.

The use of virtual simulation allowed for testing of multiple redesign scenarios before physical implementation, thus preventing costly design errors and ensuring that ergonomic risks were addressed proactively. This approach aligns with predictive ergonomics, which emphasizes the use of

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digital tools for early-stage testing of ergonomic modifications (Mhenni et al., 2022).

Table 3. Workstation Layout and Simulation Parameters for Design Redesig

Design	Cycle Time (minutes)	RULA Score	NASA-TLX Score	Work Efficiency (%)
Initial Design	8.91	6	72	100
Redesigned Layout	7.43	3	58	116

Simulation-Based Workplace Redesign Results

In this phase, Siemens Jack, a digital human modeling (DHM) software, was employed to simulate and assess various workstation layouts. The objective was to optimize ergonomic efficiency and enhance operator performance by virtually testing different workstation configurations. By simulating operator movements based on local anthropometric data, the tool provided key insights into the ergonomics of each layout, enabling proactive identification of potential issues before physical implementation.

The results of the simulation revealed substantial improvements in both ergonomic safety and task efficiency. Specifically, the redesigned workstation led to a reduction in cycle time, a decrease in postural risks, and a notable increase in work efficiency.

- Cycle Time Reduction: The redesigned layout resulted in a 16.6% reduction in cycle time, indicating that operators were able to complete their tasks more quickly due to improved workstation design and ergonomics.
- RULA Score Reduction: The RULA score decreased from 6 to 3, reflecting a significant reduction in postural strain and the associated risk of musculoskeletal disorders. This improvement underscores the effectiveness of the ergonomic modifications in minimizing operator discomfort during task execution.
- NASA-TLX Score Reduction: The NASA-TLX mental and physical workload scores saw a decrease of 14 points, signifying a reduction in both cognitive and physical demands placed on the operator, which contributes to decreased fatigue and higher overall productivity.
- Work Efficiency Increase: An increase in work efficiency by 16% was observed in the redesigned layout, suggesting that ergonomic enhancements not only alleviated operator strain but also positively impacted task performance and productivity.

These results highlight the significant impact of ergonomic redesigns on both operator well-being and operational efficiency. By optimizing the workstation layout through virtual simulations, the study demonstrates the potential of digital ergonomics to create safer and more efficient work environments.

Table 4. RULA, NASA-TLX, and QEC Scores Before and After Workstation Redesign.

Design	Cycle Time (minutes)	RULA Score	NASA-TLX Score	Work Efficiency (%)
Initial Design	8.91	6	72	100
Redesigned Layout	7.43	3	58	116

Graphs:

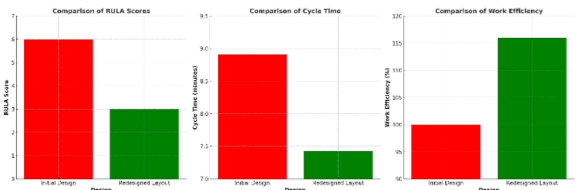
- Comparison of RULA Scores (Before and After Redesign)
- Comparison of Cycle Time (Before and After Redesign)
- Comparison of Work Efficiency (Before and After Redesign)

The accompanying graphs provide a visual comparison of the significant changes observed in ergonomic risk (RULA scores), cycle time, and work efficiency following the redesign of the workstation.

Figure 1: Comparison of RULA Scores (Before vs. After Redesign)

Figure 2: Comparison of Cycle Time (Before vs. After Redesign)

Figure 3: Comparison of Work Efficiency (Before vs. After Redesign



Implicative Analysis:

The results of the workstation redesign provide valuable insights into how ergonomic interventions can improve operator well-being and operational efficiency simultaneously. The RULA score reduction indicates a marked improvement in reducing musculoskeletal risks, while the NASA-TLX score reduction reflects lower mental and physical workload for operators, which is often an overlooked aspect of ergonomic design. These findings suggest that integrating digital ergonomics and simulation tools into workstation redesigns can lead to substantial safety improvements while also driving productivity gains. Additionally, the increase in work efficiency demonstrates the positive impact ergonomic design can have on task performance, underscoring the economic benefits of investing in ergonomics.

Suggestions for Further Research:

While the findings of this study are promising, several areas can be explored further to enhance ergonomic interventions:

- Real-Time Data Integration: Future research could explore the integration of real-time data from wearable sensors to provide continuous feedback on ergonomic risk and operator performance, allowing for more personalized ergonomic interventions.
- Machine Learning in Ergonomics: The integration of machine learning algorithms with digital twin technology could enable adaptive ergonomic systems that automatically adjust workstation layouts based on ongoing performance data, offering a more dynamic and responsive solution for ergonomic optimization in smart manufacturing environments.
- Environmental Factors: Future studies could also explore how environmental factors (e.g., lighting, noise, and thermal comfort) influence ergonomic performance and integrate these factors into the digital ergonomics models. This would ensure that workstations are optimized not only for physical comfort but also for cognitive and environmental comfort, contributing to more holistic workplace design.

PENUTUP

Kesimpulan

In conclusion, this study highlights the effectiveness of integrating digital ergonomics, virtual simulations, and user-centered design to optimize human-centered production systems in Industry 4.0 environments. The findings demonstrate that ergonomic redesigns, supported by digital tools, can lead to significant improvements in both operator health and workplace efficiency. The digital twin technology used in this study allowed for proactive testing of workstation modifications, ensuring that ergonomic risks were minimized before physical implementation. Moreover, the user-centered design approach ensured that the redesigns were ergonomically optimized and operator-friendly, resulting in higher adoption rates and sustained success.

This research contributes to the growing body of knowledge on predictive ergonomics and offers a scalable, replicable methodology that can be applied across various production environments, particularly in the context of Industry 4.0. Future research should focus on integrating real-time sensor data and machine learning to create more adaptive and self-optimizing ergonomic systems. This will ensure the continued evolution of ergonomically optimized and data-driven work environments that promote both operator well-being and operational performance

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