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Research paper

Transforming MSME assembly operations: smart manual assembly table for improved productivity

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Abstract

Micro, Small, and Medium Enterprises (MSMEs) play a crucial role in the manufacturing sector but often face challenges in maintaining efficiency and quality due to high worker attrition and skill variability. Traditional manual assembly tables (TMATs) require experienced operators, making it difficult for MSMEs to sustain productivity with novice workers. To address this, authors developed and implemented a Smart Manual Assembly Table (SMAT) that integrates smart assistance technologies (SAT) to enhance industrial efficiency. The system incorporates real-time monitoring, automated guidance, and error detection mechanisms to improve worker accuracy and productivity. Experimental evaluation compared the performance of traditional and smart assembly setups, focusing on cycle time, error rate, and overall workflow efficiency. The results demonstrated a significant reduction in assembly time and errors, enabling higher production rates and improved product quality. Additionally, the SMAT reduced the cognitive load on operators by providing automated alerts and digital work instructions, thereby enhancing adaptability for novice workers. The study also highlights the potential of integrating Industry 4.0 principles into MSME assembly operations, thereby enhancing a collaborative human-machine environment. The findings emphasize the practical benefits of smart-assisted manual assembly cells, including cost-effectiveness, scalability, and ease of implementation. Future research should focus on long-term reliability, adaptability across diverse assembly tasks, and optimized scheduling techniques to further improve efficiency. The SMAT presents a promising approach for modernizing MSME assembly processes, ensuring sustainable productivity and a competitive advantage in the evolving industrial landscape.

Keywords: *Industry 4.0; Manual Assembly; MSME; Productivity Enhancement; Real-Time Monitoring; Smart Manual Assembly Table.*

1. Introduction

Micro, Small, and Medium Enterprises (MSMEs) play a crucial role in the global manufacturing ecosystem, contributing significantly to industrial growth and economic development [1]. However, these enterprises often face challenges such as high worker turnover, skill variability, and inefficiencies in manual assembly operations [2], [3]. Traditional Manual Assembly Tables (TMATs) rely heavily on operator expertise, making them prone to human errors, inconsistent productivity, and increased operational costs [4], [5]. Addressing these challenges is essential to enhance efficiency, ensure product quality, and improve overall competitiveness in the industry.

With the rapid advancement of Industry 4.0 technologies, integrating smart systems into manufacturing processes has emerged as a viable solution for overcoming these limitations. Smart Manual Assembly Tables (SMATs) incorporate real-time monitoring, automated guidance, and digital assistance to support novice workers, reduce cognitive load, and optimize production workflow. By leveraging intelligent systems, manufacturers can achieve greater accuracy, minimize errors, and enhance productivity without requiring extensive training for workers [6-8].

This study focuses on the development and implementation of a SMAT in an MSME environment. The primary objective is to evaluate its effectiveness in addressing key operational challenges associated with traditional manual assembly processes. The SMAT utilizes digital interfaces, automated alerts, and data-driven insights to improve worker efficiency, standardize assembly tasks, and reduce operational inconsistencies. The integration of smart technologies not only enhances individual worker performance but also contributes to the broader goals of lean manufacturing and industrial automation.

The paper presents an in-depth analysis of the SMAT's impact on assembly operations, comparing its performance with TMAT. Key performance indicators such as cycle time, error rates, and production output are examined to determine the benefits of smart technology adoption in MSMEs. The findings of this research highlight the potential of SMATs to transform MSME assembly operations, making them more agile, cost-effective, and competitive in an evolving industrial landscape.

1.1. Necessity of the work

MSMEs are essential contributors to industrial growth and economic development. However, they face significant challenges in manual assembly operations, such as high error rates, inconsistent productivity, and dependency on skilled labor. The limitations of TMATs in MSMEs include long cycle times, increased defect rates, and inefficient resource utilization, which hinder competitiveness in modern manufacturing environments.

With the increasing demand for precision, efficiency, and scalability in assembly processes, MSMEs must adopt smart and technology-driven solutions to improve operational performance. The integration of real-time guidance, automated alerts, and data-driven decision-making into manual assembly cells can help reduce operator errors, optimize workflows, and enhance productivity, even for novice workers.

This research is necessitated by the need to modernize MSME assembly stations/lines while ensuring cost-effectiveness, adaptability, and ease of implementation. The SMAT presents a practical and scalable approach to overcoming the inefficiencies of traditional manual assembly processes.

1.2. What does this research paper address?

This research paper addresses the challenges faced by MSMEs in traditional manual assembly operations and proposes a SMAT that integrates real-time assistance, digital guidance, and automated monitoring to improve efficiency and accuracy. The key aspects covered in this paper include:

i) Challenges in Traditional MSME Assembly Operations
- High error rates due to operator fatigue and inexperience,
- Long cycle times are affecting production efficiency.
- Inconsistent output quality due to human-dependent processes.
- High training costs and learning curves for novice workers.

ii) Development and Implementation of SMAT
- Integration of sensor-based real-time assistance to guide workers.
- Automated feedback mechanisms for error detection and correction.
- Use of digital work instructions to streamline assembly workflows.
- Implementation of cognitive load reduction techniques to enhance worker focus.

iii) Performance Evaluation and Comparative Study
- Comparison between TMAT and SMAT in terms of cycle time, error rate, and overall productivity.
- Statistical validation of improvements, ensuring empirical reliability.
- Analysis of operational benefits and economic feasibility for MSMEs.

iv) Industrial and Academic Contributions
- Practical implementation of smart manufacturing solutions in MSMEs.
- Empirical validation of human-machine collaboration in assembly operations.
- A scalable and cost-effective model for MSMEs to transition toward Industry 4.0.

By addressing these critical areas, this paper provides a comprehensive framework for MSMEs to enhance their assembly efficiency, improve worker performance, and remain competitive in modern manufacturing landscapes.

1.3. Organization of the paper

The remainder of the paper is organized as mentioned further. Section 2, Related Work, discusses the literature review highlighting the challenges in traditional assembly processes, adoption of Industry 4.0 technologies for making the traditional assembly smart. It also analyses the technological advances in assembly operations to mitigate the various challenges. It also reviews the comparative analysis of TMATs and SMATs from other researchers, with their outcomes and limitations. The section concludes with the research gap and future directions for researchers to extend the work from this similar domain. Section 3, Methodology, discusses the detailed methodology adopted and experimentation while conducting this research. Section 4, Results, presents the benefits of the SMAT over TMAT through key performance indicators. Section 5, Discussion, explains the potential of the SMAT in transforming assembly operations within MSME by presenting key findings and their interpretation. Section 6, Conclusion, summarizes the research paper by highlighting its key accomplishments, achievements, and contributions to academia and research.

2. Related work

The integration of smart technologies in manual assembly operations has gained significant attention in recent years, particularly in the context of Industry 4.0 and its impact on MSMEs. TMATs rely on operator expertise, which can lead to inconsistencies due to variations in skill levels and human errors [9], [10].

Foundational research on single-station manual assembly systems provided early insights into workstation layout, task organization, and human performance factors. These studies form the basis for many current approaches and continue to influence ergonomic and process design in modern MSME environments [11], [12].
Researchers have explored multiple strategies to enhance assembly efficiency, including automation, real-time tracking, and cognitive assistance for workers.

2.1. Challenges in traditional assembly processes

The reliance on human operators in traditional assembly cells poses several challenges, including high error rates, increased cycle times, and inefficiencies caused by workforce turnover [13, 14]. Studies have shown that manual operations are often constrained by cognitive overload, lack of standardization, and operator fatigue, leading to variability in product quality and overall inefficiency [15], [16]. Additionally, MSMEs frequently struggle with training inexperienced workers, as skill acquisition requires significant time and resources [2], [17]. This limitation necessitates the adoption of smart technologies to reduce dependency on operator expertise and standardize assembly processes.

2.2. Smart assembly systems and Industry 4.0

The adoption of Industry 4.0 principles in manufacturing has led to the development of smart assembly systems that integrate real-time monitoring, automation, and data analytics [18-20]. SMATs leverage digital interfaces, augmented reality (AR), and sensor-based feedback mechanisms to guide operators through assembly tasks with minimal errors [21], [22]. Previous studies have demonstrated that such systems can significantly improve operational efficiency by reducing cognitive load and enhancing process standardization [23]. A single-station test set up was developed to automate the testing of automotive lift gates and door slams, ensuring precise analysis of system integrity. This system integrated a pneumatic circuit with PLC-controlled sequential operations to regulate key processes, such as measuring door opening and closing velocities and executing continuous test cycles. By leveraging PLC-based automation, the transition from a conventional test setup to an advanced single-station automated cell was achieved, demonstrating significant improvements in process efficiency, quality consistency, and overall automation in operations [24], [25]. These findings support the idea that smart manufacturing systems can facilitate continuous improvement and lean manufacturing principles while ensuring adaptability to various production environments.

2.3. Technological enhancements in assembly operations

Various technological advancements have been introduced to address the inefficiencies in manual assembly operations. Research has highlighted the effectiveness of digital work instructions [26], automated quality control mechanisms [27], and machine learning-based performance optimization [28] in manufacturing. The implementation of digital guidance systems has been found to enhance worker productivity by providing real-time feedback and reducing decision-making errors [29]. Additionally, smart manufacturing systems enable seamless data collection and analysis, which can be used for process optimization and predictive maintenance [30]. Recent efforts in AI-based optimization and collaborative robotic systems (cobots) offer flexible alternatives for manual assembly enhancement, particularly in dynamic and mixed-skill environments. Such systems are increasingly being integrated with machine learning for predictive adaptation and task distribution, adding to the evolving spectrum of smart assembly solutions [31]. These enhancements contribute to overall workflow improvements, reducing cycle times and enhancing product consistency.

2.4. Comparative analysis of TMAT and SMAT

Comparative studies between TMATs and SMATs have consistently shown significant improvements in efficiency, accuracy, and worker performance [32], [33]. Optimizing the sequence of assembly tasks has been shown to reduce operator errors by lowering cognitive load, which aligns with the structured workflow design emphasized in the proposed SMAT system [34]. Research findings suggest that the introduction of automated alerts, digital instructions, changes in the sequence of assembly operations, and sensor-driven error detection mechanisms results in substantial reductions in assembly errors and rework costs [34], [35]. Some previous studies on smart manual assembly systems, such as [36], have identified challenges in scalability, particularly when extending solutions to more complex or multi-station setups. These limitations underline the importance of context-specific designs, like our single-station focus, and suggest a need for future adaptability frameworks. Moreover, the adaptability of SMATs to different assembly environments makes them a viable solution for MSMEs seeking to enhance their competitiveness [36]. However, challenges such as initial implementation costs, system integration, and operator adaptation must be considered to ensure the successful deployment of smart technologies in manual assembly operations [13], [37], [38]. Recent developments in AI-based scheduling techniques offer promising directions for optimizing task allocation in dynamic assembly settings, particularly when integrated with real-time data streams and predictive analytics [39]. Simultaneously, understanding worker psychology, such as cognitive load and motivational factors, plays a critical role in designing novice-friendly assembly environments, complementing the technical innovations embedded in the SMAT system [40].

2.5. Non-technological interventions for enhancing manual assembly operations

In addition to technological upgrades, structured operator training programs have been shown to improve accuracy, reduce errors, and build confidence in manual assembly tasks [10]. Recent studies using electroencephalography (EEG)-based analysis confirm that task switching in manual assembly increases cognitive workload, underscoring the need for optimized task organization in human-centric systems [41]. These approaches can complement physical system enhancements, especially in resource-constrained MSME settings. In addition to technological enablers, understanding human factors such as cognitive adaptability and skill acquisition is crucial for enhancing novice operator performance in smart assembly environments. Recent studies in cognitive ergonomics and human-system interaction offer insights into designing systems that reduce mental fatigue and support user engagement, which aligns well with the intent behind the SMAT framework.

2.6. Research gaps and future directions

Despite the evident advantages of SMATs, several research gaps remain. While existing studies have focused on short-term performance improvements, there is limited research on the long-term reliability, maintenance requirements, and cost-effectiveness of such systems. Additionally, most studies have been conducted in controlled environments, which may not fully capture the variability of real-world MSME operations. Further research is needed to explore the scalability of SMATs across different industry sectors and to develop optimized scheduling algorithms that enhance production planning efficiency. Future studies should also investigate the impact of SMATs on workforce adaptability and training methodologies to maximize their potential benefits in MSME settings. Additionally, recent trends in sustainable manufacturing have gained traction alongside smart technologies, emphasizing resource efficiency, energy optimization, and waste reduction in production environments. Integrating sustainability with smart assembly systems can further support long-term resilience and environmental responsibility in MSMEs.

The literature review highlights the pressing need for integrating smart technologies in MSME assembly operations to overcome the limitations of traditional manual processes. SMATs offer a viable solution for enhancing productivity, reducing errors, and optimizing workflow in dynamic manufacturing environments. While several studies have demonstrated the benefits of such systems, further research is required to address long-term implementation challenges and explore their full potential in different manufacturing scenarios. While these studies demonstrate the effectiveness of smart and automated assembly systems, many fall short in addressing scalability for novice workers or lack contextual validation within MSMEs. Furthermore, few works provide longitudinal insights into system durability or adaptability under real-world operational constraints, highlighting a gap that this study aims to bridge through its practical implementation focus.

While this study focuses on enhancing manual assembly operations through ergonomic and process-driven interventions suited for MSMEs, emerging research trends are exploring the integration of advanced technologies such as artificial intelligence (AI)-driven assembly optimization and human-robot collaboration. These approaches offer promising avenues for intelligent decision-making and hybrid automation. Although not central to this research paper's current scope, they represent valuable directions for future research and potential scalability of the proposed system in technologically progressive industrial setups.

Building upon the insights from prior studies and identifying existing gaps in novice-targeted smart assembly technologies, the following methodology outlines the design, development, and implementation of the SMAT system. This system directly addresses the limitations identified in traditional manual assembly environments through a structured, human-centric smart assembly approach.

3. Methodology

The methodology adopted in this study focuses on the design, development, and implementation of a SMAT to enhance productivity and reduce errors in MSME assembly operations. The approach involves a structured framework that integrates real-time feedback, digital guidance, and automation support to assist inexperienced workers in performing assembly tasks efficiently. The methodology is divided into various key stages as discussed further.

3.1. System design and architecture

The authors developed the SMAT as an enhanced version of the traditional assembly setup, integrating smart technologies to improve process efficiency. The system architecture, as shown in Figure 1, consists of the following components:

- Workstation design: A structured assembly cell designed for ergonomic efficiency, ensuring ease of access to tools and components [42].
- Digital work instructions: An interactive display system providing step-by-step assembly guidance using visual and textual prompts [43].
- Sensor-based monitoring: Integration of sensors for real-time tracking of assembly progress and error detection [44].
- Automated alerts: A feedback system that provides warnings and corrective guidance when an operator deviates from standard procedures.
- Data logging and analytics: A local system that records assembly time, error rates, and operator performance metrics for continuous improvement.

The architecture supports adaptability, allowing customization based on the unique requirements of MSME production systems.

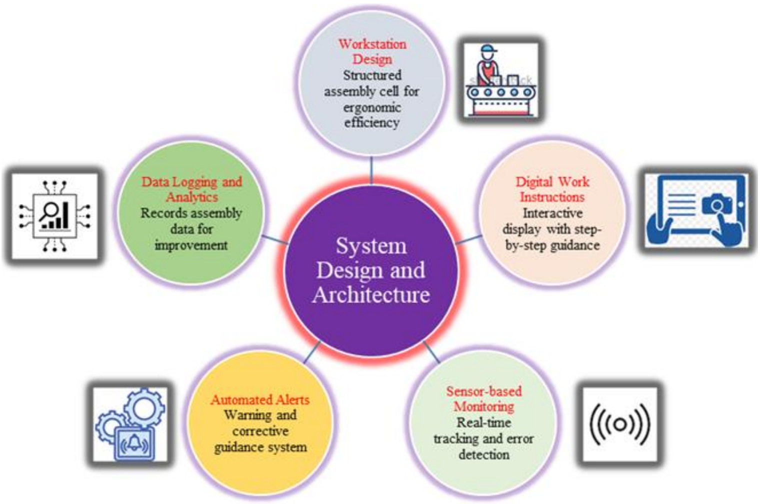

Fig. 1: The Elements of the SMAT System Design and Architecture for MSME Assembly.

3.2. Implementation of smart technologies

The SMAT integrated following several key technological enhancements as shown in Figure 2 to streamline assembly operations:

- Height-adjustable workbench: Improved ergonomics using smart actuators.
- Smart lighting: Implemented to adapt the brightness based on task requirements.
- Voice-controlled instructions: Enabled hands-free operation.
- Touchscreen display/monitor: Displayed step-by-step assembly instructions, animations, or real-time process videos. Developed to be interactive, allowing workers to zoom in, pause, or replay steps. Based on the future scope, it is also enabled to integrate with AI-based assistance systems to highlight critical areas.
- Sensor-enabled smart bins: Weight sensors detect if the correct number of parts are picked. They alert the worker if too many/few parts are taken.
- Proximity and motion sensors: Detect if a worker's hand moves towards the wrong bin. They were used to trigger alerts if an incorrect part was about to be used.
- Programmed sequence guidance system (LED indicators on bins)
  - LED-based pick-to-light system: LEDs light up to indicate which bin to pick from. Different colors signify different steps (e.g., Green = Correct, Red = Error). This helped to improve speed and accuracy in a high-mix, low-volume assembly environment.
  - Adaptive sequencing: "Adaptive sequencing," in this context, refers to the system's dynamic adjustment of assembly steps based on operator interaction or process flow conditions, thereby enhancing flexibility and error mitigation. The system can be programmed dynamically based on production variations. Based on the future scope, it is also enabled to integrate with ERP/MES'S systems to auto-update part selection.
- Error alerts through buzzers/alarms: Buzzer-based alerts trigger immediate warning if an incorrect part is picked. These alerts are reprogrammable for different sound frequencies for various error types.
- Visual alarm systems (flashing lights/beacons): Red/Yellow/Green beacons indicate process status (e.g., Green = Proceed, Red = Error). These alarms help in quick troubleshooting without stopping assembly operations.
- Integration with data logging system: Errors are logged in real-time, allowing for process improvements. Certain alerts are also sent to supervisors for monitoring and intervention whenever necessary.

By incorporating these smart technologies, the system aimed to minimize errors and improve assembly efficiency.

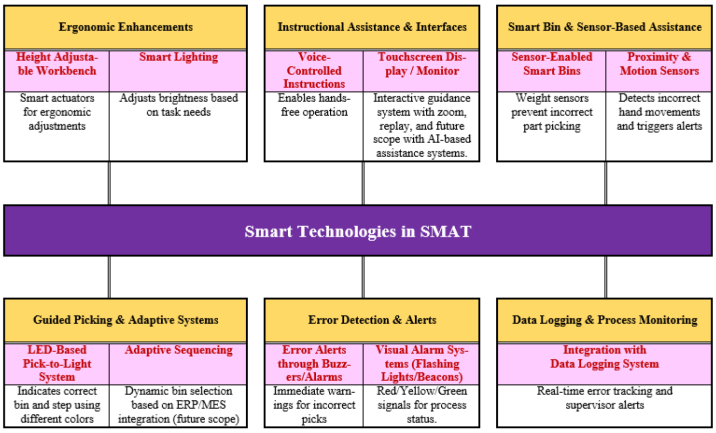

Fig. 2: Smart Technologies Integrated in the SMAT Framework Tailored for MSMEs.

3.3. Experimentation and data collection

The study experimentally evaluated SMAT performance against TMATs within an actual MSME environment. The study involved the following steps:

- Selection of participants: A group of five novice operators was chosen to test both Traditional and Smart assembly setups.
- Task execution: Participants performed identical assembly tasks using both systems while key performance metrics were recorded.
- Data collection metrics: The study focused on:
  - Assembly cycle time (time taken to complete a task).
  - Error rates (number of mistakes made during assembly).
  - Number of defective assemblies produced.
  - Operator workload (perceived cognitive effort).
  - Overall production efficiency.

Data was collected over multiple sessions to ensure the reliability and accuracy of results. Each worker completed 20 assembly cycles at each station. A total of 100 cycles per station were recorded, performed by five workers. The worker completed the assembly tasks alternating randomly between TMAT and SMAT every cycle. Data from these cycles were collected for analysis. As the goal was to compare performance differences without order biases, randomized alternation had been adopted, as it ensures a statistically unbiased comparison. In this methodology, workers alternate between TMAT and SMAT in a randomized sequence, ensuring that each participant does not follow a fixed order. The justifications for adopting this approach include (i) eliminating order and learning biases, (ii) reducing the impact of fatigue and adaptation effects, and (iii) enhancing statistical validity. Table 1 presents the experimental factors and levels used for this study. The response variables or measured outcomes are mentioned in Table 2.

Table 1: Experimental Factors and Levels

Factor	Level	Description
Assembly Method (A)	1. TMAT (T) 2. SMAT (S)	The type of system used for the assembly cycle
Worker (B)	n (number of workers) Total number of workers = 5 Worker no. 1 (W1) Worker no. 2 (W2) Worker no. 3 (W3) Worker no. 4 (W4) Worker no. 5 (W5)	Each participant performing the experiment
Cycle Order (C)	Randomized	Each worker switches between Traditional and SMAT in a randomized sequence

Table 2: Response Variables or Measured Outcomes

Response Variable	Unit of Measurement	Objective
Cycle Time (T)	Seconds per assembly cycle	Measure efficiency
Accuracy (A)	% of correct assemblies	Assess quality
Defect Rate (F)	% of defective assemblies	Assess minimum rework cost
Error Rate (E)	Number of errors per cycle	Identify activities/tasks deviating from the intended standard one

3.4. Comparative performance evaluation

To analyze the effectiveness of the SMAT, the following comparative study was performed:

- Baseline performance analysis: The initial performance of novice workers using TMAT was recorded.
- Impact of smart features: The improvements in efficiency and accuracy were evaluated after introducing the SMAT.
- Statistical validation: A comparative statistical analysis was conducted to determine the significance of performance improvements.

To assess the errors made by the worker with each station, the historical data of errors recorded by the workers while working with the TMATs for various products assembled so far were referred to and are listed in Table 3. The results were analyzed to assess the feasibility of deploying SMATs in real-world MSME production environments.

3.5. System scalability and future enhancements

The adaptability of the SMAT for different production scenarios was considered, focusing on:

- Integration with production scheduling: Exploring how smart assembly cells can be incorporated into larger manufacturing workflows [45].
- Expansion to parallel workstations: Evaluating the potential for implementing multiple SMATs in a parallel production setup [46].
- Long-term reliability assessment: Investigating maintenance requirements and system longevity for sustainable adoption.
- AI-based assistance systems to highlight critical areas: Future work may explore integrating AI to assist with real-time decision-making and adaptive workflow adjustments in manual assembly.

The methodology outlines a structured approach for implementing a SMAT in an MSME environment. By integrating digital guidance, real-time assistance, and automated quality control, the system aimed to enhance productivity and accuracy in manual assembly operations. The next stage involves analyzing the results to determine the overall impact of the SMAT on MSME production efficiency.

4. Results

Figure 3 shows the SMAT developed for the MSME under consideration for this study. Authors assessed the implementation of the SMAT in an MSME environment based on key performance indicators, including assembly cycle time, error rate, operator efficiency, and overall production output. The results demonstrated significant improvements in productivity and accuracy, validating the effectiveness of integrating smart technologies into manual assembly operations.

4.1. Comparative performance analysis

A comparative study was conducted between the TMAT and the SMAT, with novice workers performing identical assembly tasks. The results are summarized in Table 4.

- Reduction in cycle time: The SMAT reduced the average cycle time by 22.82%, allowing operators to complete tasks more efficiently.
- Decrease in error rate: The SMAT lowered the error rate by 71.43%, attributed to real-time automated guidance.
- Operator Efficiency: In the SMAT, novice operators experienced an efficiency gain of 7%, as smart assistance minimized confusion and cognitive load.
- Increase in Production Output: The SMAT increased the overall production rate by 30.49%, leading to improved throughput and higher profitability.

It is important to note that this study compares the performance of two different setups used in manual assembly - TMAT and SMAT. TMAT is a traditional setup commonly found in MSMEs, while SMAT is a modified version that includes smart assistance technologies. The performance improvements were measured by directly comparing these two setups within the same working environment. Although standard industry benchmarks for manual assembly cells are not always clearly defined, the selected baseline reflects the prevalent operational standards within the target industrial segment, making the comparisons contextually relevant. This comparison clearly shows how smart assistance can improve assembly performance in a typical MSME context.

Table 3: Historical Data of Errors Recorded by the Workers While Working with the TMAT

Category	Description
Component Placement Errors	Misalignment – Incorrect positioning of components, leading to improper fit. Incorrect Orientation – Placing components in the wrong direction. Skipping a Component – Missing a required part during assembly. Overlapping Components – Parts are placed on top of each other improperly.
Fastening and Connection Errors	Under-Tightening Screws/Bolts – Leading to lose connections. Over-Tightening Screws/Bolts – Risk of damage or breakage. Use of Wrong Fastener – Incorrect screw, bolt, or rivet selection. Partial Insertion of Fasteners – Leading to weak structural integrity. Cross-Threading – Misalignment of screw threads, reducing durability.
Wiring and Electrical Errors	Wrong Wire Connection – Connecting wires to incorrect terminals. Loose Wiring – Leading to malfunction or electrical failure. Short Circuits – Due to improper insulation or incorrect wire routing. Damaged Cables – Frayed or pinched wires causing performance issues.
Material Handling Errors	Use of Incorrect Material – Wrong component selected for assembly. Scratches/Dents on Components – Handling damage affecting quality. Contaminated Components – Dirt, grease, or moisture affecting performance.
Assembly Sequence Errors	Incorrect Order of Steps – Skipping or reversing the prescribed sequence. Delays Between Steps – Causing improper curing or settling of materials. Repeated Disassembly – Fixing mistakes leading to wasted time and resources.
Measurement and Alignment Errors	Incorrect Dimensioning – Using incorrect measurements while cutting or positioning. Gaps or Misfit – Components not sitting flush due to incorrect tolerances. Asymmetry – Uneven assembly causing imbalance or malfunction.
Operational Errors	Inconsistent Cycle Time – Varying assembly speed leading to inconsistent output. Failure to Follow Standard Procedures – Ignoring prescribed assembly instructions. Overuse of Adhesives or Lubricants – Causing component failure or contamination. Underuse of Adhesives or Lubricants – Resulting in poor bonding or increased friction.
Safety Violations and Human Errors	Failure to Wear Safety Gear – Increasing risk of accidents or injuries. Manual Handling Strain – Inefficient ergonomics leading to operator fatigue. Accidental Tool Drop – Leading to damaged components.
Final Inspection and Quality Check Errors	Failure to Detect Defects – Missing visible or functional defects. Ignoring Inspection Guidelines – Skipping final quality assurance procedures. Wrong Labelling or Tagging – Misidentifying assembled units.

Fig. 3: The Developed SMAT Setup Deployed in the Representative MSME Context.

Table 4: Performance Comparison between TMAT and SMAT

Performance Metric	TMAT	SMAT	Improvement (%)
Average Cycle Time (seconds)	1178.20	909.36	22.82% ↓
Error Rate (%)	14	4	71.43% ↓
Operator Efficiency (%)	90%	97%	7% ↑
Production Output (Units per Hour)	3.06	3.98	30.49% ↑

4.2. Impact of smart features on productivity

The effectiveness of individual smart features was assessed, revealing their contributions to performance enhancement shown in Table 5:

Table 5: Effectiveness of Individual Smart Features used in SMAT

Smart Feature	Key Benefit	Improvement (%)
Digital Work Instructions	Reduced confusion, guided step-by-step assembly	69.69% ↓
Sensor-Based Monitoring	Early error detection, minimized defects	70% ↓
Automated Alerts	Immediate feedback, prevented rework	7.2% ↓

Digital Work Instructions led to a 69.69% decrease in task completion errors by providing intuitive, real-time guidance. Sensor-Based Monitoring helped reduce defects by 70%, improving product quality. Automated Alerts minimized the need for rework by 7.2%, ensuring smoother workflow.

4.3. Statistical validation

A t-test analysis was conducted to determine the statistical significance of the improvements. The p-values obtained for cycle time reduction was $p < 0.05$, confirming that the SMAT significantly outperformed the TMAT. Table 6 presents the paired t-test results.

Table 6: Results of Paired T-Test for Cycle Time Reduction

Parameters	Description	
P value and statistical significance	The two-tailed P value is less than 0.0001. By conventional criteria, this difference is considered to be extremely statistically significant.	
Confidence interval	The mean of Traditional minus Smart equals 268.84. 95% confidence interval of this difference: From 261.54 to 276.14.	
Intermediate values used in calculations	t = 73.0375. df = 99. Standard error of difference = 3.681.	
Review of data used for the analysis:		
Group	TMAT	SMAT
Mean	1178.20	909.36
Standard Deviation	50.75	19.57
Standard Error of the Mean	5.07	1.96
Sample Size	100	100

4.4. Observations and key findings

- Smart technologies enhanced operator adaptability: Novice workers adapted 22.82% faster to the SMAT due to visual guidance and real-time feedback. Table 7 provides insights into the adaptation rate to the SMAT.
- Reduced cognitive load on operators: Digital instructions and automated assistance minimized operator stress and fatigue, promoting higher work accuracy and consistency. Self-reported fatigue questionnaires from the workers and the reduction in error rate support this finding. The questionnaire recorded and rated workers' perceived levels of fatigue and cognitive load, providing insights into their subjective experience.
- Scalability and cost justification: The efficiency improvements indicated that the SMAT could be scaled across multiple MSME production units, offering a high return on investment (ROI). For instance, with a 22.82% reduction in cycle time and a 30.49% increase in production output, preliminary ROI estimates for MSMEs deploying SMAT could range between 2.3x to 3.5x over 12 months, depending on scale and implementation cost. A detailed ROI model can be developed in future studies to validate these projections. ROI can be broadly represented as:

ROI = (Net Benefit from SMAT – Cost of SMAT Implementation) ÷ Cost of Implementation

Table 7: Adaptation Rate of each worker to the SMAT

Worker	Adaptation Rate (%)
1	21.33%
2	22.93%
3	25.96%
4	22.29%
5	21.36%

4.5. Limitations and future considerations

Despite significant performance gains, certain limitations were identified:

- Limited generalization: The study was conducted in a controlled environment. Real-world variability in operator skill levels and product complexity needs further exploration.
- Long-term reliability unassessed: While short-term benefits were evident, an extended analysis on system maintenance and long-term reliability is required.
- Production scheduling optimization: Implementing an optimized scheduling algorithm could further enhance financial and operational benefits.
- AI-based assistance systems: AI-based assistance systems can be implemented to highlight critical assembly areas, support real-time decision-making, and enable adaptive workflow adjustments. This will enhance both efficiency and operator support in dynamic production environments.

The SMAT demonstrated substantial productivity improvements over the traditional manual assembly setup. The combination of digital guidance, real-time decision making, and automation contributed to faster cycle times, reduced errors, and enhanced operator efficiency. The results validate the potential of Industry 4.0 technologies in transforming MSME assembly operations, enabling potential scale-up in similar contexts and broader adoption in diverse manufacturing settings.

5. Discussion

The findings from this study underscore the potential of the SMAT in transforming assembly operations within MSMEs. By integrating smart assistance technologies (SAT) into the traditional manual assembly process, significant improvements were observed in efficiency, accuracy, and error reduction. This discussion analyzes the key takeaways, implications, limitations, and recommendations derived from the study.

5.1. Key findings and interpretations

The implementation of SMAT resulted in notable enhancements in cycle time efficiency and error rate reduction compared to the TMAT. The real-time tracking, digital work instructions, and automated alerts helped novice workers perform tasks with higher precision and lower cognitive load. The following key findings were observed:

- Reduction in cycle time: The automation of guidance and feedback mechanisms led to a substantial decrease in the time taken per assembly cycle. Workers were able to follow optimized workflows, reducing idle time and improving throughput.
- Error rate reduction: The automated error detection system and step-by-step digital instructions minimized human errors, particularly those related to component placement, fastening, and alignment.
- Improved consistency in performance: Unlike the TMAT, where worker performance varied significantly due to skill differences, the SMAT ensured uniformity in assembly tasks, resulting in standardized output quality.
- Enhanced operator adaptability: The system effectively assisted novice workers by reducing their learning curve. This highlights the potential of SMAT in environments with high worker turnover rates, a common challenge in MSMEs.

5.2. Implications of the findings

The observed improvements indicate that smart-assisted assembly cells can enhance industrial efficiency by addressing long-standing challenges in manual manufacturing operations. The implications of these findings include:

- Productivity gains for MSMEs: The reduction in errors and cycle time directly translates to higher production output, enabling MSMEs to meet market demands more efficiently.
- Support to sustainable practice: Beyond productivity, the SMAT's ability to reduce assembly errors contributes to decreased material waste and resource use, supporting sustainable practices, particularly valuable for MSMEs with limited production margins.
- Cost-effectiveness and ROI: While the initial investment in SMAT involves technology upgrades, the long-term benefits in terms of reduced rework, optimized labor utilization, and increased throughput justify the costs. While precise ROI quantification was beyond this study's scope, the observed improvements in productivity, error reduction, and operator independence suggest potential cost benefits for MSMEs adopting SMAT. Reduced rework, shorter training time, and faster assembly cycles contribute to operational savings, supporting future ROI-oriented investigations.
- Human-machine collaboration and worker satisfaction: The study demonstrates that smart technologies can augment human capabilities, making manufacturing more inclusive for inexperienced workers rather than replacing human labor. Preliminary qualitative feedback from novice operators indicated a sense of increased confidence and ease of task execution while using the SMAT setup, suggesting a positive impact on user engagement. A detailed study focusing on worker satisfaction and long-term ergonomic effects is planned as part of future research.
- Quality improvement: The improved precision in assembly tasks results in fewer defective products, thereby enhancing the overall quality and customer satisfaction.
- Human-computer interaction (HCI): The design of SMAT consciously reflects HCI principles by emphasizing intuitive guidance, feedback clarity, and reduced task complexity, crucial for novice usability.
- Training and skill development: Beyond operational efficiency, the SMAT platform holds potential as a training-enabling tool for inexperienced operators. Its structured guidance, real-time feedback, and intuitive interface can be aligned with pedagogical strategies from vocational training and industrial psychology, supporting skill development in MSME environments.

5.3. Comparative analysis: TMAT vs. SMAT

A comparative evaluation, as shown in Table 8, highlights the impact of SMAT on assembly efficiency and accuracy.
The transition to SMAT aligns with Industry 4.0 principles, which advocate for intelligent, interconnected manufacturing systems that enhance efficiency and adaptability.

Table 8: Comparative Analysis: TMAT vs. SMAT.

Parameter	TMAT	SMAT
Cycle Time Variability	High due to operator dependency	Low due to standardized digital guidance
Error Rate	Higher due to manual oversight	Significantly lower with automated error detection
Training Time for Novices	Longer due to manual learning	Reduced with real-time guidance
Process Efficiency	Moderate	High, with optimized workflows
Scalability	Limited	Adaptable to different assembly tasks

5.4. Limitations of the study

While the results highlight the benefits of SMAT, certain limitations must be considered:

- Real-world variability: The study was conducted in a controlled environment. Real-world variability in worker behavior, production scheduling, and external factors could influence performance.
- Skill-level generalization: The study primarily focused on novice workers. Future research should examine its effectiveness across skilled and semi-skilled operators to assess broader applicability.
- Long-term maintenance analysis: The impact of hardware and software maintenance on long-term system performance and cost-effectiveness was not extensively explored.
- Limited batch size consideration: The study did not evaluate large-scale batch processing scenarios, which could introduce complexities in scheduling and workload balancing.
- Small sample size of five workers: With the small sample size of five workers, the study acknowledges the limited sample size as a constraint on generalizability, while reaffirming the study's focus on early-stage implementation within an MSME setting.

5.5. Recommendations for future research

To further enhance the effectiveness of SMAT, future research should focus on:

- Testing across diverse manufacturing environments: Expanding the study to different industries and product types will provide insights into the system's adaptability.
- Integration with advanced scheduling algorithms: Implementing AI-driven scheduling techniques could optimize batch sequencing and order fulfillment, further improving efficiency [45]. Future enhancements could explore AI-based scheduling using techniques such as genetic algorithms, rule-based optimization, reinforcement learning, or predictive analytics. These approaches may improve task allocation and resource planning in expanded multi-station setups.
- Long-term performance evaluation: A longitudinal study assessing system durability, maintenance needs, and operator adaptability will provide a clearer picture of its sustainability.
- Scalability to multi-station smart assembly cells: Exploring how multiple interconnected SMAT units' function in a parallel assembly setup can offer insights into scaling this technology for larger production systems [46].
- HCI or psychological assessment: The development of SMAT aligns with key considerations in industrial psychology, including cognitive ergonomics and operator workload. Future work could involve structured evaluation of these psychological dimensions to enhance the system's human-centric performance. Although this study primarily focused on quantifiable performance metrics and cognitive load to evaluate operator response, it did not include detailed ergonomic or psychological assessments such as stress, fatigue, or emotional response. These factors are important for a comprehensive understanding of operator well-being and long-term system efficiency. Future research could explore these aspects through collaboration with experts in occupational psychology or ergonomics to support broader interdisciplinary integration.
- AI assistance: Future work may explore integrating AI to assist with real-time decision-making and adaptive workflow adjustments in manual assembly.
- Assessing a sufficiently more number of workers: While the results are encouraging, the small sample size of five workers limits broad generalization. Future studies with larger participant pools can offer deeper statistical insights.
- Benchmarking: While the SMAT was validated in a novice-centric MSME environment, future studies could benchmark its performance against broader industrial implementations to assess scalability and adaptability.
- Human factors in smart manual assembly: While this study focused on task efficiency and system responsiveness, the user-centered design of SMAT aimed to reduce cognitive strain and simplify interaction for inexperienced operators. Future research could involve structured usability assessments and satisfaction surveys to validate the collaborative effectiveness from the human factors' perspective.

5.6. Deployment

The SMAT system was deployed in a real-time MSME environment using existing workstation infrastructure, requiring minimal alterations. This practical integration reinforces the system's applicability and cost-effectiveness in resource-constrained settings.

The SMAT presents a technological advancement that effectively enhances productivity and accuracy in manual assembly operations within MSMEs. By integrating smart technologies, real-time monitoring, and automated guidance, it bridges the gap between traditional manual workflows and modern automated systems. The findings suggest that MSMEs adopting such innovations can achieve higher efficiency, reduced error rates, and improved worker adaptability, reinforcing the importance of Industry 4.0-driven solutions in small-scale manufacturing environments. The findings contribute theoretically to the evolving discourse on human-machine integration within Industry 4.0, particularly in the context of cognitive load management and task simplification for novice workers. This aligns with socio-technical system theory and supports adaptive design principles in low-resource manufacturing settings.

6. Conclusion

The implementation of the SMAT has demonstrated significant improvements in assembly efficiency, error reduction, and worker adaptability within MSME operations. The study highlights how integrating SAT into traditional manual assembly processes can streamline workflows, reduce cognitive load, and enhance productivity, particularly for novice workers. The results indicate that real-time monitoring, automated feedback, and digital guidance contribute to reduced cycle times and improved assembly accuracy, ultimately leading to higher production rates and better product quality.

The findings suggest that SMAT can serve as an effective solution to address workforce challenges commonly faced by MSMEs, such as high attrition rates, skill variability, and inconsistent production quality. By minimizing human errors and improving operator performance, SMAT enhances human-machine collaboration where workers are supported rather than replaced by automation. The reduction in error rates and increased efficiency also align with lean manufacturing principles, reinforcing its potential to drive continuous improvement and operational excellence in MSME settings.

Preliminary indicators point toward promising ROI outcomes due to reduced cycle time and increased process reliability. Future work may include formal ROI modeling to guide scalable SMAT deployments in MSME environments. The cost-benefit analysis justifies the investment in smart technologies, as the long-term gains in productivity, waste reduction, and quality enhancement outweigh the initial implementation costs. However, the adaptability of SMAT across different assembly tasks and industrial environments requires further evaluation. The controlled environment of this study may not fully represent the dynamic conditions of real-world manufacturing. Additionally, broader benchmarking beyond the traditional setup was not included. The SMAT system showed strong potential for novice support in MSMEs. In addition to the current analysis, the study acknowledges the importance of industrial benchmarking for SMAT systems. Future research will explore comparative evaluations with existing industrial deployments to understand scalability and domain adaptability, particularly in diverse production environments. Future research should assess the system's scalability, effectiveness across different skill levels, and long-term maintenance requirements to ensure its widespread applicability. This study did not include stress or fatigue analysis, which can be explored in future ergonomic or psychological research. Future studies may incorporate AI-based assistance to identify critical tasks, support real-time decisions, and adapt workflows for improved efficiency and operator experience.

Moreover, optimizing production scheduling and order sequencing through advanced scheduling algorithms can further enhance financial benefits for MSMEs. Implementing a parallel SMAT setup and exploring its impact on batch processing could lead to further efficiency gains.

6.1. Academic contribution

This research contributes to the advancement of smart manufacturing methodologies by demonstrating the practical benefits of technology-assisted manual assembly systems. The study provides empirical data supporting the integration of digital assistance tools into MSME assembly processes, offering insights into their potential to bridge the gap between traditional and automated manufacturing environments.

6.2. Research contribution

The development and deployment of SMAT present a real-world application of smart manufacturing technologies in MSMEs. The study's findings lay the foundation for future research on optimizing manual assembly processes, integrating intelligent decision-making algorithms, and expanding smart technologies to broader industrial contexts. Beyond MSME-level benefits, the proposed SMAT system holds promise for influencing policy-level initiatives, particularly in setting benchmarks for worker-centric automation, safety integration, and scalable, low-cost smart assembly cells. Its structured approach and modular design can inform industrial standardization protocols tailored to small-scale sectors and emerging economies.

This study demonstrates the potential of the SMAT to enhance productivity and reduce errors in MSME assembly environments, particularly for novice operators. While implemented at a single site, the approach aligns with Industry 4.0 principles by incorporating real-time guidance, ergonomic design, and data-driven insights. The results suggest that such low-cost, smart interventions can support quality improvement and operational efficiency in similar contexts, offering a practical pathway for MSMEs seeking to remain competitive in a rapidly evolving manufacturing landscape.

References

[1] Suresh Vasani, and Ahmed Mahdi Abdulkareem, "MSME Market Presence and Competitiveness in a Global Economy", *Cogent Economics & Finance*, Volume 12, Issue 1, (2024), Article No. 2416992, https://doi.org/10.1080/23322039.2024.2416992.

[2] Chandan Maheshkar, and Neha Soni, "Problems Faced by Indian Micro, Small And Medium Enterprises (MSMEs)", *SEDME (Small Enterprises Development, Management & Extension Journal): A Worldwide Window on MSME Studies*, Volume 48, Issue 2, (2021), pp. 142-159, https://doi.org/10.1177/09708464211064498.

[3] Henrik Hansen, S. Kanay De, John Rand, and Neda Trifković, "Wage Returns to Workplace Training in Myanmar", *Development Policy Review*, Volume 41, Issue 2, (2022), Article No. e12658, https://doi.org/10.1111/dpr.12658.

[4] Adi Saptari, Jia Xin Leau, and Nor Akramin Mohamad, "The Effect of Time Pressure, Working Position, Component Bin Position and Gender on Human Error in Manual Assembly Line", *Proceedings of the 2015 International Conference on Industrial Engineering and Operations Management (IEOM)*, 03-05 March 2015, IEEE, (2015), pp. 1-6, https://doi.org/10.1109/IEOM.2015.7093793.

[5] Adi Saptari, Jia Xin Leau, Poh Kiat Ng, and Effendi Mohamad, "Human Error and Production Rate Correlation in Assembly Process of Electronics Goods", *Proceedings of the 2014 Design and Systems Conference*, Volume 2014.24, 2014.24, Session ID 2309, (2014) pp. 2309-1-2309-6, Released on J-STAGE June 19, 2017, Online ISSN 2424-3078, https://www.jstage.jst.go.jp/article/jsmedsd/2014.24/0/2014.24__2309-1_/_article/-char/en. https://doi.org/10.1299/jsmedsd.2014.24._2309-1_.

[6] Shady Aly, Jan Tyrychtr, and Ivan Vrana, "Optimizing Design of Smart Workplace Through Multi-Objective Programming", *Applied Sciences*, Volume 11, Issue 7, (2021), pp. 3042, https://doi.org/10.3390/app11073042.

[7] John A. Slotwinski and Robert B. Tilove, "Smart Assembly: Industry Needs and Challenges", *Proceedings of the 2007 Workshop on Performance Metrics for Intelligent Systems, in PerMIS '07*, New York, NY, USA: Association for Computing Machinery, (2007), pp. 257-262, https://doi.org/10.1145/1660877.1660914.

[8] Hassan Hijry, Syed Meesam Raza Naqvi, Kamran Javed, Omar H. Albalawi, Richard Olawoyin, and Christophe Varnier, "Real Time Worker Stress Prediction in a Smart Factory Assembly Line", *IEEE Access*, Volume 12, (2024), pp. 116238-116249, https://doi.org/10.1109/ACCESS.2024.3446875.

[9] Yaniel Torres, Sylvie Nadeau, and Kurt Landau, "Classification and Quantification of Human Error in Manufacturing: A Case Study in Complex Manual Assembly", *Applied Sciences*, Volume 11, Issue 2, (2021), p. 749, https://doi.org/10.3390/app11020749.

[10] Fahad M. Alqahtani, Mohammed A. Noman, Saad A. Alabdulkarim, Ibrahim Alharkan, Mohammed H. Alhaag, and Faisal M. Alessa, "A New Model for Determining Factors Affecting Human Errors in Manual Assembly Processes Using Fuzzy Delphi and DEMATEL Methods", *Symmetry*, Volume 15, Issue 11, (2023), p. 1967, https://doi.org/10.3390/sym15111967.

[11] Majorkumar Govindaraju, Arunkumar Pennathur, Anil Mital, "Quality Improvement in Manufacturing Through Human Performance Enhancement", *Integrated Manufacturing Systems*, Volume 12, Issue 5, (2001), pp. 360-367, https://doi.org/10.1108/EUM0000000005713.

[12] M. Eswaramoorthi, Marvyn John, C. Arjun Rajagopal, P. S. S. Prasad, P. V. Mohanram, "Redesigning Assembly Stations Using Ergonomic Methods as a Lean Tool', *Work*, Volume 35, Issue 2, (2010), pp. 231-40. Available at: https://www.researchgate.net/profile/Eswara-Moorthi/publication/41466164_Redesigning_assembly_stations_using_ergonomic_methods_as_a_lean_tool/links/00b7d534348b49533c000000/Redesigning-assembly-stations-using-ergonomic-methods-as-a-lean-tool.pdf. https://doi.org/10.3233/WOR-2010-0975.

[13] Adrian Miqueo, Marta Torralba, and José A. Yagüe-Fabra, 'Lean Manual Assembly 4.0: A Systematic Review', Applied Sciences, Volume 10, Issue 23, (2020), Article No. 8555, https://doi.org/10.3390/app10238555.

[14] Nils Boysen, Philipp Schulze, and Armin Scholl, "Assembly Line Balancing: What Happened in the Last Fifteen Years?", *European Journal of Operational Research*, Volume 301, Issue 3, (2022), pp. 797-814, https://doi.org/10.1016/j.ejor.2021.11.043.

[15] Matilda Wollter Bergman, Cecilia Berlin, Maral Babapour Chafi, Ann-Christine Falck, and Roland Örtengren, "Cognitive Ergonomics of Assembly Work from a Job Demands–Resources Perspective: Three Qualitative Case Studies", *International Journal of Environmental Research and Public Health*, Volume 18, Issue 23, (2021), pp. 12282, https://doi.org/10.3390/ijerph182312282.

[16] Cecilia Berlin, Matilda Wollter Bergman, Maral Babapour Chafi, Ann-Christine Falck, and Roland Örtengren, "A Systemic Overview of Factors Affecting the Cognitive Performance of Industrial Manual Assembly Workers", *Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021)*, Volume 221, N. L. Black, W. P. Neumann, and I. Noy, Eds., Cham: Springer International Publishing, (2021), pp. 371-381, https://doi.org/10.1007/978-3-030-74608-7_47.

[17] Dilip Chenoy, Shobha Mishra Ghosh, and Shiv Kumar Shukla, "Skill development for accelerating the manufacturing sector: the role of "new-age" skills for "Make in India"", *International Journal of Training Research*, Volume 17, No. Sup1, (2019), pp. 112-130, https://doi.org/10.1080/14480220.2019.1639294.

[18] Mohd Javaid, Abid Haleem, Ravi Pratap Singh, Rajiv Suman, and Ernesto Santibañez Gonzalez, "Understanding the Adoption of Industry 4.0 Technologies in Improving Environmental Sustainability", *Sustainable Operations and Computers*, Volume 3, (2022), pp. 203-217, https://doi.org/10.1016/j.susoc.2022.01.008.

[19] Md Mosleuzzaman, Imran Arif, and Amir Siddiki, "Design and Development of a Smart Factory Using Industry 4.0 Technologies', *Academic Journal on Business Administration, Innovation & Sustainability (AJBAIS)*, Volume 4, Issue 04, (2024), pp. 89-108, https://doi.org/10.69593/ajbais.v4i04.131.

[20] Mohsen Soori, Behrooz Arezoo, and Roza Dastres, "Virtual manufacturing in Industry 4.0: A review", *Data Science and Management*, Volume 7, Issue 1, (2024), pp. 47-63, https://doi.org/10.1016/j.dsm.2023.10.006.

[21] Josef Wolfartsberger, Jan Zenisek, Mathias Silmbroth, and Christoph Sievi, "Towards an Augmented Reality and Sensor-Based Assistive System for Assembly Tasks", *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments (PETRA'17)*, Island of Rhodes Greece: ACM, (2017), pp. 230-231, https://doi.org/10.1145/3056540.3064969.

[22] Ze-Hao Lai, Wenjin Tao, Ming C. Leu, and Zhaozheng Yin, "Smart Augmented Reality Instructional System for Mechanical Assembly Towards Worker-Centered Intelligent Manufacturing", *Journal of Manufacturing Systems*, Volume 55, (2020), pp. 69-81, https://doi.org/10.1016/j.jmsy.2020.02.010.

[23] Agnese Brunzini, Fabio Grandi, Margherita Peruzzini, and Marcello Pellicciari, "Virtual Training for Assembly Tasks: A Framework for the Analysis of the Cognitive Impact on Operators", *Procedia Manufacturing*, Volume 55, (2021), pp. 527–534, https://doi.org/10.1016/j.promfg.2021.10.072.

[24] Maneetkumar Dhanvijay, Vinay Kulkarni, N. Patil, and Anand Bewoor, "Development of PLC-Based System for Lift Gate Slam Platform", *AIP Conference Proceedings (Proceedings of the International Conference on Materials for Emerging Technologies: ICMET-2021*, 18-19 February 2022, Phagwara, India), Volume 2800, Issue 1, (2023), Article number 020231, https://doi.org/10.1063/5.0163916.

[25] Maneetkumar Dhanvijay, Rohit Patki, and Bharatkumar Ahuja, "Development of PLC-Based Controller for Door Slam Platform", *Frontiers of Mechanical and Industrial Engineering: Optimization Methods for Engineering Problems*, Editors: Dilbagh Panchal, Prasenjit Chatterjee, Mohit Tyagi, and Ravi Pratap Singh, Chapter 2, (2023), pp. 17-30, Apple Academic Press, available at: https://www.taylorfrancis.com/chapters/edit/10.1201/9781003300731-2/development-plc-based-controller-door-slam-platform-maneetkumar-dhanvijay-rohit-patki-ahuja. https://doi.org/10.1201/9781003300731-2.

[26] Sebastian Pimminger, Werner Kurschl, Lisa Panholzer, and Johannes Schönböck, "Exploring the Learnability of Assembly Tasks Using Digital Work Instructions in a Smart Factory", *Procedia CIRP*, Volume 104, (2021), pp. 696-701, https://doi.org/10.1016/j.procir.2021.11.117.

[27] Shin Joe Ch'ng, "Automated Manual Assembly Station Using Computer Vision", *Final Year Project, UTAR*, (2024), Available at: http://eprints.utar.edu.my/6628/.

[28] Tingting Chen, Vignesh Sampath, Marvin Carl May, Shuo Shan, Oliver Jonas Jorg, Juan José Aguilar Martín, Florian Stamer, Gualtiero Fantoni, Guido Tosello, and Matteo Calaon, "Machine Learning in Manufacturing towards Industry 4.0: From "For Now" to "Four-Know"", *Applied Sciences*, Volume 13, Issue 3, (2023), p. 1903, https://doi.org/10.3390/app13031903.

[29] Christopher Stockinger, Lucas Polanski-Schräder, Ilka Subtil, "The Effect of Information Level of Digital Worker Guidance Systems on Assembly Performance, User Experience and Strain", Applied Ergonomics, Volume 106, (2023), Article No. 103896, https://doi.org/10.1016/j.apergo.2022.103896.

[30] Mohsen Soori, Behrooz Arezoo, and Roza Dastres, "Internet of Things for Smart Factories in Industry 4.0, A Review", *Internet of Things and Cyber-Physical Systems*, Volume 3, (2023), pp. 192-204, https://doi.org/10.1016/j.iotcps.2023.04.006.

[31] Muhammad Hamza Zafar, Even Falkenberg Langås, and Filippo Sanfilippo, "Exploring the Synergies between Collaborative Robotics, Digital Twins, Augmentation, and Industry 5.0 for Smart Manufacturing: A State-Of-The-Art Review", *Robotics and Computer-Integrated Manufacturing*, Volume 89, (2024), Article No. 102769, https://doi.org/10.1016/j.rcim.2024.102769.

[32] Oliver Sand, Sebastian Büttner, Volker Paelke, and Carsten Röcker, "smARt.Assembly - Projection-Based Augmented Reality for Supporting Assembly Workers", *Virtual, Augmented and Mixed Reality*, Stephanie Lackey and Randall Shumaker, Eds., Cham: Springer International Publishing, (2016), pp. 643-652, https://doi.org/10.1007/978-3-319-39907-2_61.

[33] Sarah R. Fletcher, Teegan Johnson, Tobias Adlon, Jon Larreina, Patricia Casla, Laure Parigot, Pedro J. Alfaro, and María del Mar Otero, "Adaptive Automation Assembly: Identifying System Requirements for Technical Efficiency and Worker Satisfaction", *Computers & Industrial Engineering*, Volume 139, (2020), pp. 105772, https://doi.org/10.1016/j.cie.2019.03.036.

[34] Carlos Real and Yaniel Torres, "Effect of Changes in the Sequence of Assembly Operations on Error Rates: A Case Study from the Car Manufacturing Industry", *IEEE Access*, Volume 12, (2024), pp. 34644-34655, https://doi.org/10.1109/ACCESS.2024.3371980.

[35] Muhammad Hariz Mohd Rizal, and Ramhuzaini Abd. Rahman, "Improvement of DLA Sealing Machine Monitoring Process: Mechanical Design and Prototyping of Automatic Alert System", *Research Progress in Mechanical and Manufacturing Engineering*, Volume 4, Issue 1, (2023), pp. 347-358, available at: https://penerbit.uthm.edu.my/periodicals/index.php/rpmme/article/view/9260/397.

[36] Moh. Muklis Sulaeman, Anjelina Sindy Parwati, M. Sholla Alfatih Saputra, Ririn Pinatih, and Khoirul Abidin, "Strategies for Improving the MSME Economy through the Implementation of Technology-Based Business Management", *Technology and Society Perspectives (TACIT)*, Volume 2, Issue 2, (2024), pp. 218-224, available at: https://journal.literasisainsnusantara.com/index.php/tacit/article/view/193/176.

[37] Li Xu, Yang Zou, Yuqian Lu, and Alice Chang-Richards, "Automation in Manufacturing and Assembly of Industrialised Construction", *Automation in Construction*, Volume 170, (2025), 105945, https://doi.org/10.1016/j.autcon.2024.105945.

[38] Marianna Ciccarelli, Alessandra Papetti, and Michele Germani, "Exploring how New Industrial Paradigms Affect the Workforce: A Literature Review of Operator 4.0.", *Journal of Manufacturing Systems*, Volume 70, (2023), pp. 464-483, https://doi.org/10.1016/j.jmsy.2023.08.016.

[39] Cristina Morariu, Octavian Morariu, Silviu Răileanu, and Theodor Borangiu, "Machine Learning for Predictive Scheduling and Resource Allocation in Large Scale Manufacturing Systems", *Computers in Industry*, Volume 120, (2020), Article No. 103244, https://doi.org/10.1016/j.compind.2020.103244.

[40] Francesco N. Biondi, Angela Cacanindin, Caitlyn Douglas, and Joel Cort, "Overloaded and at Work: Investigating the Effect of Cognitive Workload on Assembly Task Performance", *Human Factors*, Volume 63, Number 5, (2021), pp. 813-820, https://doi.org/10.1177/0018720820929928.

[41] Bin Ren, Qinyu Zhou, and Jiayu Chen, "Assessing Cognitive Workloads of Assembly Workers During Multi-Task Switching", *Scientific Reports*, Volume 13, Number 1, (2023), pp. 16356, https://doi.org/10.1038/s41598-023-43477-0.

[42] Marco Bortolini, Lucia Botti, Francesco Gabriele Galizia, and Cristina Mora, "Ergonomic Design of an Adaptive Automation Assembly System", *Machines*, Volume 11, Issue 9, (2023), pp. 898, https://doi.org/10.3390/machines11090898.

[43] Yuchen Fan, Alessandro Simeone, Dario Antonelli, Alessandro Caggiano, Paolo C. Priarone, and Luca Settineri, "A Framework for Digital Assembly Instructions as a Step Towards Manufacturing Inclusiveness", *Procedia CIRP*, Volume 132, (2025), pp. 116-121, https://doi.org/10.1016/j.procir.2025.01.020.

[44] Mathias Nausch, Philipp Hold, and Wilfried Sihn, "A Methodological Approach for Monitoring Assembly Processes", *Procedia CIRP*, Volume 104, (2021), pp. 1233-1238, https://doi.org/10.1016/j.procir.2021.11.207.

[45] Dharmik Chiragkumar Hajariwala, Srishti Sudhir Patil, Sudhir Madhav Patil, "A Review of Metaheuristic Algorithms for Job Shop Scheduling", *Engineering Access*, Volume 11, Issue 1, (2025), pp. 65-91, available at: https://ph02.tci-thaijo.org/index.php/mijet/article/view/254023/171453.

[46] Pranav Shivraj Patil, Srishti Sudhir Patil, Sudhir Madhav Patil, Maneetkumar Rangnath Dhanvijay, "Development of MS Excel and Power BI Integrated Production Scheduling System for an MSME", *Engineering Access*, Volume 10, Issue 2, (2024), pp. 124-142, available at: https://ph02.tci-thaijo.org/index.php/mijet/article/view/252664/170668.