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LEAN-DRIVEN SUSTAINABLE ENGINEERING ENHANCED BY TRIZ: A CONCEPTUAL APPROACH TO WASTE ELIMINATION IN MANUFACTURING SYSTEM LABORATORY

Uly Amrina[1*], Hendi Herlambang[2], Galang Persada Nurani Hakim[3], Irkham Syifaul Qulub[4], Lutfi Saputro[5]
Industrial Engineering Department, Faculty of Engineering, Universitas Mercu Buana, Indonesia[1]
PT. JST Indonesia, Indonesia[24]
Electrical Engineering Department, Faculty of Engineering, Universitas Mercu Buana, Indonesia[3]
Mechanical Engineering Department, Faculty of Engineering, Universitas Mercu Buana, Indonesia[5]
uly.amrina@mercubuana.ac.id[1]

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**Corresponding Author*

ABSTRACT
Manufacturing system laboratories are essential in engineering education, however, existing laboratory-scale equipment often exhibits long cycle times, high energy consumption, poor ergonomics, and limited integration of sustainability principles. Prior studies generally address lean manufacturing, TRIZ-based innovation, or sustainable engineering separately, leaving a gap in a unified framework tailored for laboratory environments. This study aims to develop an integrated lean-driven sustainable engineering framework enhanced by TRIZ to systematically eliminate waste in a manufacturing system laboratory. A conceptual–experimental approach was adopted by combining lean waste analysis, TRIZ-based technical contradiction resolution, and sustainable engineering principles to redesign a modular Heating–Vacuum–Trimming (HVT) system. The proposed system was evaluated through prototyping and laboratory testing. The results demonstrate a reduction in process cycle time of up to 33% and a decrease in electrical energy consumption of approximately 16% compared to conventional equipment. From a practical perspective, the framework enables the development of modular, ergonomic, and energy-efficient laboratory tools that improve operational efficiency. From a theoretical perspective, this study extends the integrated application of lean manufacturing, TRIZ, and sustainable engineering into a cohesive framework suitable for laboratory-scale manufacturing systems. The proposed approach offers transferability.
Keywords: *lean manufacturing, TRIZ, sustainable engineering, waste elimination, laboratory*

1. Introduction

The rapid advancement of manufacturing technologies and the increasing emphasis on sustainability have significantly reshaped the competencies required of future engineers. (Sultana et al., 2024). Manufacturing system laboratories play a critical role in engineering education by serving as experimental platforms where students internalize industrial practices, process integration, and continuous improvement principles (Kozub et al., 2021; Sremcev et al., 2018). However, laboratory-scale manufacturing systems often face persistent challenges, including long cycle times, inefficient energy usage, poor ergonomics, fragmented equipment, and limited incorporation of sustainability concepts. These limitations reduce not only operational efficiency but also the effectiveness of laboratories in reflecting real-world manufacturing environments. As a result, these systems often fail to accurately represent real industrial conditions and limit students' understanding of contemporary manufacturing challenges (Fernández-Maldonado, 2012; Zhengzhou et al., 2021).

Quantitative evidence from a university manufacturing systems laboratory reveals significant inefficiencies in the existing laboratory-scale production system. The observed average cycle time for a miniature car manufacturing process reached 592.25 seconds, exceeding the target cycle time of 482.50 seconds by 109.75 seconds. Among all workstations, the Heating–Vacuum–Trimming (HVT) workstation exhibited the largest performance gap, with an average cycle time of 363.97 seconds compared to the target of 286.50 seconds, resulting in a deviation of 77.47 seconds. This inefficiency directly contributes to increased idle time, higher energy consumption, operator fatigue, and material waste, as shown in Table 1.

Table 1 - Cycle Time Calculation

Workstation / Process	**Cycle Time (in seconds)**		
	Target	**Actual (Average)**	**Gap**
WS 1: Heating-Vacuum-Trimming	**286.50**	**363.97**	**77.47**
WS 2: Press Tyre	11.00	10.95	(0.05)
WS 3: Assembly	161.00	183.50	22.50
WS 4: Quality Control	18.00	22.49	4.49
WS 5: Packaging	6.00	11.34	5.34
TOTAL	**482.50**	**592.25**	**109.75**

Further observations at the HVT workstation, conducted through direct observation and interviews with student operators, revealed that the existing devices were non-specific and ergonomically suboptimal, thereby hindering safe and timely operations. The heating process involved significant idle time as operators waited for the oven to reach the proper temperature for molding. Similarly, the vacuum process was affected when the PVC plastic did not meet the required temperature, complicating mold removal. The manual trimming with dull scissors often resulted in inaccurate shapes, contributing to inefficiencies, operator fatigue, and compromised product quality. These issues result in material waste, increased energy consumption, and rework, underscoring the importance of sustainable engineering principles that emphasize resource minimization, modularity, material reuse, and disassembly for enhanced environmental and operational efficiency. These findings highlight a clear need for redesigning laboratory manufacturing equipment to align with productive and sustainable engineering objectives.

Lean Manufacturing has long been recognized as an effective approach for eliminating waste, improving process flow, and enhancing productivity in industrial systems. Recent studies highlight its growing relevance in educational and small-scale manufacturing contexts, where resource constraints demand efficient and structured process design (Amrina et al., 2024; Rizkiyah et al., 2024). In laboratory environments, lean principles are particularly valuable for reducing idle time, minimizing non-value-added activities, and improving repeatability in learning-oriented production systems. Nevertheless, the application of lean tools alone often encounters limitations when improvements in efficiency introduce new technical constraints or design conflicts. In parallel, Sustainable Engineering has emerged as a fundamental paradigm in manufacturing, emphasizing energy efficiency, material conservation, modularity, and environmentally responsible system design impacts (Purba et al., 2025; Gama and Bonamigo, 2024). The integration of sustainability into engineering education laboratories is increasingly necessary to align academic training with global industrial and environmental demands (Raoufi and Haapala, 2024; Qamar et al., 2025). Laboratory-scale manufacturing systems, however, frequently lack explicit sustainability-oriented design considerations, resulting in excessive energy consumption, material waste, and limited reuse or recyclability of components. Although Lean tools are effective in identifying waste, they often lack systematic mechanisms for resolving technical contradictions inherent in equipment redesign, especially in constrained laboratory environments. The Theory of Inventive Problem Solving (TRIZ) provides a structured framework for resolving such contradictions through inventive principles and contradiction matrices (Anuar et al., 2022; Hia et al., 2025). TRIZ has been widely applied in product design and industrial innovation to generate inventive solutions without compromising system performance (Ekmekci and Nebati, 2019; Gdoura et al., 2024; Qulub et al., 2024). In manufacturing laboratories, TRIZ is particularly relevant for resolving conflicts between efficiency, system complexity, ergonomics, and sustainability. Despite its potential, TRIZ is still underutilized in laboratory-scale manufacturing system design, especially in combination with lean and sustainable engineering principles. TRIZ has been widely applied in product design and industrial innovation to generate inventive solutions without compromising system performance (Ekmekci and Nebati, 2019). In manufacturing laboratories, TRIZ is particularly relevant for resolving conflicts between efficiency, system complexity, ergonomics, and sustainability. Despite its potential, TRIZ is still underutilized in laboratory-scale manufacturing system design, especially in combination with lean and sustainable engineering principles.

A review of recent literature indicates that existing studies predominantly address lean manufacturing, sustainable engineering, or TRIZ as separate or partially combined approaches. While some research explores lean–green manufacturing integration or TRIZ-assisted design, most studies focus on large-scale industrial applications, with limited attention to laboratory-scale manufacturing systems used for education and training (Rahardjo et al., 2025; Slim et al., 2021). Moreover, there is a lack of a comprehensive framework that simultaneously integrates lean principles, TRIZ-based contradiction resolution, and sustainability considerations into a unified approach tailored specifically for manufacturing system laboratories. This gap limits the development of laboratory equipment that is efficient, innovative, and environmentally responsible. The absence of such integrated frameworks highlights the necessity of this research. As universities strive to produce industry-ready graduates with sustainability-oriented mindsets, manufacturing laboratories must evolve beyond conventional, fragmented tools toward systems that embody lean efficiency, systematic innovation, and sustainable design. Addressing these needs is essential not only for improving laboratory performance but also for strengthening the relevance of engineering education to contemporary industrial challenges.

Therefore, the objective of this study is to develop an integrated Lean–TRIZ–Sustainable Engineering framework for redesigning laboratory-scale manufacturing systems to systematically eliminate waste and enhance sustainability performance. This research focuses on the development of a modular Heating–Vacuum–Trimming (HVT) system as a representative case in a manufacturing system laboratory. The novelty of this study lies in the unified integration of lean manufacturing, TRIZ-based inventive problem-solving, and sustainable engineering principles into a laboratory-oriented framework, which has not been sufficiently addressed in previous research. By bridging this gap, the study contributes theoretically to the advancement of integrated sustainable manufacturing frameworks and practically by providing a transferable model for designing efficient, ergonomic, and sustainable educational systems.

2. Literature Review

This study combines the approaches of Lean Manufacturing, TRIZ (Theory of Inventive Problem Solving), and Sustainable Engineering within an integrated conceptual framework designed to systematically address process waste, inefficiency, and sustainability challenges in an engineering education laboratory environment. This literature review was conducted using a structured approach to ensure relevance, quality, and recency. Scientific articles were retrieved from Scopus and Google Scholar databases using keywords such as *lean manufacturing*, *sustainable engineering*, *TRIZ*, *laboratory-scale manufacturing*, and *engineering education*. The selection criteria included (1) peer-reviewed international journal articles, (2) publication period between 2018 and 2025, and (3) relevance to manufacturing system design, process improvement, sustainability, or systematic innovation. Studies focusing exclusively on large-scale industrial applications without transferable insights to laboratory or small-scale systems were excluded. This approach ensured that the reviewed literature provides a strong theoretical and empirical foundation for identifying gaps relevant to manufacturing laboratories.

Lean Manufacturing, Sustainable Engineering, and TRIZ represent three complementary but often separately applied approaches in manufacturing system design. Recent studies show that lean manufacturing is effective in educational and small-scale manufacturing systems for identifying non-value-added activities, reducing cycle time, and improving process flow efficiency under constrained resources (Ikatrinasari et al., 2018), however, lean-based improvements alone tend to be incremental and frequently generate new technical constraints related to ergonomics, automation, or system complexity. In parallel, sustainable engineering research emphasizes energy efficiency, material optimization, modularity, and lifecycle-oriented design (Cabrita & Cruz-Machado, 2023), yet in laboratory-scale manufacturing systems these principles are often implemented independently of process optimization, limiting their operational impact. TRIZ, as a systematic innovation methodology, has demonstrated strong capability in resolving technical contradictions without performance trade-offs (Ghane et al., 2024;Donnici et al., 2018; Rahman et al., 2026) but its application remains largely confined to product development and industrial-scale systems (Seo et al., 2025;Soares and Navas, 2023). A synthesis of recent literature (2020–2025) indicates that existing studies predominantly address these approaches in isolation or partial combinations, with limited research proposing an integrated framework specifically tailored to laboratory-scale manufacturing environments. This fragmentation constitutes a critical research gap, particularly for educational laboratories that must simultaneously achieve efficiency, innovation, and sustainability. Accordingly, this study adopts an integrated theoretical framework in which Lean Manufacturing functions as the waste identification mechanism, TRIZ serves as the contradiction-resolution and inventive problem-solving tool, and Sustainable Engineering provides the system-level performance and environmental perspective, directly informing the research objective of developing a modular and sustainable manufacturing laboratory system. Figure 1 illustrates the integrated conceptual framework adopted in this study, highlighting the complementary roles of Lean Manufacturing, Sustainable Engineering principles, and TRIZ methodology.

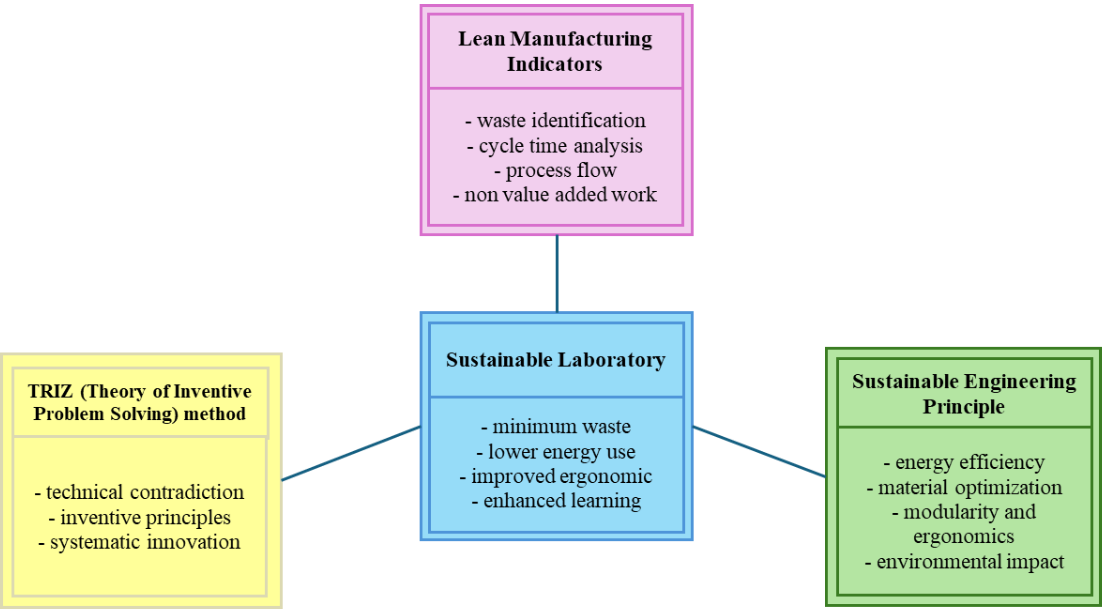

Fig. 1. Conceptual Framework of Lean Manufacturing-Sustainable Engineering-TRIZ Integration

This theoretical framework in Figure 1 positions Lean Manufacturing as the primary mechanism for identifying waste and inefficiencies within laboratory-scale manufacturing systems. Once inefficiencies are identified, TRIZ is applied as a systematic problem-solving methodology to resolve technical contradictions that arise when improving efficiency, automation, or precision. Sustainable Engineering serves as an overarching design principle, ensuring that the resulting solutions are environmentally responsible, energy-efficient, modular, and ergonomically sound. The integration of these three approaches enables the development of manufacturing laboratory systems that simultaneously enhance operational efficiency, sustainability performance, and educational effectiveness.

Despite increasing attention to lean, sustainability, and TRIZ in manufacturing research, there is a clear lack of studies that holistically integrate these three approaches within laboratory-scale manufacturing systems. Existing research often overlooks the unique constraints and educational objectives of laboratory environments. Therefore, the research gap lies in the absence of a unified, systematic framework that simultaneously addresses efficiency, sustainability, and innovation in manufacturing laboratories. This study seeks to fill this gap by developing and validating an integrated Lean–TRIZ–Sustainable Engineering framework, thereby directly linking the literature findings to the research objectives and contributing both theoretically and practically to sustainable manufacturing education. Table 2 presents an overview of the current research on Lean manufacturing, sustainable engineering, and TRIZ integration.

Table 2 - Previous Research Mapping on Lean, Sustainable Engineering, and TRIZ

No	Author	Research Focus		Research Method			Industry Scale			Validation		
		Efficiency / Effectiveness	Sustainability	Lean Methods	TRIZ	QFD	Large	Small-Medium	Lab	Group Perception	Experiment / Observation	Prototype
1	(Renjith et al., 2020)	x			x				x		x	
2	(Asyraf et al., 2020)	x			x				x			x
3	(Dias et al., 2020)	x		x	x			x		x		
4	(Meng et al., 2021)		x		x						x	
5	(Albayrak et al., 2023)	x			x			x			x	
6	(Da Silva et al., 2020)	x			x		x				x	
7	(Fijra et al., 2022)	x			x				x		x	x
8	(Morales Morales et al., 2023)		x		x	x			x		x	
9	(Feng & Zhou, 2023)	x			x			x			x	
10	(Liao et al., 2020)	x				x			x	x		x
11	(Slim et al., 2021)	x		x	x				x			x
12	(Wang & Yang, 2023)	x				x	x				x	
13	(Haleem et al., 2022)	x			x		x					x
14	(Alešnik et al., 2025)	x	x	x	x		x			x	x	
15	(Hanifi et al., 2021)	x		x	x				x		x	
16	This Research	x	x	x	x				x	x	x	x

The originality of this research lies in explicitly bridging this gap by proposing a unified and systematically structured framework that integrates Lean Manufacturing, TRIZ methodology, and Sustainable Engineering principles specifically tailored for laboratory-scale manufacturing applications. As synthesized in Table 2, most prior studies focus on partial integrations such as Lean-based efficiency improvement or TRIZ driven innovation while experimental validation at the laboratory scale and sustainability-oriented evaluation remain limited. This research directly addresses the gap identified in the literature by linking Lean-based waste analysis to TRIZ contradiction formulation and sustainability-driven design evaluation within a single coherent framework. Unlike previous studies that focus narrowly on waste elimination or inventive design alone, the proposed framework enables the simultaneous development of modular, ergonomic, energy-efficient, and resource-conscious laboratory equipment. Furthermore, Table 2 highlights that only a small number of studies incorporate prototype development and experimental validation in educational laboratory settings, reinforcing the novelty of the present work. By positioning laboratory-scale educational manufacturing systems as both learning platforms and testbeds for sustainable innovation, this study extends existing research beyond descriptive analysis toward experimentally validated design implementation. Consequently, this research establishes a novel reference model for designing sustainable and innovation-oriented laboratory manufacturing systems, thereby contributing both theoretically by extending Lean TRIZ integration into educational contexts and practically by providing a replicable framework for engineering laboratories and small-scale manufacturing environments. Based on the state-of-the-art comparison, this study is among the few that simultaneously integrate Lean methods, TRIZ contradiction resolution, sustainability evaluation, and prototype-based experimentation within a laboratory-scale manufacturing context.

3. Research Methods

3.1. Research Design and Rationale

This study employed a design-oriented experimental research approach aimed at developing and evaluating a sustainable manufacturing laboratory system. The research design integrates Lean Manufacturing, TRIZ, and PID-based control to address efficiency, innovation, and sustainability challenges in laboratory-scale manufacturing systems. Lean Manufacturing was selected to systematically identify and quantify process waste, cycle time inefficiencies, and non-value-added activities. TRIZ was chosen as a structured problem-solving methodology to resolve technical contradictions that arise when improving efficiency, ergonomics, and system automation without increasing complexity (Berdonosov, 2015). To help formulate and resolve these contradictions, TRIZ provides two main components: 39 system parameters and 40 problem-solving principles (Robles, 2023). The redesigned heating module was equipped with a PID (Proportional–Integral–Derivative) temperature control system to ensure thermal stability during the forming process. The system utilized a thermocouple temperature sensor connected to a microcontroller-based PID controller. The operating temperature setpoint was maintained at 170°C, with an allowable deviation of ±1°C, based on the thermal requirements of the PVC material used. The PID control logic continuously adjusted heater output to minimize temperature fluctuations, thereby reducing material defects and unnecessary energy consumption. While the vacuum forming module operated within a controlled pressure range suitable for laboratory-scale applications. Heat-resistant molds were produced using 3D printing technology, allowing rapid modification and reuse. Vacuum pressure was regulated using a solenoid valve and monitored to ensure consistent forming quality while avoiding excessive energy use. The trimming module was designed as an ergonomic jig with fixed positioning to improve cutting accuracy and reduce operator fatigue.

3.2. Research Setting and Participants

The study was conducted in a manufacturing system laboratory at a university-level industrial engineering program. The laboratory simulates a miniature production line for educational purposes. Participants involved in this study consisted of 10 undergraduate industrial engineering students who acted as system operators during experimental trials. In addition, three experts, two industrial engineering lecturers and one manufacturing practitioner, were involved for design validation and expert judgment. The students were selected based on prior exposure to basic manufacturing process courses to ensure familiarity with laboratory operations.

3.3. Data Collection Methods

Both qualitative and quantitative data were collected to support systematic analysis (Gillespie et al., 2024). Quantitative data included cycle time measurements for each workstation, electrical energy consumption of laboratory equipment, and process performance indicators before and after system redesign. Qualitative data were obtained through direct observation, semi-structured interviews with student operators and laboratory technicians, and expert evaluations of the proposed design. Data collection was conducted in two stages: baseline measurement using conventional laboratory equipment and post-implementation measurement using the redesigned system.

Electrical energy consumption was measured using a digital power meter installed between the power source and the laboratory equipment. Energy measurements were recorded for each production cycle under two conditions: baseline operation using conventional equipment and post-implementation operation using the redesigned system. To ensure measurement validity, identical production sequences, material types, and operating durations were applied in both conditions. The comparative energy data were then used to evaluate the effectiveness of the proposed system in reducing electrical energy consumption.

3.4. Experimental Setup

The experimental setup focused on the Heating–Vacuum–Trimming (HVT) workstation, identified as the primary bottleneck in the laboratory production process. The redesigned system consisted of three integrated modules:

1) a heating module equipped with a PID-based temperature controller to maintain thermal stability during material forming,
2) a vacuum forming module utilizing heat-resistant molds produced via 3D printing,
3) a trimming module designed as an ergonomic jig to improve cutting precision and reduce operator fatigue.

Experiments were conducted under controlled laboratory conditions using the same material type and production sequence to ensure comparability between baseline and redesigned systems.

3.5. Research Procedure

The research procedure followed a systematic sequence in Figure 2.

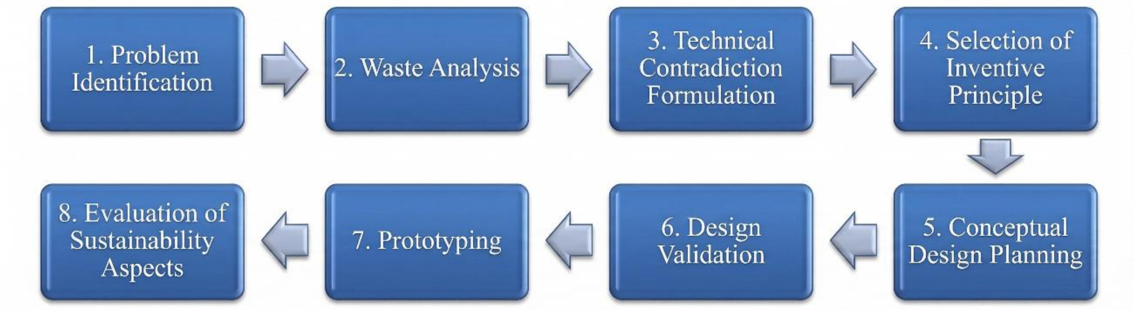

Fig. 2. Research Steps

Figure 2 illustrates a systematic, multi-stage development process, beginning with problem identification through direct observation and measurement at each workstation (Heating, Vacuum, and Trimming). The first stage involved problem identification through direct measurement and observation at each workstation to identify discrepancies between actual and target cycle times, ergonomic issues, and operational inefficiencies. The second stage applied Lean-based waste analysis to classify problems into waiting, motion inefficiency, overprocessing, energy waste, and quality-related waste, with root causes analyzed using the 4M framework (Man, Machine, Method, and Material), including heating temperature instability and manual variability in vacuum–trimming operations. The third stage translated the identified root causes into technical contradictions, defined as trade-offs where improvement in one system parameter caused deterioration in another. The fourth stage mapped these contradictions into the TRIZ contradiction matrix using relevant parameters from the standard set of 39 engineering parameters, including temperature, energy consumption, productivity, accuracy, ergonomics, and system complexity. Based on the matrix results, appropriate inventive principles were selected to guide expert validation focused on feasibility, safety, and ergonomics after solution development. The fifth stage involved conceptual design development, translating the selected TRIZ principles into a PID-controlled heating system and a semi-automated Vacuum–Trimming (VT) jig, with Sustainable Engineering principles embedded through modularity, energy efficiency, and ergonomic design. The sixth stage consisted of expert validation conducted after solution development, focusing on feasibility, safety, ergonomics, and alignment with Lean Manufacturing and sustainability principles. The final stage involved fabrication and performance evaluation, where cycle time and electrical energy consumption were compared under identical operating conditions to assess efficiency and sustainability improvements.

4. Results and Discussions

The results reveal that the Heating–Vacuum–Trimming (HVT) workstation constitutes the primary bottleneck within the educational car manufacturing process, exerting a disproportionate influence on overall system performance. Integrated evidence from direct observation, operator (student) interviews, and time study analysis indicates a substantial mismatch between planned and actual operational performance. As summarized in Table 1, the actual cycle time reached 363.97 seconds, exceeding the target of 286.5 seconds by 77.47 seconds (27%), which directly contributed to production delays, extended working hours, and a measurable decline in process efficiency.

4.1. Waste Analysis

The waste analysis reveals that inefficiencies at the Heating–Vacuum–Trimming (HVT) workstation originate not only from excessive cycle time, but also from systematic waste embedded across human, machine, method, and material dimensions. The dominant requirement identified is the need for higher process flexibility to support diverse training scenarios, while simultaneously maintaining low system complexity to ensure ease of operation, maintainability, and cost efficiency. This inherent conflict between flexibility and simplicity forms the basis of the waste patterns summarized in Table 3.

Table 3 - Waste Analysis and Root Causes

4M Aspects	Problems	Root Causes	Impact on Process	Impact on Sustainability
Man	Operators experience physical fatigue	The trimming process using manual scissors is not ergonomic	Processing time increased, high risk of human error, and productivity decreases	Energy consumption increases due to idle time, the potential for work injuries and the physical burden on operators increases.
Machine	Equipment does not support efficiency and accuracy	The oven does not have an automatic control system, the vacuum system is unstable, and the cutting tool is not precise and cannot be adjusted to suit the material.	Cycle time increased The product deformed due to unstable temperature/vacuum conditions	Wasted material (high scrap) and high-power consumption for rework
Method	Working methods are not standardized and not ergonomic	Tools are not integrated into one working system	Operators are often idle, or multitasking is ineffective	Waste of time and labor and difficulty in replicating methods in the learning process
Material	PVC material often fails to be formed perfectly	The oven temperature is inconsistent. The material is too cold or too hot during forming	Many defective products, high rework process	Material waste. Energy and time consumption increase for process repetitions

Based on the analysis in Table 3, systematic waste is caused by a combination of non-automatic equipment and the lack of real-time temperature and process quality control systems. These root causes directly contribute to low energy efficiency, material waste, and the ineffectiveness of the continuous learning process of manufacturing techniques. The proposed solution involves redesigning an integrated and modular assistive device, equipped with an automatic control system (PID for the oven), reduced tool transfer, and precision cutting capabilities. These findings confirm that waste accumulation at the HVT workstation is the primary driver of the observed bottleneck, directly linking operational inefficiencies to sustainability and learning effectiveness issues.

4.2. Formulation of Technical Contradictions and Selection of Inventive Principles (TRIZ)

To design an efficient and sustainable aid system in the manufacturing system laboratory, an integrative approach combining 4M analysis (Man, Machine, Method, Material), TRIZ concepts, and Lean Manufacturing principles provides a systematic basis for identifying root causes and developing innovative solutions, as shown in Table 4.

Table 4 - Technical Contradiction Formulation and Selection of Invective Principles

Root Causes (4M)	System Requirement	Technical Contradiction	Improved Parameters	Deteriorating Parameters	TRIS Inventive Principles
Operator fatigue due to the manual trimming process (Man)	Fast and easy trimming process	If the accuracy of the cutting tool is increased, then the ergonomics and ease of operation deteriorate.	32 – Ease of Operation	28 – Accuracy of Manufacturing	10 – Prior Action 28 – Mechanics Substitution
Oven and vacuum are not automatic (Machine)	Automatic temperature and vacuum control system	If the temperature control accuracy is increased, then the system complexity increases.	9 – Speed	36 – Device Complexity	15 – Dynamics 24 – Intermediary 40 – Composite Structure
Tools are not integrated into one working system	One multifunctional and modular tool	If tool integration is increased, then the ease of maintenance and flexibility of the tool decrease.	6 – Area Productivity	33 – Ease of Repair	1 – Segmentation 3 – Local Quality 6 – Universality
PVC material is difficult to shape in the unstable temperature (Material)	Material is ready for forming consistently and safely	If the temperature is kept constant, then energy consumption increases.	25 – Loss of Material	22 – Energy Consumption	35 – Parameter Change 19 – Periodic Action 20 – Continuity of Useful Action

Referring to Table 4, the analysis begins by categorizing the waste generated during the miniature car production process into four main aspects: human, machine, method, and material. Each root cause of the waste is examined to figure out the ideal system requirements. Furthermore, a mapping of technical contradictions is carried out according to the TRIZ approach, which serves to describe two conflicting parameters: one parameter that is to be improved, and another that is indirectly getting worse. This mapping is the essence of contradiction in TRIZ. For example, in the human aspect, it was found that the operator experienced fatigue because he had to cut manually. In this case, the system requirement is to create an ergonomic and efficient cutting process. However, if the accuracy and strength of the cutting tool are increased, then the ergonomics or ease of operation can decrease.

Technical contradictions like this are then addressed using TRIZ Inventive Principles, such as Prior Action or Mechanics Substitution. In terms of machines, the limitations of tools such as ovens and vacuum systems, which lack automatic control, result in inefficiency and a high degree of operator dependence. An ideal system is expected to be able to regulate temperature and pressure automatically. However, increasing accuracy and automation can also lead to increased system complexity. Here, TRIZ principles such as Dynamics, Composite Structure, and Intermediary are recommended to overcome these problems through modular and automatic systems. In the method dimension, the problem of tedious manual work methods and the transfer of many tools causes process time to increase and the potential for errors to rise. An integrated work system is needed that allows transitions between processes to be carried out without tool transfers. However, this increased integration can reduce flexibility or ease of maintenance. Therefore, TRIZ solutions such as Segmentation, Local Quality, and Universality can be applied in the design of modular, multifunctional tool systems. Meanwhile, in terms of material, the PVC material used in the forming process is susceptible to temperature changes. Temperature instability causes increased product defects and the need for rework. The goal is to maintain a stable temperature that allows the material to be easily formed and shaped. However, temperature stabilization often causes increased energy consumption. Here, the principles of Parameter Change, Continuity of Useful Action, and Periodic Action from TRIZ provide direction for solutions that maintain stability without sacrificing energy efficiency.

4.3. Modular Jig Conceptual Design

The design of this tool incorporates three main functions: a heating oven with PID-based temperature control, a vacuum system with a pressing mechanism and molds made from heat-resistant 3D-printed materials, and a precision cutting jig. The system is designed in a modular form, featuring mechanical connectors that allow for repositioning between modules. In the 3D design developed using CAD software, ergonomics and space efficiency are the primary concerns. Table 5 maps the TRIZ inventive principles.

Table 5 - TRIZ Inventive Principles Mapping Matrix Based on Tool Implementation Groups

Tools	TRIZ Inventive Principles	Implementation of Tools	Benefit	Design Description
1. PID Controller (Heating)	15. Dynamics	Oven system with temperature control	Flexibility to various materials, energy efficiency	PID controller with multi-level temperature control
	10. Preliminary Actions	Oven pre-heating feature before the main operation	Reduce idle time and improve output quality	Auto-warmup oven and temperature indicator reached before use
	35. Parameter Changes	Temperature and time settings according to material characteristics	Avoid defects, stable product quality	Integration of temperature control with a microcontroller and a simple interface
	24. Intermediary	A temperature sensor serves as automatic control between the human and the device	Temperature consistency, reducing excessive manual involvement	NTC sensor + microcontroller for closed-loop PID control
2. Vacuum System	15. Dynamics	Adjustable vacuum pressure adjusts to the shape and thickness of the material	Mold forming precision, vacuum energy efficiency	Solenoid valve + pressure transducer integrated in the PID control system
	13. Reversal	Reverse mold or bottom opening design for easy removal	Avoiding defects and material release time	Vacuum molding with spring ejector or open bottom system
	24. Intermediary	Pressure sensor to maintain stability during the vacuum process	Process stability and product yield	Pressure transducer with minimum and maximum limit alarms
3. Trimming System	3. Quality	Cutting jig with a special area and position locking	Cutting precision increases, reducing defects	Ergonomic guide rail and locking system on the cutting jig
	19. Periodic Action	Mechanical lever with repetitive motion for precision cutting	Consistency of results, reduced operator fatigue	Manual push lever with spring-based support force

Based on Table 5, in the PID controller group for the heating process, the dynamic principle (principle 15) is applied to enable flexible temperature settings according to the type of material used, as well as the parameter change principle (principle 35), which allows adjustment of the heating time based on the material's characteristics. The pre-action principle (principle 10) is utilized through the design of the pre-heating function to reduce idle time and increase tool readiness. Additionally, the use of a temperature sensor as an intermediary medium (principle 24) contributes to automation and temperature stabilization, aligning with the principle of energy efficiency in sustainable engineering.

In the vacuum system, the dynamic principle is also applied to accommodate pressure according to the mold geometry, while the reversal principle (Principle 13) is proposed to facilitate the release of the product from the mold. The pressure sensor, acting as an intermediary (principle 24), is used to maintain process stability and prevent product deformation.

For the trimming process, the local quality principle (principle 3) is applied through the design of a precise and ergonomic cutting jig, with position locking for consistent cutting results. The periodic action principle (principle 19) supports repeated mechanical jig operations, thereby reducing operator fatigue and increasing time efficiency.

The 3D design of the HVT process, which integrates Lean principles, TRIZ methodology, and Sustainable Engineering concepts, is illustrated in Figure 3.

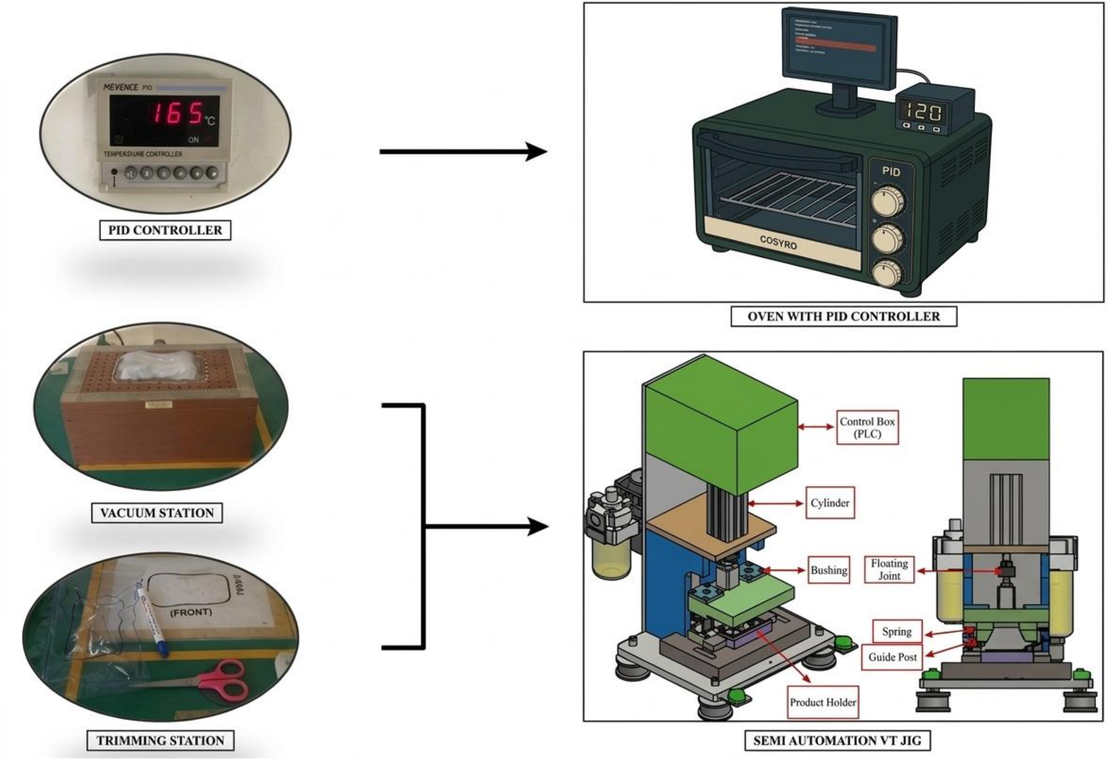

Fig. 3. Visualization Design of HVT Process Tools

Based on Figure 3, the 3D design representation of the system used in the Heating, Vacuum, and Trimming (HVT) process is shown, consisting of two main parts: the Oven with PID Controller and the semi-automated VT Jig. The oven is equipped with a PID (Proportional-Integral-Derivative) controller, which precisely regulates the temperature during the material heating process, ensuring the temperature remains stable according to the predetermined setpoint for optimal heating. The design also illustrates the transition from manual vacuum and trimming processes to a semi-automated tool known as the VT Jig (Vacuum & Trimming Jig). The VT Jig is equipped with several key components such as a Control Box (PLC) that manages the operational cycle automatically, a Pneumatic Cylinder that applies vertical pressure during trimming, Bushing and Guide Posts that maintain alignment, a Floating Joint that distributes pressure evenly, a Spring that provides return force, and a Product Holder that supports the mold. This integrated system is designed to improve precision, increase production speed, and ensure more consistent product quality.

4.4. Conceptual Design Validation

Design Validation and prototype implementation validation were conducted through an expert judgment session involving two industrial engineering lecturers and one manufacturing practitioner. Expert input included aspects of work safety, ease of operation, and the integration of functions. After validation, the prototype was created and tested in the Lean Manufacturing laboratory.

Trial Results and Data Analysis: The trial was conducted on three primary parameters: oven temperature stability at 170°C, maximum variance of ±1°C, vacuum effectiveness in forming PVC material, and precision of cutting results with a maximum dimensional deviation of ±0.5 mm. The results showed that the tool functioned as designed. Additionally, a perception test was conducted on 10 students using a Likert scale questionnaire. The results showed that 90% of students felt that this tool helped them understand the relationship between production processes more clearly.

4.5. Prototyping and Evaluation of Results

After developing the conceptual design based on Lean–TRIZ–Sustainable Engineering principles, the prototyping process was carried out using a rapid development approach with readily available components, in line with sustainable design considerations. The prototype consists of two main subsystems. The heating subsystem employs an insulated electric oven equipped with a Proportional–Integral–Derivative (PID) temperature control system. Real-time temperature feedback is provided by thermocouple sensors, enabling stable operation at a setpoint of 170 °C with a maximum deviation of ±1 °C. Compared to the previous manually controlled heating process, this configuration minimizes temperature fluctuation, reduces overheating, and lowers unnecessary energy consumption during idle periods. The vacuum–trimming subsystem integrates vacuum forming and trimming operations using heat-resistant molds produced via 3D printing technology. The mold assembly consists of a holder die and a punch die designed to facilitate uniform forming and easy product release, followed by a semi-automated trimming process using a VT jig. This configuration standardizes vacuum pressure application and trimming positioning, significantly reducing operator-dependent variability observed in the conventional manual process.

Figure 4 is a prototype photo of the tool installed in the HVT process in the Lean Manufacturing Laboratory.

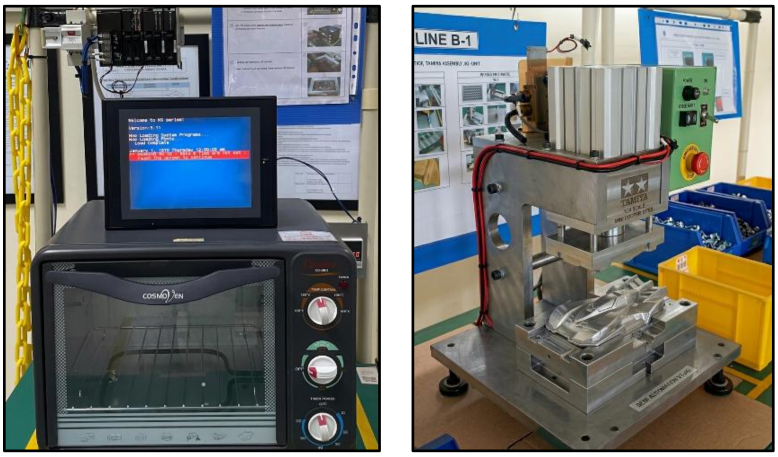

Fig. 4. Prototype of Lean-Driven Sustainable Engineering HVT Process Equipment

Figure 4 presents the installed prototype in the Heating–Vacuum–Trimming (HVT) process of the Lean Manufacturing Laboratory. The prototype represents the implementation of design improvements through semi-automation, PID-based thermal regulation, and an ergonomically designed VT jig, aiming to enhance efficiency, precision, and sustainability. Sustainability performance was evaluated across environmental, economic, and social dimensions using qualitative and semi-quantitative criteria, as summarized in Table 6.

Table 6 - Results of Sustainability Aspect Evaluation on Prototype Performance

Aspects	Indicators	Evaluation Result	Detail Data
Operational and Economic	Process efficiency	✔	Cycle time was reduced by 33% (193 seconds) based on initial simulations.
	Product development costs	✔	The prototype was constructed using parts that were no longer in use in the electronics industry.
Environment	Use of environmentally friendly materials	✔	The vacuum forming process utilizes a thermal press with aluminum molds produced through 3D printing technology.
	Electricity consumption	✔	A PID controller reduces power fluctuations in the oven. Energy savings are around 16 %
	Process waste	✔	a. Reduce waste from damaged wax molds during the vacuum process. b. The trimmed material can be recycled.
Social	Ergonomics of the User	✔	a. Installation of the PID controller in a position that is easily visible to users b. Vacuum jigs and trimming can reduce student fatigue associated with manual work.
	User Involvement in Design	✔	Students were involved in FGD and initial trials.
	Potential for replication in other institutions or industries	✔	The modules are knockdown and can be easily replicated by other laboratories.

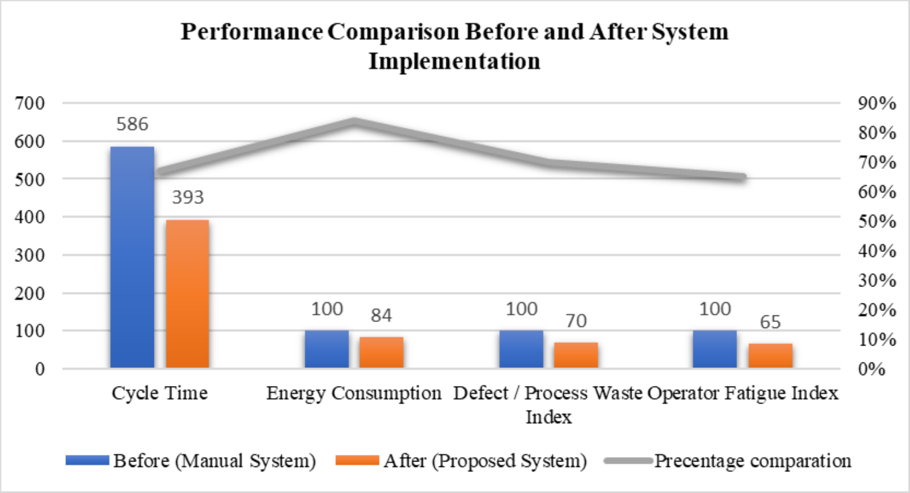

Fig. 5. Performance Comparison Before and After System Implementation

Based on the comparative results presented in Table 6 and illustrated in Figures 5, the proposed system achieved a 33% reduction in cycle time (193 seconds) compared to the original manual configuration. This improvement was primarily driven by the elimination of waiting time, stabilized heating duration through PID control, and the integration of vacuum–trimming operations into a single semi-automated VT jig. Electrical energy consumption was reduced by approximately 16%, which can be attributed to the PID controller's ability to suppress power fluctuations and prevent excessive heating. In addition, the defect and process waste index decreased by 30% due to improved forming consistency and standardized trimming, while ergonomic improvements reduced the operator fatigue index by 35%, indicating a substantial reduction in physical workload. These results confirm that the proposed prototype not only enhances operational performance but also delivers measurable sustainability benefits within constrained laboratory manufacturing environments.

4.6. Discussion

The experimental results confirm that the Heating–Vacuum–Trimming (HVT) workstation is the primary source of inefficiency in the laboratory-scale manufacturing system. Prior to redesign, the HVT workstation exhibited a cycle time deviation exceeding 20% from the target, largely due to unstable thermal control, manual vacuum handling, and ergonomically suboptimal trimming operations. After implementation of the integrated Lean–TRIZ–Sustainable Engineering framework, the total cycle time of the HVT process was reduced by approximately 33%, indicating a substantial improvement in operational efficiency. This result is consistent with previous lean-based studies that reported cycle time reductions in the range of 15–30% in educational or small-scale manufacturing contexts, although most of those studies relied solely on process reorganization rather than system redesign (Renjith et al., 2020; Rizkiyah et al., 2024; Slim et al., 2021). The higher reduction achieved in this study suggests that combining lean waste identification with design-level innovation provides additional performance gains beyond conventional lean implementation.

From an energy performance perspective, the redesigned system achieved an average electrical energy consumption reduction of approximately 16%. This improvement can be directly attributed to the PID-controlled heating module, which minimized temperature fluctuations and reduced unnecessary reheating cycles. Similar energy efficiency improvements have been reported in sustainable manufacturing studies emphasizing thermal control and process stability, typically ranging from 10% to 15% (Raoufi and Haapala, 2024; Qamar et al., 2024; Gama and Bonamigo, 2024). However, unlike prior studies that addressed energy efficiency independently, the present work integrates energy reduction as a direct outcome of resolving technical contradictions between temperature stability and energy consumption using TRIZ principles. This integrated approach aligns with recent calls for combining sustainability and systematic innovation in manufacturing system design (Gdoura et al., 2024; Rahardjo et al., 2025).

The application of TRIZ played a critical role in resolving contradictions that emerged during lean-driven improvement efforts. For instance, increasing temperature control accuracy typically leads to higher system complexity and energy usage; however, the use of PID-based control combined with modular system design enabled improved accuracy without sacrificing simplicity or sustainability. Similar TRIZ-based contradiction resolution has been reported in industrial product and process design contexts (Da Silva et al., 2020; Feniser et al., 2017; Donnici et al., 2018), yet its application at laboratory scale remains limited. Compared to studies that applied TRIZ primarily for conceptual ideation, this research demonstrates its practical effectiveness in guiding tangible system redesign within constrained educational environments, thereby extending its applicability domain.

Ergonomic improvements observed in the trimming process further support the effectiveness of the integrated framework. The introduction of a precision trimming jig significantly reduced operator fatigue and variability in cutting accuracy. Previous studies in educational manufacturing laboratories have highlighted ergonomics as a secondary or qualitative concern (Sremcev et al., 2018; Kozub et al., 2021), whereas the present study embeds ergonomic considerations directly into the system redesign process through TRIZ-based local quality and periodic action principles. This approach not only improves operator comfort but also contributes to consistent product quality, reinforcing the interdependence between human factors and process efficiency.

When compared to prior research that partially integrated lean and sustainability or lean and TRIZ, this study demonstrates a more comprehensive performance improvement. Studies by Meng et al. (2021), Wang and Yang (2023), and Morales Morales et al. (2023) reported benefits in either sustainability metrics or innovation outcomes, but lacked a unified framework capable of addressing efficiency, contradiction resolution, and environmental performance simultaneously. The results of the present study indicate that the simultaneous integration of Lean Manufacturing, TRIZ, and Sustainable Engineering generates synergistic effects, resulting in performance improvements that exceed those achieved through isolated or pairwise methodological combinations.

The novelty of the findings lies in demonstrating that laboratory-scale manufacturing systems can achieve industrially relevant efficiency and sustainability improvements through an integrated, framework-driven redesign rather than incremental process adjustments. Unlike most existing studies that treat laboratories as simplified teaching tools, this research positions laboratory systems as scalable testbeds for sustainable manufacturing innovation. This perspective advances current literature by bridging the gap between educational manufacturing systems and real-world industrial practices.

From a broader perspective, the findings of this study can be generalized to other laboratory-scale and small-scale manufacturing environments that face similar constraints related to energy usage, ergonomics, and process inefficiency. While the experimental validation was conducted within a specific laboratory setting, the underlying framework (lean-based waste identification, TRIZ-driven contradiction resolution, and sustainability-oriented system evaluation) is transferable to a wide range of educational and small-scale industrial contexts. Therefore, the results suggest that integrated methodological frameworks are essential for achieving meaningful and sustainable performance improvements in constrained manufacturing systems, providing a foundation for future research and implementation beyond the studied case.

5. Conclusion

This study aimed to develop an integrated Lean–TRIZ–Sustainable Engineering framework to redesign a laboratory-scale manufacturing system and systematically eliminate waste while improving efficiency and sustainability performance. The results demonstrate that the proposed approach successfully reduced process cycle time by approximately 33% and electrical energy consumption by around 16% through a modular redesign of the Heating–Vacuum–Trimming workstation supported by TRIZ-based contradiction resolution and PID-controlled thermal stability. From a practical perspective, the findings highlight the feasibility of implementing industrially relevant efficiency and sustainability improvements within educational manufacturing laboratories, providing a replicable model that can enhance operational performance, ergonomics, and learning effectiveness. From a theoretical perspective, this research contributes by extending the application of integrated Lean Manufacturing, TRIZ, and Sustainable Engineering frameworks to laboratory-scale systems, an area that remains underexplored in existing literature. The novelty of this study lies in demonstrating that the systematic combination of waste identification, inventive problem-solving, and sustainability-oriented design can generate synergistic performance gains in an educational manufacturing laboratory context. The results are relevant not only for academic institutions but also for small-scale industrial environments seeking cost-effective and sustainable process improvements. Future research should explore the scalability of the proposed framework to full-scale industrial production lines and investigate its integration with Industry 4.0 technologies, such as real-time monitoring, data analytics, and intelligent control systems, to further enhance adaptability and performance.

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