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RESEARCH ARTICLE

Waste Assessment Model for Hot Coil Spring Production Using Lean Approach

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ABSTRACT – This study develops and validates customized waste assessment methods for the hot coiling spring manufacturing process. This is due to the high demand for springs in the automotive industry and the potential for a significant impact on the overall supply chain of the component. This study uses a case study approach with quantitative methods to assess waste in a hot coiling production line. Data were collected through direct observation (Genba) and documentation, with key waste types identified using a wastage check sheet. Microsoft Excel and VBA macros were used for analysis, enabling the ranking and prioritization of waste based on cost, cycle time and production efficiency. The assessment method successfully identifies and ranks various types of waste in terms of cycle time and cost analysis. Notably, the bar loading process exhibited a significant inefficiency, with an actual cycle time exceeding 3 times higher than the ideal time of 3 seconds. Similarly, the heating process had a 30% deviation from its ideal cycle time, indicating room for optimization. The cost analysis identifies the pre-treatment stage as a major contributor to high expenses, with a high actual cost rate of RM4.29 per piece, which is over 13 times higher than the average actual cost rate of RM0.33 across other processes. The painting process incurs the highest reject cost, which is 102% higher than the average reject cost. Rework analysis highlights the Pre-Treatment stage with a rework cost of 41% above the overall average reject cost. The findings offer critical insights for prioritizing improvements to optimize operations, minimize delays, and reduce production costs, particularly by addressing inefficiencies in the Pre-Treatment process, painting process, and bar loading. Simplifying the method and developing an automated waste assessment can prioritize cost-saving areas, enabling faster decisions, less manual effort, and continuous improvement of the respective processes through lean implementation.

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1. INTRODUCTION

Lean manufacturing is about the enthusiasm for waste elimination. Lean manufacturing is a philosophy based on the Toyota Production System and other Japanese management practices that strive to shorten the timeline between the customer order and the shipment of the final product by consistent elimination of waste [1]. Lean manufacturing practices are a combination of techniques deployed for productivity improvement and reduction in manufacturing costs [2]. A lean manufacturing system (LMS) is one of the significant methods used to maximize customer value and minimize the waste that occurs. The use of LMS in Malaysia is still in the early stages and is hardly seen, especially among small and medium enterprises (SMEs) in rural areas [3]. In accordance with the growth of manufacturing practices, LMS is very important for a manufacturer to fully utilize its resources while maximizing profits.

A study was conducted to assess waste practices in the management of seven waste automotive vendors in Malaysia. Out of the seven LMS wastes, it was found that the three most critical causes of downtime in the assembly line were waiting, transportation and movement [4]. Other researchers have also suggested that applying the full set of lean principles and tools contributes to the successful transformation of LMS[5]. However, in reality, not many companies in the world have successfully implemented this system. There is no “cookbook” to explain the LM process step by step and how exactly to apply the tools and techniques [6]. An analysis found that the major difficulties companies encounter in attempting to apply lean are a lack of direction, a lack of planning, and a lack of adequate project sequencing [7]. Besides, five automobile manufacturers have dropped out of the market during the last 20 years as a result of failure to manage the wastage (Stone). From here, it is clear some automotive manufacturers still do not fully implement LMS in their operational and functional work.

The automotive industry has a huge impact on the worldwide system, going through rapid changes every single year. Three enemies of lean are identified as *Muda* (waste), *Muri* (overburden), and *Mura* (unevenness) [8]. Muda is any activity or process that does not add value or waste time, resources, and money. At the same time, Muri is defined as any activity that puts stress or effort on personnel, equipment, or material. Lastly, Mura is defined as any activity that leads to unbalanced situations or environments. These three types of waste are important to understand as they help to understand what waste is and where it occurs.

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The automotive industry deals with a lot of components, materials, and processes. All these elements are tuned to match the requirements of different customers. In matching those requirements, non-value-added activities may be presented in these elements, which ultimately cause waste. If the matching process is not well managed, a lot of wastage will occur, and the company's profit will be cut silently. As this industry grows from time to time, eliminating waste and stabilizing it are crucial to keep it sustainable. Eliminating waste has become a major concern for most of the top management as it can increase company profit substantially. Unwanted waste can also hinder production line efficiency in achieving its highest pass rate. A study conducted in the Malaysian automotive industry found that most Malaysian manufacturing industries did not provide information on how to implement lean practices and eliminate waste [9].

Generally, spring-making involves a lot of manufacturing processes. Currently, it is difficult to estimate the wastage in spring manufacturing plants. The use of lean practice, which eliminates waste, is still lacking, especially among SMEs in rural areas [3]. If this situation continues, wastage will continue occurring in the manufacturing process, causing drawbacks to the company’s performance and efficiency. The concern arises from the unwanted process that restrains the production process from achieving its highest level of performance. All the wastage problems are worth eliminating by conducting a scientific investigation. This research focuses on automotive parts manufacturing plants, as the automotive industry is a major consumer of springs, accounting for over 50% of global spring production. Springs are essential components in many automotive systems, so optimizing their manufacturing process can have a significant impact on the overall automotive supply chain [10]. This paper attempts to develop waste assessment methods according to the parameters of the hot coiling spring manufacturing process. Additionally, it aims to validate these waste assessment methods by ranking the significance of the various waste types and quantifying the potential savings.

1.1 Lean Manufacturing

Many manufacturers across different industries are moving to an improved system of production called lean manufacturing. Lean manufacturing is adding value by eliminating waste, being responsive to change, focusing on quality, and enhancing the effectiveness of the workforce [11]. Another definition of lean manufacturing is a systematic approach to identifying and eliminating waste (non-value-added activities) through continuous improvement by following the product at the pull of the customer in pursuit of perfection [12]. Lean manufacturing is a concept whereby all production employees work together to eliminate waste. It is not about adding some new techniques to build products but about changing the way of thinking about manufacturing.

Researchers have addressed the effect of lean manufacturing on production cost and process efficiency. A case study conducted in India revealed that the implementation of lean manufacturing tools led to reduced inventory by 14%, weekly planning improved tool setup time by 29% and minimized delays, while in-house training reduced absenteeism by 15% [13]. Various studies have reported remarkable improvements in productivity, quality, and cost reduction through the implementation of lean manufacturing across different industries, including aerospace, computer and electronic manufacturing, automotive, and process industries. Lean manufacturing, far from being rendered obsolete by the fourth industrial revolution, is essential for manufacturing firms to effectively leverage digitalization and achieve substantial operational improvements [14]. Deuse et al. make a significant contribution by illustrating how lean management principles can be effectively integrated with digitalization to optimize production systems [15]. Another study demonstrated that implementing structured problem-solving, specifically Lean Six Sigma, can yield substantial operational improvements. By addressing root causes, the project successfully reduced downtime, improved product flow, minimized backlog, eliminated waste, and increased productivity, ultimately enhancing the customer experience without compromising cost, production time, or product quality [16]. Principally, high-quality products, low production cost, efficient production operations, and higher customer satisfaction are all strongly related to the lean manufacturing system and waste elimination process. A lean organization can make twice as much product with twice the quality and half the time and space, at half the cost, with a fraction of the normal work-in-process inventory. Lean management is about operating the most efficient and effective organization possible, with the least cost and zero waste.

Implementing lean manufacturing has never been an easy duty. Lean manufacturing implementation depends on four critical factors: leadership and management, finance, skills and expertise, and a supportive organizational culture. Despite the huge benefits gained from Lean manufacturing (LM) implementation, in reality, not many companies are successful in implementing this system. Many researchers believe that the main problem lies in the misunderstanding of the real concept and purpose of LM. The reason for this misunderstanding is due to cultural differences that occur during the transition or translation of LM. A company that is in the early stage of implementing lean must keep its efforts for an effective communication process at all levels in order to successfully implement LM. The first formal lean transformation in Malaysia’s manufacturing sector was reported in 2006 [17]. This transformation involved local automotive industries through the initiation of the Malaysia–Japan Automotive Industries Cooperation (MAJAICO) program to develop and mold the local automotive industry into competitive industry players globally [18]. Based on the current state of lean implementation, the work carried out here intended to expand the implementation of lean tools in the automotive industry, focusing on coil spring manufacturers. Therefore, the purpose of this study is to discuss the lean assessment method in manufacturing further while the investigation is conducted in coil spring manufacturers in the automotive industry as the automotive industry has led the lean implementation to compare to other industries.

1.2 Type of Waste

Overproduction is identified as the most significant type of waste, occurring when products are made too early or in excess of demand [19]. This leads to other waste types and results in excess inventory, increased storage costs, and inefficiencies in production. Overproduction can mask other wastes within the manufacturing line, such as excessive lead and storage times, and cause a significant impact on costs due to unnecessary inventory and wasted materials. To mitigate this, organizations should adopt the Just-In-Time (JIT) philosophy, producing only what is needed when it is needed [20]. Defects and inventory waste are other critical areas of concern. Defects occur when products deviate from standards or customer expectations, leading to rework or scrap, additional inspections, and design or process changes. This not only wastes materials and labor but also disrupts production schedules and increases lead times. Inventory waste involves storing unprocessed items, which leads to higher financing and storage costs and can obscure problems within the production process. Both types of waste highlight the importance of maintaining quality and accurate production planning to avoid unnecessary expenses and inefficiencies.

Transportation, waiting, motion, and over-processing are additional forms of waste that impact efficiency and costs. Transportation waste involves unnecessary movement of materials, which does not add value and can cause damage [21]. One example of transportation waste is the unnecessary transportation of finished goods from one process to the next due to poor plant processes or necessary plant process layouts. Waiting for waste arises from production bottlenecks, leading to idle time for workers and machines. Motion waste is defined as any unnecessary physical movement of people in which the movement does not add value to the actual processing work. This might include walking around the factory floor to look for a tool or even unnecessary or difficult physical movements due to poorly designed ergonomics, which slow down the workers. It involves poor ergonomics of production, where operators must stretch, bend, and pick up when such actions could be avoided. Over-processing involves performing more work than required by the customer, leading to inefficiencies. One of the most common examples of over-processing waste is in an office environment, which often comes in the form of reviews and approvals needed to make decisions. Reducing these wastes requires optimizing workflows, improving plant layouts, and ensuring that processes add value to the final product.

In the coil spring industry, defects waste significantly impacts production performance as it is easily identifiable and quantifiable in terms of cost. Cycle time waste, reject waste, and rework waste fall under different types of waste in manufacturing. Cycle time waste is a form of overproduction waste, as it leads to inefficiencies and excess inventory. Reject and rework wastes fall under defects waste, arising from product deviations that require rework, scrap, and additional resources, disrupting production and increasing costs. These wastes contribute to overall inefficiencies and higher operational costs. Customers often choose to do business with manufacturers based on defects and rework counts per month. These statistics allow for straightforward measurement of production efficiency and process capability without the need for deep, full-scale analysis. To ensure organizational success, it is crucial to eliminate all seven types of waste, as waste or non-value-added activities can lower profit margins, decrease product quality, and negatively affect worker satisfaction. Organizations should focus on reducing waste as much as possible to avoid operating under wasteful conditions. This approach helps them seek valuable opportunities to enhance product quality and satisfaction, thereby improving overall performance.

1.3 Waste Measurement Across Various Industries

Demands for high competitiveness and world-class standards have compelled many manufacturing firms to reduce production waste to increase efficiency. Consequently, companies across various sectors have adopted lean manufacturing practices to enhance quality and productivity. Previous studies have documented the use of different tools and techniques tailored to firms' understanding of lean manufacturing [18]. This has resulted in various methods for measuring waste.

1.3.1 Wastes Relations Matrix

The Wastes Relations Matrix (WRM) aims to identify and eliminate waste by analyzing whether one type of waste influences another [22]. This method involves brainstorming sessions with professional managers to address specific questions, resulting in a matrix that illustrates and analyzes the relationships among the seven types of waste. Based on literature reviews and brainstorming outcomes, the WRM shows that the seven types of waste Over-production (O), Inventory (I), Defect (D), Motion (M), Process (P), Transportation (T), and Waiting (W) are interdependent, with each type directly or indirectly affecting the others. Figure 1 illustrates these complex relationships. The diagonal matrix represents the highest value of the relationship, indicating that each waste type has a strong relationship with itself. A study on waste in a job shop environment proposed an assessment method using the Waste Relations Matrix (WRM) to assist companies in identifying root causes of waste. The method involved preparing six questions for each relationship, resulting in a total of 186 questions (31 relationships × 6 questions). The scores from these questions were summed to determine the total value of each relationship. This total value was then converted into symbols (A, I, U, E, O, and X) according to the conversion rules in the WRM table, indicating the strength of each relationship. All types of waste are shown to mutually influence each other.

The results of implementing the WRM show that defect waste takes the first rank as major waste (approximately the same as motion waste) with 20.5%. Transportation waste was ranked as the waste that is least likely to exist. This is because the shop floor layout is designed on a straight-line flow pattern, and no back-stream flows are allowed. The advantage of WRM is that it clarifies the relationships among the different types of waste. It also provides a rank of wastes in terms of weight contributions to the occurrences of waste. However, the disadvantage of WRM is the improvement activities cannot be directly derived from this method. It shows the rank of waste, but the management team needs to brainstorm by using another method to yield beneficial improvement activities in order to reduce the waste and lower the production cost.

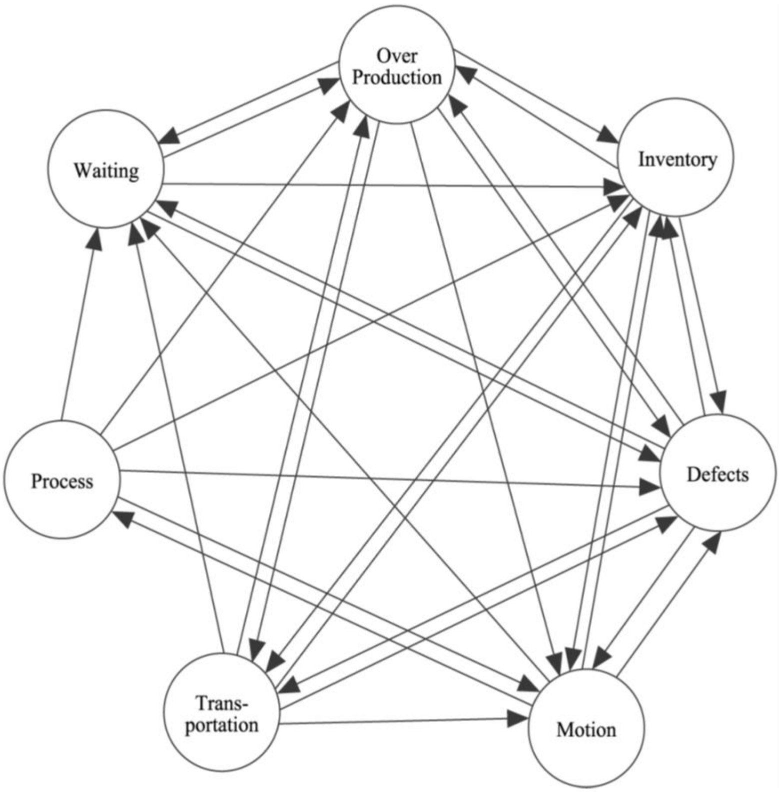


Figure 1. Direct waste relationship [23]

1.3.2 Waste Assessment Questionnaire

The Waste Assessment Questionnaire (WAQ) is designed to identify and categorize waste occurring in the production line [19]. This method was implemented in the assembly process of electronic car components for the Daihatsu SIGRA. The questions are divided into the “From” type, which refers to waste that can trigger other types of waste, and the “To” type, which represents waste generated by other wastes. The questions are generally categorized into four main groups: man, machine, material, and method.

The following steps are recommended to analyze the WAQ:

i) Calculate the number of waste questions of the “From” and “To” types for each waste category.

ii) Apply the initial weighting of WAQ questions based on WRM.

iii) Divide each weight by the number of questions (Ni) to account for variations in the number of questions.

1.3.3 Operation Process Chart

The Operation Process Chart (OPC) is a detailed working map that breaks down the work into specific operating elements [24]. The OPC outlines the operations and inspection steps from the beginning to the end of the material’s transformation into a whole product or semi-finished material. The OPC uses five parameters: operations, movements, inspections, delays, and storage, which are simplified in a chart form. These charts are used for method study analysis in industrial applications to eliminate waste more effectively. The process map is crucial for the effective development of simulation models and the implementation of lean principles, as it visualizes the workflow [25].

Efficiency is a key performance indicator in a process. A case study of the bricklaying process quantified the impact of applying lean principles. The process map before and after implementing lean principles showed that over 70% of activities were non-value-adding, including waiting time. Applying three key lean principles resulted in improved labor productivity, enhanced process efficiency, and increased productivity at both the task and project levels [26]. This demonstrates that lean principles can be successfully implemented by altering processes in the OPC, enabling better visualization and optimization of workflow.

1.3.4 Value Stream Mapping

Value Stream Mapping (VSM) is a lean manufacturing tool derived from the Toyota Production System (TPS), originally known as ‘material and information flow mapping’. According to Reda H. and Dvivedi A., VSM is a powerful tool that identifies process inefficiencies, transactional and communication mismatches and also guides improvements [27]. It visually maps the flow of information and materials to develop better methods and performance in a proposed future state. VSM is divided into six phases (Figure 2). The first phase involves developing the current state value stream map, which shows the current manufacturing process practices. The second phase identifies all related waste in the process. In the third phase, a proposed solution is developed, leading to the creation of a future state value stream map in the fourth phase. The fifth phase involves implementing the proposed improvement activities, and finally, the outcome is measured in the sixth phase.

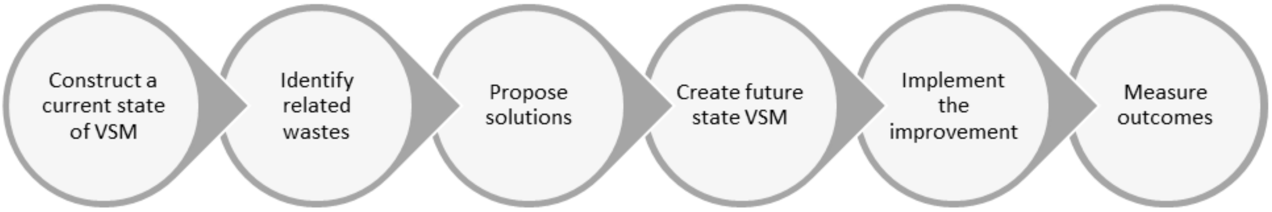


Figure 2. Six phases of VSM

A case study in a plastic bag manufacturing plant in MIDC, Nagpur, utilized VSM to study the process before and after its implementation. The current state map of XYZ Laboratories helped identify various wastes, such as idleness, underproduction, unwanted Work-in-Progress (WIP,) high Takt times, and lack of pull and proper scheduling [28]. A future VSM map was then used to eliminate non-value-added activities. The implementation of VSM increased the percentage of value-added time from 15% to 89.85%, reduced Takt time from 46.6 to 26 minutes, and increased the number of rolls made to 50 per day. This led to significant improvements in cycle time, labor productivity, and process efficiency. VSM integrates material and information flows, relating the manufacturing process to supply chains and distribution channels.

1.3.5 Pareto Chart for Waste Ranking

Several studies have adopted Pareto tools to identify and rank significant wastes in their processes. Pareto analysis selects limited factors causing production problems, allowing for targeted improvement plans [29]. For example, a glass bottle manufacturing study used Pareto charts to identify defects, such as blister defects (22.14%), double seam defects (14.06%), and stone defects (10.78%), which contributed to 46.98% of overall rejections. Two major defects, pressure failure (69.36%) and overweight (19.32%), accounted for 88.68% of rejections [30]. The Pareto chart was plotted based on the data collected, which aimed to identify the most common defects (Figure 3).

In addition, Pareto analysis is used to rank the determinants of manufacturing conversion costs, which can further aid in waste elimination. By ranking these conversion costs, manufacturers gain valuable insights into their processes. Data from Figure 3 indicates that over 52% of the total conversion cost is attributed to frame plant operations, specifically welding and painting, with the second highest contributor being the machine shop [31]. The frame assembly has the least contribution to conversion costs. According to the Pareto chart, the main cost contributors, making up 80% of the total, are tool costs, gas for the baking oven, consumables for the machine shop, paper masking, graphic rejection, brazing filler rods, and sheet metal parts rejection. By focusing on these major contributors, manufacturers can reduce overall manufacturing costs, eliminate waste, and make their processes more sustainable [32].

WRM identifies and eliminates waste by exploring the interrelationships between different types of waste. Similarly, the WAQ examines how each type of waste influences others and measures these impacts on the overall manufacturing process. Both WRM and WAQ rely on questionnaire-based input from experts, typically top management. These methods precisely identify interdependent waste types, calculating scores based on responses that reflect the four main manufacturing categories: man, machine, method, and material. However, WRM and WAQ are primarily diagnostic tools; they identify waste but do not directly propose improvement activities for the manufacturing process.

The Operation Process Chart (OPC) illustrates manufacturing routings but can be overly complex and difficult for management to understand, sometimes oversimplifying processes. In contrast, Value Stream Mapping (VSM) is a powerful visual tool that addresses OPC’s disadvantages. VSM allows for the visualization of complex workflows, quantification of necessary resources, and reorganization of workflows. It helps organizations eliminate waste by mapping current processes and identifying future improvement opportunities. This project aims to develop a mathematical model to calculate wastage (in terms of cost) in the hot coiling spring production line and identify the best improvement activities to eliminate or reduce the highest percentage of waste in this process. Given the various lean tools used in other industries, VSM was chosen for this research due to its significant advantages. VSM’s ability to visualize waste, plan improvements, and provide a clear roadmap for reducing inefficiencies makes it an ideal choice for optimizing the hot coiling process.

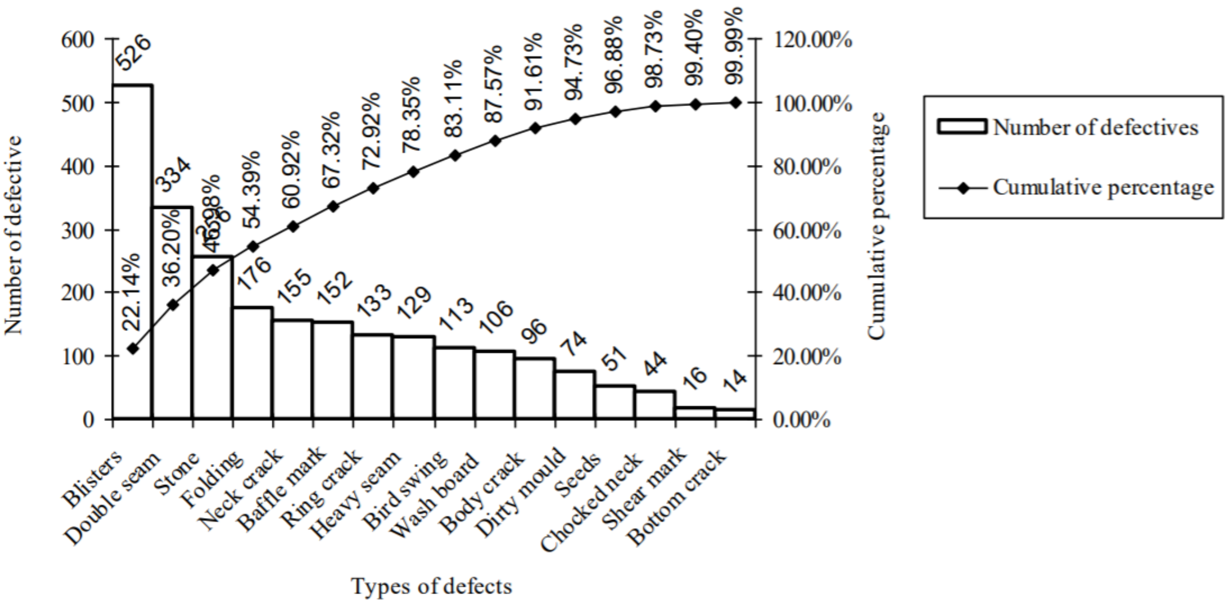


Figure 3. Pareto Chart for types of visual defects observed [29]

2. METHODOLOGY

A comprehensive flowchart in Figure 4 is established to guide the development of a waste calculator for the spring manufacturing process. It systematically progresses through several key steps: first, identifying where waste occurs within the process; second, precisely measuring the identified waste; third, conducting a detailed analysis of the measured waste to understand its impact and sources; fourth, developing a robust waste calculator model based on gathered data and analytical insights. Any necessary modifications to the model are implemented to enhance its effectiveness in capturing and quantifying waste. Ultimately, the culmination of these efforts results in the presentation of comprehensive findings and recommendations derived from the waste calculator. This approach not only aims to streamline production processes but also supports strategic decision-making by providing clear insights into waste reduction opportunities within manufacturing operations.

The spring manufacturing process is complex, especially the hot coiling method, which involves multiple stages such as bar loading, heating, coiling, pigtailing, quenching, tempering, hot setting, shot peening, load testing, scragging, pre-treatment, drying, painting, printing, and packaging. Each stage can harbor hidden waste. To define the process, observations were made on the production floor from start to finish, with production team members describing their tasks at each station. This involved listing all processes and verifying them through cross-checking with documented workflows.

This research focuses on coil spring products, which are made from custom-length, durable steel as specified by customers. The steel is first arranged on a conveyor and heated for 22 minutes to become malleable. The crucial coiling process shapes the steel into springs per customer specifications. After coiling, the springs undergo quenching, tempering in batches of 280, hot setting, shot peening to relieve stress and load testing. Springs passing the load test are pre-treated in a zinc phosphate solution, dried, painted, touch-up, printed with batch codes, inspected, and finally packaged. Small round steel is used to shoot the spring in a circular motion to release the stress and strengthen the inner durability of the spring. The organization manufactures three main types of coil springs: Helical Coil Spring (Spring A), Pig Tail Coil Spring (Spring B), and Banana Coil Spring (Spring C), as illustrated in Figure 5. The waste study begins with a Genba walk-through of the process involving peer evaluation. Thirteen production team members describe their processes, which are systematically recorded through manual data collection and digital recording. Key processes are captured using cameras and stopwatches.

The Toyota Production System identifies seven common types of waste, known as the Seven Muda, frequently found in manufacturing. In the hot coiling manufacturing process, any detected waste is categorized under these seven types. Verification by senior specialists ensures each waste type is correctly classified. Measuring waste involves collecting cycle time data using a stopwatch. Observers must maintain a perpendicular eye position to avoid inaccuracies and redundant cycle times. Clear visibility of the process is essential for accurate data collection.

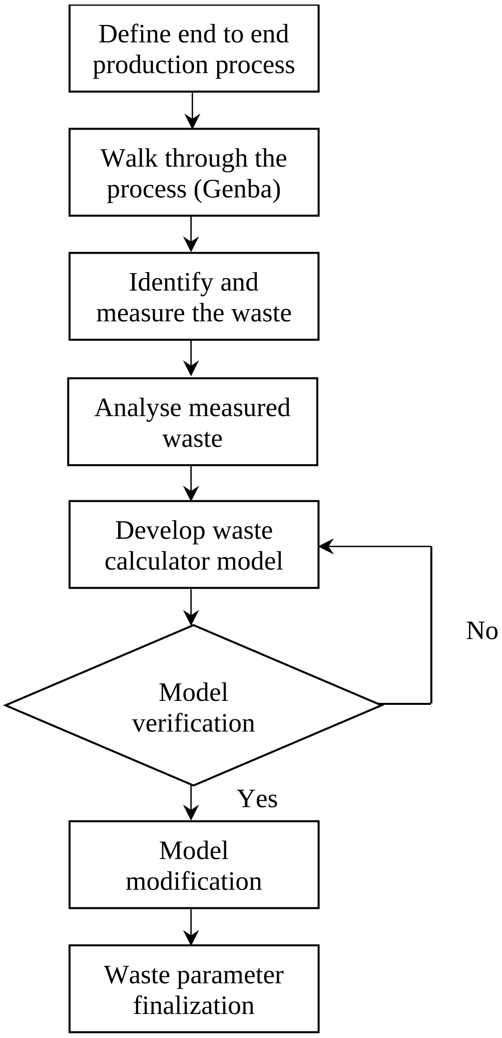


Figure 4. Flowchart of the waste assessment model development

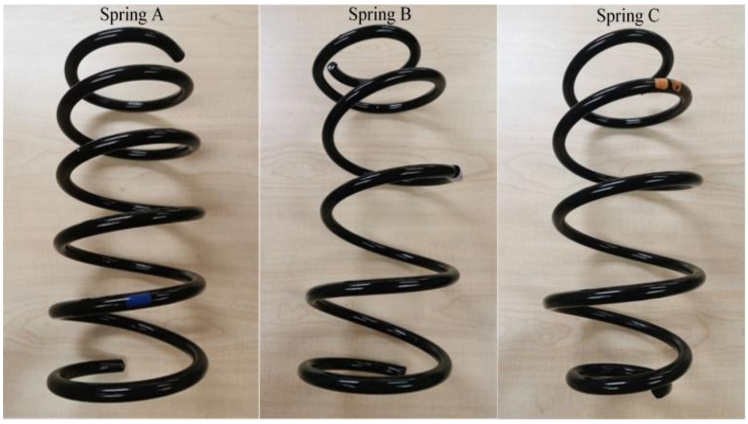


Figure 5. Helical Coil Spring (Spring A), Pig Tail Coil Spring (Spring B), and Banana Coil Spring (Spring C)

The waste data is then presented in Table 2 to Table 4, quantifying the measured parameters and type of waste. Calculations include the percentage and volume of waste, along with a forecasted return on investment. Waste is also presented in a cost-based format, revealing that more waste types correlate with higher overall production costs. A waste calculator is developed using a statistical approach to average the waste elements. Costs such as consumable, rework, and reject costs are classified, and regression analysis is applied. Verification involves manual data collection and assigning weightage to each process based on its criticality, cross-checked with the accounts department's monthly report. The confidence level of the calculator is determined through this verification.

Table 1. Wastage process parameter

Parameter	Equation	Description	Unit	Symbol
Space rental	$R = Fp * g$	Space rental per m^2 for a specific process	RM/month	R
		Factory price per m^2	RM	Fp
		Floor area allocated to a specific process	m^2	g
Rework	$P = (aj * c) + (x * c)$	Rework cost per piece	RM/pc	P
	$F = aj * 2$	Machine rate per second	RM/sec	aj
	$G = r * p$	Actual cycle time	Second	c
		Labor cost per second	RM/sec	x
		Rework cost rate	RM/sec	F
		Rework waste	RM/process	G
		Rework frequency per process	pc/process	r
Reject	$W = e + l$	Reject cost per piece	RM/pc	W
	$z = y * w^2$	Actual cost per piece	RM/pc	e
		Material cost per piece	RM/pc	l
		Reject cost rate	RM/sec	x
		Total process cost rate per second	RM/sec	w^1
		Reject waste	RM/process	z
		Reject frequency per process	pc/process	y
		Reject cost per piece	RM/pc	w^2
Ideal pieces can be produced per hour	$aa = 3600/r$	Ideal pieces can be produced per hour	pc/hour	aa
		Ideal cycle time per batch	second/batch	r
Ratio of in-process capacity utilization	$ac = aa/ab$	The ratio of in-process capacity utilization	ratio	ac
		Actual pieces produced per hour	pc/hour	ab
Cycle Time Waste	$ad = e - d$	Cycle time waste	second	ad
		Actual cycle time per piece/batch	second/batch	e
		Ideal cycle time per piece/batch	second/batch	d
Cost of cycle time waste	$bb = ad * total\ w^1$	Cost of cycle time waste	RM/pc	bb
Ideal cycle time per piece	$ae = d/b$	Ideal cycle time per piece	second/pc	ae
		Batch capacity	pc	b
In-process capacity utilization	$af = d/e$	In-process capacity utilization	ratio	af
Ideal cost rate per piece	$ag = d * ak$	Ideal cost rate per piece	RM/pc	ag
		Total process cost rate per second	RM/second	ak
Actual cost rate per piece	$ah = e * ak$	Actual cost rate per piece	RM/pc	ah
Waste cost rate per piece	$ai = ah - ag$	Waste cost rate per piece	RM/pc	ai
Actual cost rate per hour	$al = ai^2 + 11.68$	Actual cost rate per hour	RM/hour	al
		Machine rate per hour	RM/hour	ai^2
Machine cost per piece (without manpower)	$am = aj * c$	Machine cost per piece (without manpower)	RM/pc	am

The model is refined to address discrepancies between actual and declared costing data, incorporating feedback from senior specialists. Waste parameters are verified by comparing actual data with costing data, and discrepancies are classified into the Seven Muda categories. A mathematical method formulated over three months of brainstorming and discussions with company specialists reflects the actual conditions of the hot coiling process. Data related to man, machine, material, and method, primarily in cost terms (Ringgit Malaysia), is retrieved from the Group Business & Development department. This project's goal is to identify and visualize waste monetarily.

After formulating waste calculations, improvement activities are proposed to top management, with VSM being a key method due to its visualization and quantification capabilities. The VSM approach is adopted to address waste effectively. The study acknowledges complexities such as uncertain waste relationships and exact costs, aiming to uncover hidden production line waste that contributes to unmeasured costs. The calculation process is based on the equation listed in Table 1, which includes parameters like factory space rental, rework waste, reject waste, ideal pieces ratio, in-process capacity utilization, cycle and cycle time costs, cost rate per piece, and machine cost per piece. These parameters are identified through real-time data, discussions with specialists and team members and documented references.

2.1 Data Collection and Modelling Approach

For this research, a case study method was employed, focusing on a hot coiling production line to explore real-world issues within the manufacturing process. The primary method of data gathering and analysis was quantitative, emphasizing numerical data. Quantitative techniques involve any data collection or analysis procedure (such as graphs or statistics) that generates or uses numerical data. Given the descriptive nature of this research, numerical data such as cost (in Ringgit Malaysia), time (seconds and hours), and production quantities were crucial for statistical analysis. Data collection was conducted through two primary methods: Genba (observation) and documentation. The observation method was utilized to understand the production process in its natural setting without interfering with its normal operation. This was achieved by avoiding interactions with operators, which could potentially delay the production process and skew the data. There are two types of observation: participant observation, where the observer is also a participant, and direct observation, where the observer does not interact with those being observed. For this research, direct observation was adopted, ensuring that the operators were unaware of being observed to maintain the authenticity of the data collected. This approach prevented operators from altering their behavior, which could lead to inaccurate cycle time measurements.

Documentation and records focused on the spring hot coiling process. A wastage check sheet was prepared before conducting Genba to ensure all significant waste was recorded and identified. The collected data was then organized and documented. Figure 6 categorizes the records into four main categories: reject waste, rework waste, actual and ideal cycle time, and the estimated potential cost of improvements. Microsoft Excel and Visual Basic for Applications (VBA) were used to analyze the data. Microsoft Excel was employed to store all data and formulations, while VBA was used to analyze and summarize the data. The approach involved saving formulations in "macros" available in Excel. The VBA function allows users to easily retrieve analyzed data for specific production processes with minimal input simply by clicking a button. This waste summary feature transforms complex and lengthy data sheets into more user-friendly interfaces.

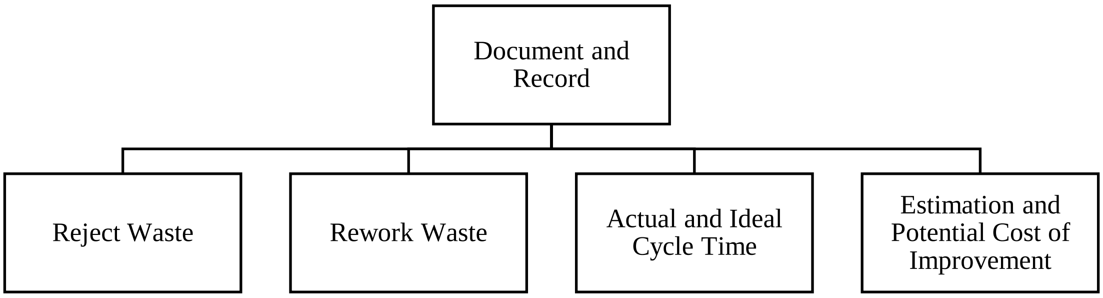
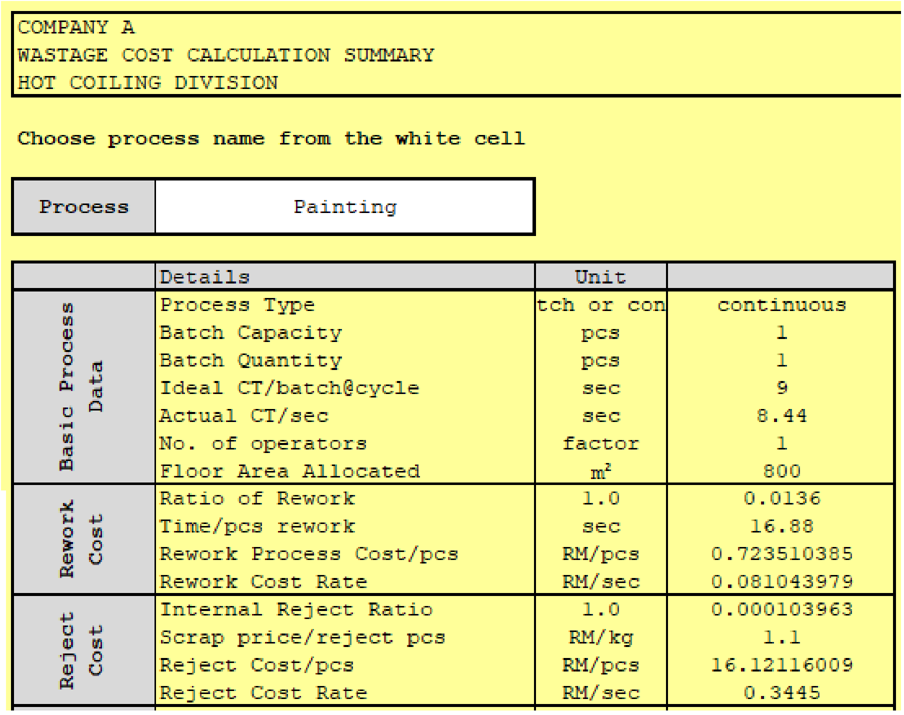


Figure 6. Categories in Data Collection

3. RESULTS AND DISCUSSION

3.1 Wastage Cost Calculation Tools

Using raw data in Excel, a comprehensive table was constructed that combined all the collected data over three months. This table integrates crucial key processes, production plan utility, resources, depreciation ratio, and raw materials, with units varying in Ringgit Malaysia (RM), square feet, meters, kilowatt-hours, and seconds. Each type of waste was calculated by multiplying specific variables with others. The purpose of this waste calculation was to determine the waste occurring in the coil spring production line based on the seven-waste theory: transportation, inventory, motion, waiting time, over-processing, overproduction, and defects. The calculated results provide an initial analysis to identify the points of highest wastage, which can then be targeted for improvement activities. The waste calculator was designed to analyze the resource consumption of each production process. Built-in Microsoft Excel, the calculator links to raw data retrieved from daily production line reports and customer requirement data. Using the painting process as an example, the interface of the calculator that highlighted the key results is presented in Figure 7. The data was computed based on the equations from Table 1 and then transformed into a Value Stream Mapping (VSM) format. This approach helps visualize which processes have the highest cycle times.



COMPANY A
WASTAGE COST CALCULATION SUMMARY
HOT COILING DIVISION

Choose process name from the white cell

Process	Painting

	Details	Unit	
Basic Process Data	Process Type	tch or con	continuous
	Batch Capacity	pcs	1
	Batch Quantity	pcs	1
	Ideal CT/batch@cycle	sec	9
	Actual CT/sec	sec	8.44
	No. of operators	factor	1
	Floor Area Allocated	m²	800
Rework Cost	Ratio of Rework	1.0	0.0136
	Time/pcs rework	sec	16.88
	Rework Process Cost/pcs	RM/pcs	0.723510385
	Rework Cost Rate	RM/sec	0.081043979
Reject Cost	Internal Reject Ratio	1.0	0.000103963
	Scrap price/reject pcs	RM/kg	1.1
	Reject Cost/pcs	RM/pcs	16.12116009
	Reject Cost Rate	RM/sec	0.3445

Figure 7. Wastage Cost Calculation Summary

The calculator uses the acquired data to generate calculations, which are then analyzed with the waste assessment model to identify opportunities for improvement. The crucial results from this analysis are proposed to the management team, who will decide which production process has the most wastage and prioritize improvement activities accordingly. The results were analyzed based on the cycle time waste (second), reject cost (RM/piece) and rework cost (RM/piece) according to the 11 main hot coiling processes.

3.2 Cycle Time Waste

When comparing cycle times, it's important to look at the difference between the actual cycle time and the declared cycle time (as agreed with the customer) for each process. This comparison helps identify where actual cycle times exceed ideal cycle times, indicating waste and extra costs for the organization. Conversely, if the actual cycle time is lower than the ideal cycle time, there are cost savings. Based on Table 2, The comparison of key processes in the coil spring production line reveals noteworthy insights into cycle time efficiencies and inefficiencies. Among these processes, bar loading emerges as a critical point of concern, as its actual cycle time of 11 seconds significantly exceeds the ideal time of 3 seconds by 8 seconds. This discrepancy suggests potential challenges related to equipment capabilities or operational constraints that hinder faster processing. Similarly, in the heating process, where the actual cycle time of 13 seconds surpasses the ideal time of 10 seconds by 3 seconds, there is room for improvement to streamline heating procedures.

Table 2. Cycle time comparison

Process Name	Ideal Cycle Time (seconds)	Actual Cycle Time (seconds)	Difference (seconds)
Bar Loading	3	11	8
Heating	10	13	3
Coiling	12	13	1
Auto Transfer	2	4	2
Second Pig Tail	8	13.33	5.33
Quenching	10	10	0
Tempering	12	10	-2
Shot Peening	12	10	-2
Load Testing	13	9	-4
Pre-Treatment	1344	553	-791
Painting	9	8.44	-1.44

Conversely, processes like quenching operate at optimal efficiency, precisely matching the ideal cycle time of 10 seconds. This indicates that the quenching process is well-controlled and meets expected operational standards without unnecessary delays. Processes such as tempering, shot peening, and load testing exhibit efficiencies with actual cycle times shorter than their ideal counterparts. For instance, tempering and shot peening show actual cycle times of 10 seconds against an ideal time of 12 seconds, suggesting potential opportunities for faster throughput or improved process management. This comparison underscores the critical need to address cycle time discrepancies to enhance overall production efficiency and reduce operational costs. By identifying areas where actual cycle times deviate from ideal standards, manufacturers can implement targeted improvements in equipment maintenance, workflow optimization, or resource allocation. This approach not only improves process reliability but also supports cost-effective manufacturing practices aligned with customer expectations and industry standards.

3.3 Reject Waste

The detailed cost breakdown across different stages of the production line provides a nuanced view of where resources are allocated and where potential inefficiencies lie. For instance, while material costs remain consistent across all processes at RM8.12 per piece, the actual cost rate per piece varies significantly. Processes like Pre-Treatment incur a higher actual cost rate of RM4.29, indicating potentially higher resource consumption or operational complexities in this stage. Moreover, the variation in reject costs per piece further underscores areas of concern. Processes such as Painting, with a reject cost of RM16.12 per piece, indicate higher rates of material wastage or quality issues that contribute significantly to overall production costs. This means each unit of coil spring rejected during the painting process will cost RM16.12 in loss to the organization. From the results tabulated in Table 3, the painting process has the highest reject waste due to the process being executed at the end section of the hot coiling process before the inspection process took place. The cost of rejection is identified by calculating the cost incurred from the beginning of the process, which is the machine setting process. The cost is cumulative from the beginning of the process and causes the end process to have the highest reject waste cost. The bar loading has the lowest rework cost per piece due to its position in the beginning section of the whole process, thus, the rate of rework being done here is typically low. This highlights a critical area where improvements in quality control and waste reduction strategies could lead to substantial cost savings and enhanced product consistency.

Table 3. Reject waste calculation

Process Name	Actual Cost Rate (RM/pcs)	Material Cost (RM/pcs)	Reject Cost per pcs (RM/pcs)
Bar Loading	0.03	8.12	8.15
Heating	0.52	8.12	8.67
Coiling	1.25	8.12	9.92
Auto Transfer	0.00	8.12	9.92
Second Pig Tail	0.13	8.12	10.05
Quenching	0.56	8.12	10.61
Tempering	0.19	8.12	10.81
Shot Peening	0.36	8.12	11.17
Load Testing	0.32	8.12	11.49
Pre-Treatment	4.29	8.12	15.78
Painting	0.34	8.12	16.12

3.4 Rework Waste

Table 4 presents a rework of waste that occurred in the production line, highlighting key areas of concern and potential improvement. A few critical insights emerge from this data. The Pre-Treatment process stands out due to its exceptionally high actual cycle time of 553 seconds, resulting in a substantial rework cost of RM11.17 per piece. This is due to the high cost of the chemical solution involved in this process, which is zinc phosphate. Indirectly, the rework waste in this process indicates a major bottleneck in the production line, where extended processing time and potential inefficiencies significantly impact overall productivity and cost-effectiveness. The data reveals that the auto-transfer process incurs the lowest rework cost per piece, valued at RM0.023. This low cost can be attributed to the simplicity of the process, which does not involve the use of chemicals or heavy machinery. The auto-transfer process primarily focuses on moving materials between stages, requiring minimal intervention and resources. This straightforward approach reduces the likelihood of errors and the need for rework, thus keeping the associated costs exceptionally low. In contrast, processes involving more complex operations, such as quenching or pretreatment, tend to have higher rework costs due to the increased potential for mistakes and the need for correction in these more intricate and resource-intensive stages. This suggests that even low-cost processes can accumulate costs if not optimized for efficiency and quality. Conversely, the "Painting" process, despite a relatively moderate machine rate of 0.041 and a shorter actual cycle time of 8.44 seconds, incurs a rework cost of RM0.74 per piece. This highlights that even processes with lower cycle times and costs need quality checks to avoid rework and associated costs. Overall, this detailed rework waste calculation emphasizes the importance of targeted improvements in high rework cost processes like Coiling and Pre-Treatment. Addressing inefficiencies and quality issues in these areas could lead to significant cost savings and enhanced productivity in the production line.

Table 4. Rework waste calculation

Process Name	Machine Rate	Actual Cycle Time (seconds)	Manpower Cost Rate (RM/minute)	Rework cost per pcs (RM/pcs)
Bar Loading	0.030	11.00	0.19	0.13
Heating	0.040	13.00	0.19	1.10
Coiling	0.096	13.00	0.19	2.56
Auto Transfer	0.001	4.00	0.19	0.02
Second Pig Tail	0.010	13.33	0.19	0.32
Quenching	0.056	10.00	0.19	1.17
Tempering	0.019	10.00	0.19	0.44
Shot Peening	0.036	10.00	0.19	0.77
Load Testing	0.036	9.00	0.19	0.68
Pre-Treatment	0.008	553.00	0.19	11.17
Painting	0.041	8.44	0.19	0.73

The aforementioned data in Table 2, Table 3 and Table 4 highlighted three prominent types of waste: cycle time waste, reject waste and rework waste. These are the most prevalent in the production process and the easiest to quantify in terms of cost. For cycle time waste, 5 out of 11 processes are affected, contributing 45.45% of the total production process. This indicates that almost half of the processes are running inefficiently. Regarding reject waste, the painting process incurs the highest cost, calculated at RM16.12 per piece out of a total of RM122.69 for the entire production line. This means that reject costs at this stage contribute 13.13% of the total reject waste. Similarly, the painting process also has the highest rework cost, at RM11.79 per piece out of an overall RM19.09. This accounts for 61.76% of the total rework cost, a significant proportion. This high value is due to the painting process being located at the final phase of the spring manufacturing process, where the cost rate is higher compared to earlier stages. Additionally, the painting process involves high-quality paint, which increases the costs. The data highlights the painting process as a major area of concern for both reject and rework wastes. Since this process occurs at the final phase of the production line, the costs associated with any inefficiencies are amplified. The high reject and rework costs indicate that significant improvements can be made by focusing on this stage. The data extracted from this analysis can help management make better decisions by focusing on which processes to target first for waste elimination and improvement activities. By addressing the inefficiencies in the painting process, the organization can reduce a substantial portion of its overall waste. This can be achieved through better quality control, improved process parameters, and possibly investing in more advanced technology or materials that reduce the likelihood of defects. Additionally, the focus on reducing cycle time waste in the identified five processes can streamline operations, reduce delays, and lower production costs.

4. CONCLUSIONS

The developed assessment method successfully identified various types of waste in the coil spring manufacturing process, ranked them, and quantified potential cost savings. By comparing actual cycle times to declared cycle times**,** the method pinpointed inefficiencies. For instance, the bar loading process shows an actual cycle time of 11 seconds, far exceeding the ideal time of 3 seconds by 8 seconds, indicating significant inefficiencies potentially due to equipment limitations. Similarly, the heating process has an actual cycle time of 13 seconds compared to the ideal 10 seconds, suggesting further room for optimization. The detailed cost breakdown reveals key insights into resource allocation and inefficiencies. While material costs are consistent at RM8.12 per piece, actual cost rates vary significantly, with the Pre-Treatment stage incurring a high actual cost rate of RM4.29, suggesting higher resource consumption or operational complexities. The painting process has the highest reject cost at RM16.12 per piece**.** This high reject cost is due to the painting process being at the final stage, where defects incur cumulative costs from the entire production process.

Rework waste analysis further highlights critical areas for improvement. The Pre-Treatment process, with an actual cycle time of 553 seconds, results in a substantial rework cost of RM11.17 per piece, primarily due to the high cost of the chemical solution involved. This comprehensive waste assessment method provides valuable insights for management to prioritize improvement activities. Addressing inefficiencies in high-cost processes like painting, coiling, and pretreatment can lead to significant cost savings and enhanced productivity. The comparison of actual cycle times with the declared cycle times reveals important insights into process efficiency. If the actual cycle time exceeds the ideal, it leads to waste and higher costs. Conversely, faster actual cycle times result in cost savings. While the quenching process showed no difference, the remaining five processes, tempering, shot peening, load testing, pretreatment, and painting, demonstrated faster cycle times, leading to production cost savings. This emphasizes the importance of monitoring cycle times to reduce waste and improve cost efficiency. Implementing targeted improvements based on this analysis can help streamline operations, reduce delays, and lower production costs. While the current method is detailed and effective, it is presented in a complex worksheet format. Simplifying this method and developing an automated version could enhance its usability and facilitate lean implementation in the future. By doing so, organizations can more precisely assess and improve their manufacturing processes, ensuring they operate efficiently and cost-effectively.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to the publication of this article. They affirm that they have no financial, personal, or professional affiliations that could be perceived as influencing the research or conclusions presented in this work.

AUTHORS CONTRIBUTION

R.S. Hasan: Data collection and analysis for cycle time, reject, and rework costs; Drafted the manuscript.

M.N. Osman Zahid: Validated the methodology for waste analysis and cost optimization; Critically reviewed; Edited the manuscript.

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