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Sustainable Innovation in HFW Steel Pipe Manufacturing: A Synergistic Approach of Lean Tools and Material Circularity

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Abstract

Steel Pipe Manufacturer (abbreviated as SPM) is a manufacturing company that produces integrated steel pipes and performs anti-corrosion coating in Indonesia, often facing the problem of inefficient material usage due to product defects. This condition causes their production results not to reach the target, producing waste of up to 1253.09 tons. Through Value Stream Mapping (VSM) analysis, the team identified that the cutting machine is the workstation with the highest material consumption, while the welding station shows the highest product defects. In addition, the company's Material Circularity Indicator (MCI) is still low, which is 0.13, indicating that the material flow is not entirely circular. As an innovative solution to overcome these problems and increase eco-efficiency in the production process, this study offers a circular economy-based approach. This approach includes scheduling routine machine inspections and maintenance that must be adhered to by operators, as well as utilising production waste to create new and valuable products. The study also proposes an optimal material recycling strategy to reduce dependence on new raw materials. By implementing this strategy, the company reduced product defects by 23.1%. In addition, they processed 26.7% of pipe manufacturing waste into steel poles for construction needs with a recycling efficiency of 70%, which increased the MCI to 0.22. On the other hand, steel scrap that was melted and reused for building components showed a recycling efficiency of 100%, thus increasing the MCI further to 0.32. These results indicate that implementing circular strategies can significantly improve material efficiency and reduce industrial waste.

Keywords: *Circular Economy, Eco-efficiency, Material Circularity Indicator (MCI), Value Stream Mapping (VSM).*

Introduction

Steel Pipe Manufacturing (SPM) is a manufacturing company in Indonesia that produces steel pipes and integrated corrosion layers. It has earned both domestic and international certifications. SPM uses an engineering-to-order (ETO) system in its production process and operates under a high-mix, low-volume (HMLV) manufacturing model. HMLV is a type of production with a high product variation level and a low production quantity (Andreasi Bassi et al. 2021; Burinskienė, Lingaitienė, and Jakubavičius 2022; Daramola et al. 2025; dos Santos Gonçalves, Claes, and Ritzen 2025). The steel pipes produced by SPM have several types based on their functions, including structural pipes used in construction projects, water pipes used for water transmission networks, and oil and gas pipes used in the oil and gas industry. Based on

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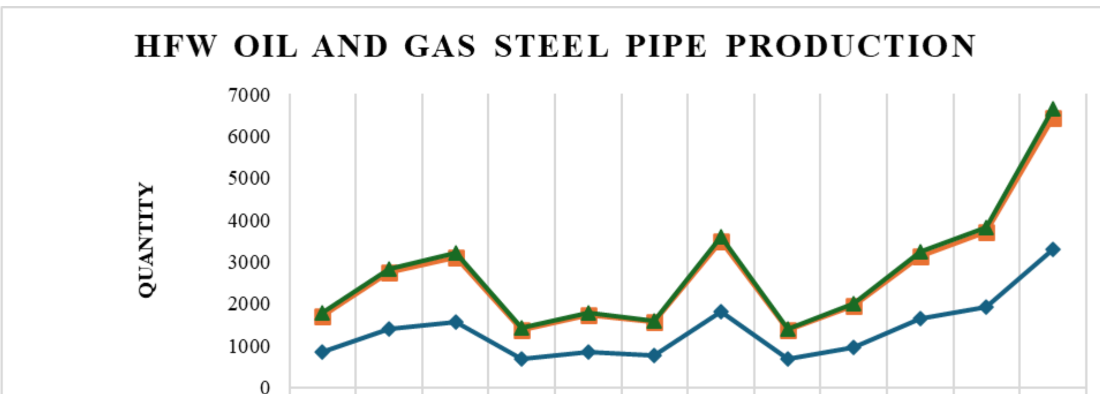
the steel welding type, SPM has two processes: submerged arc helical welding (SAWH) and high-frequency welding (HFW). SPM has been certified, including ISO 9001:2015 quality management, which is the company's guideline in making pipelines, as well as ISO 45001:2018 and ISO 14001:2015 on Policy, Health, Occupational Safety, and Environment (K3LL), which is an important aspect that every oil and gas business operator must fulfil. During interviews, the company's leaders identified inefficient material usage as a key issue, often preventing production yield from reaching its target. Figure 1 presents the production project data for HFW oil and gas steel pipes. Based on Figure 1, shows that, in aggregate, the total production realisation is 15,859 units, and below the annual target of 16,465 units, so there is a gap of 635 units or 3.68%. In April, July, August, and December showed that production exceeded the target, this indicates good production capacity potential, but in January, February, March, May, June, and October the production output was below the target which had an impact on revenue decline or delivery delays if not immediately in your hands. The total product defects during this period were 1,063 units, with the highest number of product defects in March of 224 pcs. The highest disability rate in percentage terms occurred in April at 8.86%, in June at 8.42%, and in August at 8.18%. Although the number of product defects in recent months appears small, the percentage of defects to realisation indicates consistent quality issues, especially in the first and fourth quarters.



	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March
Total Defect (pieces)	76	85	128	52	72	38	96	33	53	98	108	224
Realization (pieces)	858	1340	1520	702	880	788	1672	688	995	1473	1786	3128
Target (pieces)	840	1411	1575	682	836	770	1824	682	966	1659	1920	3300

Figure 1 The Production Project Data for HFW Oil and Gas Steel Pipes

Regulations issued by the government regarding the processing of waste in the national iron and steel industry are in Government Regulation No. 22 of 2021. Several types of iron and steel industrial waste fall under the non-B3 category, which means industries cannot store or dispose of them using treatable methods that offer economic and environmental benefits (The Indonesian Iron & Steel Industry Association 2021). The implementation of VSM reduces waste, and by improving the quality and efficiency of the production process (Salwin et al. 2021). The Material Circularity Indicator (MCI) is the initial framework for eco-design in the circular economy model. MCI can measure the product's overall economic and environmental aspects by focusing on reducing inputs, using natural resources, and material losses (Desing and Blum 2023). This result becomes a reference for further determining alternative improvements that can increase eco-efficiency by reducing the potential for SPM steel pipe waste. In this study, there are five sections, namely: the first section, literature review about the eco-efficiency concept, lean and green manufacturing, value stream mapping, 4 R Strategies, and Material Circularity Indicator. The second section is related to research methodology. The third section is related to results and discussions, and the fourth section is related to research conclusions; the five section is: recommendations, further research, limitations, and implications.

Literature Review

Eco-Efficiency Concept

The eco-efficiency is calculated using absolute values for the product value and environmental influence (Michelsen, Fet, and Dahlsrud 2006). The framework to evaluate the eco-efficiency performance of firms. It combines the GRI(environmental) indicators, the EMAS and formal financial statements (balance sheet and profit and loss account) information and scoring-benchmarking techniques. (Nikolaou and Matrakoukas 2016). Eco-efficiency is a concept that helps companies move towards sustainability. The idea has a framework that any business can use to measure progress toward economic and environmental resilience. There are seven elements for improved eco-efficiency (Verfaillie and Bidwell 2001):

1. Reduces material intensity.
2. Reduces energy intensity.
3. Reduces the dispersion of toxic substances.
4. Increased recycling.
5. Maximising the use of renewable energy.
6. Extended product life.
7. Increased service value or product quality.

The researchers focused on eco-efficiency indicators in the following two studies (Hartini et al. 2019; Irsyad and Hartini 2024). There are:

1. Economic Indicators: Quality, lead time, inventory, and cost.
2. Environmental Indicators: Material consumption, water consumption, energy consumption, emissions, and waste treatment.

Lean and Green Manufacturing

Lean principles play a central role in achieving manufacturing excellence through waste elimination and streamlined operations (Kusumawardani and Singgih 2025). According to the Environmental Protection Agency (EPA), Lean Manufacturing (LM) can significantly improve an organisation's environmental performance by reducing the materials, energy, water, space, and equipment required per production unit while increasing resource productivity and production efficiency. Manufacturers can reduce the environmental impact of production activities by applying lean principles. The implementation of LM has a positive effect on the promotion of green practices and consequent achievement of high environmental performance; employee involvement is a moderator that affects the relationship between green practices and environmental performance; pressure to “go green” is a mediator in the relationship between LM and green practices; however, the adoption of ISO 14001 does not act as a moderator on the relationship between LM and green practices, but synergies emerge if ISO 14001 is integrated with LM (Chen et al. 2020). The review revealed significant gaps in understanding, particularly regarding the factors that shape the efficacy of Lean manufacturing tools in enhancing eco-efficiency performance (Ferrazzi et al. 2024). The synergy of the lean and green manufacturing approach has shown a better effect that will benefit operational and environmental performances (Leong et al. 2019).

Value Stream Mapping

Value Stream Mapping is a method for mapping value stream details so that waste can be identified and can be found several reasons that cause waste can occur, as well as provide the right way to eliminate or reduce the waste (Koh and Singgih 2021). Value Stream Mapping (VSM) has become an important performance measurement tool in various industries (Irsyad and Hartini 2024). The implementation of the VSM tool in the Lean Manufacturing area was aimed at reducing waste, and thus increasing the quality and efficiency of the production process (Salwin et al. 2021). By utilising Green-VSM (process visualisation) and LCA (environmental impact assessment), this study is intended to assess each production process of the insecticide and the environmental impact that is caused by the process, material and waste that occur within each process (Dimyati and Singgih 2020).

4R Strategy

To achieve a sustainable business model, the circular economy employs different so-called "R strategies", the "Reduce" strategy of the circular economy and different types of PSS, showing that the relationship with product-oriented services is more nuanced than expected. When addressing the "Reuse" or "Recycle" strategies (Bressanelli et al. 2020; Rahman 2000; Saccani et al. 2023). The following is an explanation of the 4R Strategy (Kazerooni Sadi et al. 2012; Rahman 2000; Saccani et al. 2023; Study 2023):

1. Reduce consumption by reducing the consumption of raw materials or resources that can potentially damage the environment. Collect data for use in the analysis of factors that play a role in the occurrence of problems.
2. Reuse is a reuse movement by modifying a product.
3. Remanufacture is returning a durable used product to its new condition.
4. Recycling involves processing goods categorised as waste and converting them into similar or new products.

Material Circularity Indicator

A circular economy is a global economic model that seeks to extend the product cycle by reusing resources. Implementing a circular economy (CE) in companies requires continuous monitoring to assess their financial, environmental, and social effectiveness. One of the indicators used to measure the circulation of material flow is the Material Circularity Indicator (MCI). With MCI, companies can measure the reduction of inputs, the use of natural resources, and material losses (Fernández-Torres, Dednam, and Caballero 2022; Rigamonti and Mancini 2021; dos Santos Gonçalves, Claes, and Ritzen 2025). The Material Circularity Indicator (MCI) quantifies the reduction of linear material flows, the increase in restorative flows for resource reuse in product components, and the duration and intensity of product use (Daramola et al. 2025; Desing and Blum 2023). Here, the product rating is on a scale of 0 to 1. A value of 0 indicates a linear flow of material, and 1 indicates a circular flow of material. The principles focus on the selection of product material flow in MCI (Bellini et al. 2024; Desing and Blum 2023; Linder, Sarasini, and van Loon 2017; Rigamonti and Mancini 2021; Vidal et al. 2022):

1. Using feedstock from reused or recycled sources.
2. Reuse recycled components or materials after using the product.
3. Keep the product in use longer. For example, with reuse/redistribution.
4. Use the product more intensively (for example, through a service or performance model).

Research Methodology

In this study, by integrate the Lean Tools and Material Circularity approach. Some of the stages carried out are: (1) Data Collection Stage; (2) Data Processing Stage; (3) Analysis and Improvement Stage; (4) Conclusion. In detail, here is an explanation of each stage.

A. Stages of Data Collection

Before collecting research data, interviews were conducted with company consultants to determine the selected indicators from the economic and environmental indicators available and related to the circular economy. There are four methods of data collection carried out in the research, namely:

1. Observation: Observe the production process, material flow, material consumption, and waste produced during the production process.
2. Interview: ask operators, production managers, or stakeholders questions related to the research conducted directly.
3. Documentation: The activity was conducted by studying company documents containing reports on the number of rejected steel pipes, historical data on the production of HFW oil and gas steel pipes, and the number of pipe rework.
4. Benchmarking: The activity of comparing waste treatment or waste related to the research field in determining alternatives that companies can choose for unused waste.

B. Stage of Data Measurement

1) Value Stream Mapping (VSM)

To prepare for the current state of Value Stream Mapping, the team collects data that describes the flow of materials and information from suppliers to customers. The team illustrated the flow of the HFW oil and gas steel pipeline production process using a flowchart based on the company's Manufacturing Procedure Specification document and the author's direct observations. They also conducted interviews and on-site observations with relevant managers to gather the necessary data. After collecting data from documents, observations, and interviews, they processed the information and created a Value Stream Mapping (VSM) diagram to represent the current conditions of the production process. The following data is needed to map the oil and gas HFW steel pipeline process using VSM.

1. The flow of information and material flow throughout the process of production.
2. The amount of material used throughout the process of production.

3. The amount of waste output or waste generated throughout the production process.

4. Rework is the process of repairing pipes.

Based on the collected data, the team calculated the level of material consumption and identified defects that occurred during the production of HFW oil and gas steel pipes.

2) Material Circularity Indicator (MCI)

The team used the data collected during the preparation of the Value Stream Mapping, along with selected economic and environmental indicators from the company, to calculate the current Material Circularity Indicator (MCI). Before performing the calculation, they modified the equation to align with the specific conditions of the observation object. They then calculated the values for virgin feedstock, unrecoverable materials, linear flow index, utility, and the final MCI.

C. Stage of Analysis and Improvement Alternative

1. Value Stream Mapping analysis to find out the location of the workstation with the lowest level of efficiency and then identify the root cause of the problem of the workstation.

2. Analysis of Current Material Circularity Indicator (MCI) based on the 4R strategy (Reduce, reuse, recycle, and remanufacture).

3. Alternative Improvements include recommendations on alternative improvements to the production process of HFW oil and gas steel pipes by improving efficiency and reducing environmental impact. Alternative repairs are made based on the preparation of 5 whys to find the root cause of the problem in waste defects.

Data Analysis

A. Project Quality Description

Production of offshore steel pipes with API material grade 5L grade X65. With 101 pipe orders, the pipe width is 323.85 mm, and the average pipe length is 12.1 m.

B. Production Process Flow of HFW Oil and Gas Steel Pipe

1. Incoming HRC: The process of making HFW SPM oil and gas steel pipes began with inspecting the HRC materials received from PT. Krakatau Steel. The teams inspected factory certification, labels, dimensions, visual inspection, mechanical tests (tensile properties), chemical composition, and grain size measurements.

2. Uncoiling: The coil is inserted into the uncoiling machine to unroll the coil to make it easier to cut the coil edge.

3. Flattening/Leveller: level the non-compliance of the coil length, and there is a copper machine that can cut the edge 1 times the thickness of the coil plate.

4. Slitting: This flattened coil is then cut at each end with a slitter machine with a maximum size of 30 mm.

5. Coil Joint: The coil joint process combines one coil plate with the other to produce a specified pipe length.

6. Levelling: The level machine will level the coil before it enters the milling machine.

7. Edge Milling: The edges of the coil plates are smoothed and cut at an angle of 0°5° using

a milling machine so that the edges of the pipe plates become even and shiny.

8. Forming: In the forming process, the coil sheet is bent with the help of a roll until it is round through several stages of formation.

9. Welding: The coil that has formed the pipe is then welded from the inside and outside of the pipe with High-Frequency Welding (HFW).

10. After welding the pipes, the team treats the welded areas by reheating them with a Post Weld Heat Treatment (PWHT) machine. They control the heating rate to bring the pipe to its transformation temperature, which helps relieve stress and prevent cracking in the welded sections.

11. Sizing: Adjustment of the size of the pipe diameter desired by the consumer.

12. Pipe Numbering: The worker gives a serial number to the pipe consisting of the purchase order/production request, engine code, year of production, and pipeline production order.

13. 13) Pipe Cutting: The cutting length of the pipe is according to the length of the pipe desired by the customer.

14. Visual and Dimensional Inspection: Inspect each pipe visually and dimensionally to ensure that the pipes produced meet the acceptance criteria specified by the company.

15. End Beveling: In this process, cut the end of the pipe at a certain degree of angle. The degree of bevel used in this project is 30°. Pipe bevelling is essential in preparing for welding to connect pipes.

16. Hydrostatic Test: a test on a pipe by applying water pressure for a specific period.

17. Ultrasonic Inspection: an examination of the pipe to find out any indications of defects using an ultrasonic test machine.

18. Final Inspection: Final inspection is the process of inspecting finished steel pipes in dimensions, visuals, and masses to verify the results of previous tests to match the set specifications, and then the test results are documented in the report.

19. Marking: Mark pipes to identify the pipe, namely the pipe fabrication, pipe diameter, pipe length, pipe number, and pipe specifications. Next, move the pipes to shelves or warehouses to wait for coating.

C. ***Quality Improvement***

Table 1 presents the production project data for HFW oil and gas steel pipes.

No.	Month	Target (pieces)	Realisation (pieces)	Total *Defect* (pieces)
1	April	840	858	76
2	May	1411	1340	85
3	June	1575	1520	128
4	July	682	702	52
5	August	836	880	72
6	September	770	788	38
7	October	1824	1672	96

No.	Month	Target (pieces)	Realisation (pieces)	Total *Defect* (pieces)
8	November	682	688	33
9	December	966	995	53
10	January	1659	1473	98
11	February	1920	1786	108
12	March	3300	3128	224
	Total	16465	15830	1063

Table 1 HFW Oil and Gas Steel Pipe Production

Based on the SPM inspection report data, there are several categories of rejected, accepted, and short-length pipes, as shown in Table 2. Table 2 shows that the team identified 13 defective pipes out of the 147 pipes produced.

Pipe Category	Number
Pipa Accepted	108
Pipa Short Length	4
Pipa Rejected	35
Total	147

Table 2 Recapitulation of Project Q Production After Final Inspection

D. Material Consumption

The weight of one coil is 21629.97674 kg or 21.63 tons. To fulfil HFW's oil and gas pipeline order in the Q project, as many as 101 pipes are needed, and the number of coils used is nine, with a total weight of 194669.7907 kg or 194.7 tons. As well as the weight of steel pipes per bar is 1178.767041 kg or 0.15 tons. Table 3 shows the waste material derived from machine operation. From Table 3, six production processes produce waste, namely those that occur in copper, slitter, milling, cutting, end beveling, and welding machines, with the number of material losses or waste material from production machine activities being 24.9 tons or 12.8% of the weight of the initial material used.

No	Waste Type	Previous Process	Weight (kg)	Material Reduction Information
1	*Chip Chopper*	*Flattening Chopper*	523,23	The material is cut twice the plate's thickness along the coil's length.
2	*Trailing end and Leading end*	*Slitting*	61,289	There is a maximum material loss of 30 cm at both the leading and trailing ends of the coil.
3	*Chip Milling*	*Milling*	123,24	A reduction of 3 mm occurs on the coil's left and right edges.

No	Waste Type	Previous Process	Weight (kg)	Material Reduction Information
4	*Coil Joint*	*Cutting*	1248,49	The flying saw blade has a thickness of 80 mm, and the average pipe loss due to coil joining is 4 meters.
5	*Chip Bevel*	*End Beveling*	0,29259	Cut the pipe ends at an angle of up to 30 degrees.
6	*Weld Bead*	*Welding*	813,15	There are external scrap welds (1 and 2) and internal scrap welds.

Table 3 Waste Material Derived from Machine Operation

E. Waste Treatment

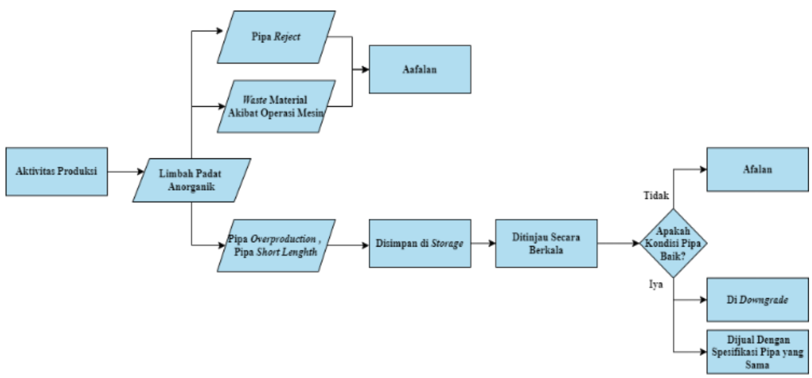


Figure 1. SPM Waste Origin and Treatment Flow

Figure 2 illustrates how waste material generated during machine operations enters the waste stream and sells the waste to other companies that require steel. The team stores rejected pipes and review them periodically. If a pipe is in good condition, they either downgrade it or sell it with the exact specifications. If not, they classify it as scrap and sell it accordingly. PMPB did not perform any downgrading during data collection, as this process depends on incoming product orders. However, the team retrieved historical downgrading data presented in Table 4.

Downgrade Pipe Specification		Number
219.1 mm X 12.7 mm X 12 M	Pipa *stock premier coil*	55
219.1 mm X 12.7 mm X 12 M	Pipa *stock* PHM	17

Table 4 Number of Pipeline Downgrades in the Last 1 Year

Table 4 reveals that the factory produced only 72 out of 15,830 pipes in the past year, resulting in a recycled materials percentage of just 0.045%.

F. Material Circularity Indicator (MCI)

MCI calculation will use the following equation

$$MCI' = 1 - LFI'.\, F(X) \tag{4.1}$$

From equation 4.1, the result of the current MCI score of SPM steel oil and gas pipelines is 0.13.

G. Preparation of Value Stream Mapping

Table 5 indicates that the workstations that have the highest efficiency are the workstations that have the lowest defect rate. The welding workstation recorded the lowest quality efficiency, with workers producing 10 defective pipes.

Workstation	Number of Reject Pipes	Efficiency
Coil Loading and Flattening	0	100,00%
Slitting	0	100,00%
Coil Joint	8	94,56%
Leveling	0	100,00%
Milling	0	100,00%
Forming	9	93,88%
Welding	10	93,20%
PWHT	1	99,32%
Sizing	0	100,00%
Numbering	0	100,00%
Cutting	5	96,60%
Visual and Dimensional Inspection	0	100,00%
End Bevelling	0	100,00%
Hydrotester	0	100,00%
Ultrasonic Test	6	95,92%
Final Inspection	0	100,00%
Marking	0	100,00%

Table 5: Quality Efficiency of Each Steel Pipe Production Workstation

Table 6 shows the material efficiency of each steel pipe production workstation.

Workstation	Material Losses (kg)	Efficiency (%)
Coil Loading and Flattening	0,00	100,00%
Slitting	5.260,75	97,30%
Coil Joint	0,00	100,00%
Leveling	0,00	100,00%

Workstation	Material Losses (kg)	Efficiency (%)
Milling	1.109,17	99,41%
Forming	0,00	100,00%
Welding	7.318,39	96,11%
PWHT	0,00	100,00%
Sizing	0,00	100,00%
Numbering	0,00	100,00%
Cutting	11.236,40	93,79%
Visual and Dimensional Inspection	0,00	100,00%
End Bevelling	2,63	100,00%
Hydrotester	0,00	100,00%
Ultrasonic Test	0,00	100,00%
Final Inspection	0,00	100,00%
Marking	0,00	100,00%

Table 6 Material Efficiency of Each Steel Pipe Production Workstation

Table 6 shows that the lowest efficiency is found in the cutting workstation, with an efficiency value of 93.79%, because the material occurs the most loosely in the workstation compared to other workstations.

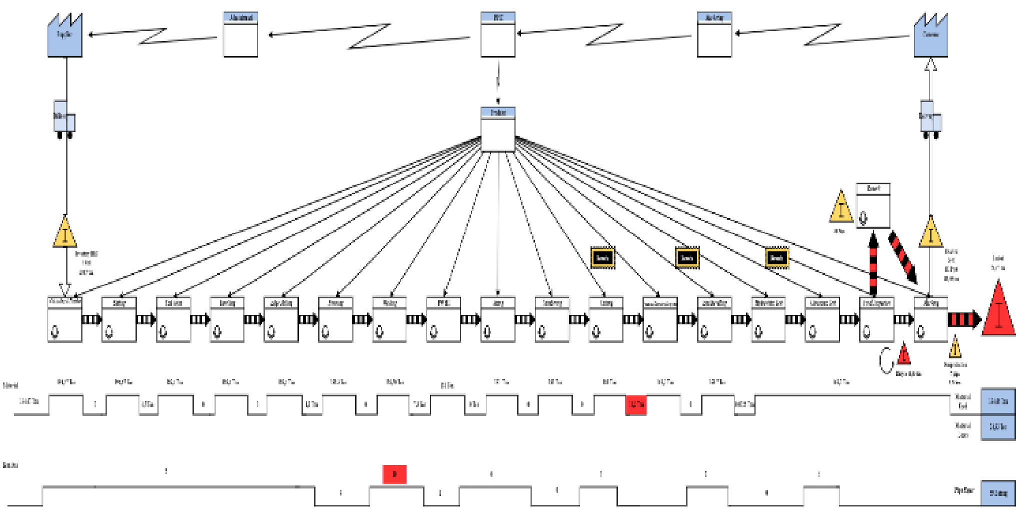


Figure 2. Current State Integrated Value Stream Mapping

Result and Discussion

Result

A. Value Stream Mapping Analysis

Based on the results of value stream mapping, there are 17 HFW oil and gas steel pipe production activities consisting of coil loading or flattener, slitting, coil joint, leveling, milling, forming, welding, PWHT, sizing, numbering, cutting, visual and dimensional inspection, end bevelling, hydro tester, ultrasonic test, final inspection, and marking. The flow shown starts from the production process flow, starting from the coil loading with the weight of the incoming coil at 194.7 tons, until the pipe is ready to be delivered to the customer at 127.3 tons. Using colour coding and informational symbols, the visualization presents a helicopter view of the HFW oil and gas steel pipe production process, highlighting that the cutting machine workstation consumes the most material. The quality indicator that causes low-quality efficiency is the welding workstation.

B. Analysis of Material Circularity Indicator

Steel Pipe Manufacturing (SPM) manufactures HFW welded oil and gas steel pipes. SPM implements a make-to-order business system, where demand depends on the order from the customer. The team measures the MCI based on implementing Project Q's production process. The team calculates the Material Circularity Indicator (MCI) and determines that the carbon footprint of SPM oil and gas steel pipe products is 0.13, indicating that the material flow is not linear due to some recycling efforts, such as producing downgraded pipes. The MCI calculation approach used is an adaptation of the company's conditions. Improving the circularity of this material by increasing the flow of recycled and reused materials.

C. Analysis of Waste Causes

Analyze the root cause of the problem *with the 5 Whys* as follows.

1. Defect no scrapping

Why 1: *The scrap* does not lift properly.

Why 2: Breakdown tools *scrap*

Why 3: *Breakdown tools scrap.*

Why 4: Not being treated well.

Why 5: Lack of operator discipline in carrying out *maintenance*

2. Material Consumption

Why 1: Improper pipe cutting tolerance.

Why 2: Inappropriate etiquette and practice in the field.

Why 3: Limited length between *coils*.

Why 4: PPIC lacks an understanding of tolerance for machines.

Why 5: Limited knowledge of developing parameters for estimating material requirements and pipeline length.

3. Waste Treatment

Why 1: The role of the steel industry is that it does not make use of waste.

Why 2: Only treat a small part of the waste.

Why 3: Not all companies care about environmental issues.

Why 4: The high *amount of material waste* or inorganic waste produced. So, the company will incur significant additional costs if it does waste treatment.

Why 5: The company's strategy has not fully attempted to build a green industry.

D. Proposed Alternative Improvements

Based on the root cause of the problem, 5 *Whys* are proposed alternative solutions with 4W+2H, namely *Where* (where is the lowest efficiency), what (what is the cause), *Why* (why causes low efficiency to occur), How 1 (how is the solution), *How* 2 (How to implement the solution), *Who* (who will apply).

1. Defect no scrapping

Where: Workstation welding

What: There is no scrapping.

Why: The operator's lack of discipline in carrying out maintenance.

How 1: Perform checking and maintenance of the machine regularly.

How 2: Make a checking or maintenance schedule that is complied with by the operator.

Who: Production manager, welding machine operator.

2. Material Consumption

Where: Cutting

What: The waste of material used with the most wasted material.

Why: Limited knowledge of developing parameters for estimating material requirements and pipe length.

How 1: Provide training to PPIC and mechanics. How: Invite or send competent employees to participate in training and elaborate on the skills of a PPIC and a mechanic.

Who: Production manager, cutting machine operator.

3. Waste Treatment

Where: After the team completes production.

What: Waste materials that can harm the environment.

Why: The company's strategy has not fully attempted to build a green industry.

How 1: Increase product recycling to reduce the amount of unmanaged waste.

How: Make a static proposal to improve the circular economy with the 4Rs (Reduce, Remanufacture, Reuse, Recycle)

Who: Factory manager.

The team analysed efficiency and proposed improvements for the workstation with the lowest performance. They selected an alternative aimed at enhancing the circular economy. To support this, they introduced a maintenance form that operators must follow to reduce defect rates. They also proposed new product designs for building poles to boost the recycling rate and increase the volume of recycled waste.

Discussion

The use of Value Stream Mapping (VSM) offers a comprehensive overview of the 17 activity points in the HFW steel pipe production process. It identifies the material and information flow from raw coil loading (194.7 tons) to finished pipe delivery (127.3 tons), enabling a data-driven visualisation of losses in both volume and quality. The cutting workstation emerges as the most significant material consumer, signalling inefficiency due to tolerance-related errors. Meanwhile, the welding workstation is pinpointed as a major quality bottleneck, affecting overall efficiency. This diagnosis underscores the power of VSM not only as a lean tool for waste visualisation but also as a strategic guide to where improvement efforts should be prioritised. The results of this study are in line with the research conducted by Rasyid et al (2021), who found that applying VSM can reduce waste by 1.7 times compared to existing conditions; besides that, it also increases efficiency by 17% (Irsyad and Hartini 2024).

The Material Circularity Indicator (MCI) analysis reveals a baseline score of 0.13, reflecting early efforts toward circularity, such as repurposing downgraded pipes. Though still low, this MCI indicates a departure from a purely linear material economy, marking a significant first step in sustainable transformation. It also illustrates that recycling and reuse practices, while present, remain underutilised in this make-to-order business model. The company has room to strengthen its circular strategy by increasing the proportion of recycled inputs and finding secondary uses for production waste. This reinforces the importance of coupling lean process mapping with sustainability metrics to align economic efficiency with environmental performance. Hasil penelitian ini sama dengan penelitian yang dilakukan oleh Michelsen et al (2006), that the use of eco-efficiency indicators solves the problem that 'traditional' environmental performance indicators might fluctuate as a result of changes in production volume and thus hide real changes in environmental performance (Michelsen, Fet, and Dahlsrud 2006).

Using the 5 Whys technique, the team effectively drills down into core issues: mechanical neglect, knowledge gaps, and insufficient green policy integration. The lack of operator maintenance discipline at the welding station leads to defective outputs. Meanwhile, tolerance miscalculations at the cutting station cause significant material waste due to poor interdepartmental understanding between PPIC and machine operators. Lastly, inadequate waste treatment stems from both cultural and strategic gaps, highlighting that green manufacturing has not yet become an embedded practice in company policy. These insights reveal systemic weaknesses that extend beyond technical inefficiencies to organisational culture and training.

The 4W+2H method—Where, what, why, how (1 & 2), Who—enables a structured plan for intervention. It assigns accountability and outlines practical steps to improve each critical area. For instance, welding defects are addressed through scheduled maintenance enforced by production management. Material waste at the cutting stage is tackled through upskilling the PPIC and technical team with specialised training. On the environmental front, the solution extends beyond operational fixes, proposing the integration of a 4R (Reduce, Reuse, Remanufacture, Recycle) framework into the company's sustainability roadmap. These structured actions highlight that solving lean and circularity problems requires a combination of process discipline, education, and strategic alignment.

One of the most promising improvements is the conversion of steel pipe waste into construction materials, such as iron poles. This initiative not only reduces unmanaged waste but also opens a new secondary revenue stream, increasing overall material efficiency. The recycling efficiency jumped to 70%, raising the MCI to 0.22, and even further to 0.32 with steel scrap smelting for construction use. This showcases the practical and measurable benefits of combining Lean Manufacturing with Circular Economy principles. It illustrates how manufacturing waste, when treated as a resource rather than a liability, can deliver economic and environmental returns.

These findings highlight that eco-efficiency in steel pipe manufacturing is achievable through holistic process improvements. However, they also reveal a need for a strategic cultural shift within the company, where green practices are not only encouraged but institutionalised. From operator discipline to waste valorisation, success depends on leadership commitment, training investment, and clear policy frameworks. The organisation must evolve from reactive improvements to a proactive green manufacturing strategy, driven by data, integrated planning, and continuous feedback. What began as a project-specific improvement (Project Q) can serve as a replicable model for broader application. The principles applied here—VSM, MCI, 5 Whys, 4W+2H—can be adopted across other production lines or facilities. This scalability potential strengthens the business case for embedding lean-circular frameworks as a standard operating paradigm. Moreover, as environmental regulations and carbon accounting grow more stringent globally, such practices position the company as a forward-looking industry leader, prepared to meet both market and regulatory demands.

Conclusion

Based on the research conducted, the conclusions are:

1) The team used Value Stream Mapping to identify the cutting machine and the workstation with the highest material consumption. They also found that the welding workstation was responsible for the low-quality efficiency due to quality issues.

2) The team measured the Material Circularity Indicator (MCI) based on the implementation of the project production process. They calculated the MCI and found that the carbon footprint of SPM oil and gas steel pipe products is 0.13. This result indicates that the material flow is no longer linear.

3) The team proposed several improvements to enhance eco-efficiency and support the circular economy. They created a maintenance schedule for operators to follow, aiming to reduce the defect rate to 23.1%. They also utilised 26.27% of pipe manufacturing waste to produce iron poles for construction, achieving a 70% recycling efficiency and raising the MCI to 0.22. Additionally, they smelted steel scrap from production machinery activities for use in construction and other components, reaching a 100% recycling efficiency and increasing the MCI to 0.32.

Recommendations, Further Research, Limitations, And Implications

Recommendations

The recommendations based on the conclusion are: 1) The company needs to establish a cross-functional committee to supervise the implementation of regular machine maintenance and evaluate the results of the implementation of VSM and MCI; 2) Periodic technical training programs are needed for PPIC operators and technicians to improve their understanding of cutting tolerances and estimation of material requirements; 3) There is a need to integrate green industry policy into long-term corporate strategy, including the comprehensive implementation of the 4R principle; and 4) Companies are advised to make a lean circular approach (VSM + MCI) a standard operating practice that can be replicated on other production lines.

Further Research

The further research are: 1) Advanced research can explore real-time MCI measurements using IoT technology to dynamically monitor the material cycle; 2) The study can be extended by using the Life Cycle Assessment (LCA) method comprehensively to assess the total environmental impact of the pipeline production process; 3) Future research needs to explore the relationship between lean-circular performance and financial indicators, such as reduced raw material costs and increased profit margins; 4) It can be examined how organizational culture and leadership play a role in encouraging green manufacturing practices and the effectiveness of technical training.

Limitations

The limitations of this research are: 1) This research only focused on one project (Project Q) and one type of product (HFW pipeline), so the results could not be generalised for all production lines; 2) MCI calculations use an adaptive approach and do not consider the entire product life cycle (focusing only on the inputs and outputs of raw materials); 3) The root cause analysis using the 5 Whys is qualitative and subjective, depending on internal observations and interviews; 4) No external validation of the effectiveness of the proposed solution such as post-implementation MCI enhancement was performed.

Implications

The implications of this research are: 1) This research combines Lean Manufacturing (VSM) and Circular Economy (MCI) approaches in one analytical framework, which is rarely done in the steel industry; 2) provides a 4W+2H-based solution model that is applicable and easily replicated for increased efficiency in the make-to-order industry; 3) A real contribution to the implementation of green manufacturing with a strategy of utilizing waste into construction products with high selling value; and 4) This research strengthens the role of integrating lean and circular methods as the basis for energy efficiency policies and industrial carbon emission reduction.

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