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Improving Energy Efficiency in Flavor Enhancer Production Using an Integrated Lean Manufacturing and Energy Value Stream Mapping Approach

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Abstract

The flavor enhancer industry faces significant challenges in improving energy efficiency because steam, electricity, and cooling utilities contribute approximately 16% of the Cost of Goods Manufactured (COGM). Although Lean Manufacturing has been implemented, most improvement initiatives have focused on production output and defect reduction rather than energy efficiency. This study aims to identify and reduce operational and energy waste in the Refinery unit using the Energy Value Stream Mapping (EVSM) approach. The proposed framework integrates EVSM for process and energy flow mapping, the Dotoli Matrix for critical waste prioritization, Root Cause Analysis using the 5 Whys method for identifying the underlying causes of waste, and Heat Exchanger Network (HEN) analysis for evaluating energy recovery opportunities, thereby providing a comprehensive approach to energy mapping, waste prioritization, root cause identification, and energy recovery evaluation. The results indicate that the dominant wastes are excessive cooling energy consumption and defect waste caused by delayed thin broth handling. Improvement proposals were developed through Heat Exchanger Network integration by utilizing glutamic mother liquor-1 as an internal cooling medium, generating potential savings of IDR 1,229,384,800 per year with a payback period of 2.4 years. In addition, the implementation of an automatic spray ball system reduced tank cleaning time from 49 minutes to 19 minutes and generated potential savings of IDR 274,007,580.52 per year. The study demonstrates that integrating Lean Manufacturing and EVSM effectively reduces energy consumption and operational waste in the Refinery unit.

Keywords: Energy Efficiency, Energy Value Stream Mapping, Lean Manufacturing, Heat Integration, Energy Waste Reduction.

1. Introduction

Energy efficiency has become an important issue in manufacturing industries due to increasing utility costs and the need to improve operational competitiveness. High energy consumption often indicates the presence of non-value-added activities that increase production costs without contributing to product value. Lean Manufacturing has been widely recognized as an effective approach to improve efficiency by systematically eliminating waste. In recent years, lean principles have also been extended to address energy waste because several classical wastes, including waiting, overprocessing, and defects, directly contribute to excessive energy consumption [1], [2].

One of the lean-based approaches for identifying energy waste is Energy Value Stream Mapping (EVSM), which extends conventional Value Stream Mapping by incorporating energy-related metrics such as cycle time, waiting time, value-added time, non-value-added time, and utility consumption into process mapping. EVSM enables simultaneous visualization of material flow, information flow, and energy consumption, allowing manufacturers to identify operational inefficiencies and major energy-consuming processes [3]. Several studies have successfully applied EVSM in discrete manufacturing industries to improve energy efficiency and reduce utility consumption. For example, Müller et al. [1] introduced EVSM by integrating production and energy information into value stream analysis, while Schillig et al. [5] and Verma and Sharma [6] extended its application for energy efficiency assessment and green manufacturing. More recently, Wen et al. [2] incorporated additional energy performance indicators into EVSM to improve energy monitoring in manufacturing systems.

Despite these developments, previous studies have primarily focused on visualizing energy consumption and identifying general energy-saving opportunities [7]. Quantitative evaluation of thermal energy transfer using heat duty (Q) analysis has rarely been incorporated into EVSM, particularly in continuous-process industries where heating and cooling utilities dominate overall energy consumption. Moreover, existing studies generally lack a systematic mechanism for prioritizing critical waste based on its operational impact before proposing energy improvement alternatives [8]. Consequently, decision-making is often based on qualitative observations rather than an integrated assessment of process waste, energy waste, and thermal recovery potential.

To address these limitations, this study proposes an integrated framework combining Energy Value Stream Mapping (EVSM), the Dotoli Matrix, Root Cause Analysis (5 Whys), and Heat Exchanger Network (HEN). EVSM is employed to simultaneously map process and energy flows, the Dotoli Matrix is used to quantitatively prioritize critical waste, Root Cause Analysis identifies the underlying causes of inefficiencies, and HEN evaluates thermal energy recovery opportunities through heat duty analysis [9]. Compared with previous EVSM studies, the proposed framework provides a more comprehensive decision-support approach by integrating energy mapping, waste prioritization, root cause identification, and energy recovery evaluation within a continuous manufacturing process.

In the flavor enhancer industry, especially in the Refinery unit, utility consumption is highly intensive and strongly influenced by cooling load, steam usage, and process synchronization [10]. Based on the company's Cost of Goods Manufactured (COGM) data, energy contributes approximately 16% of total manufacturing cost, with the Refinery unit contributing 66.75% of steam usage, 59.89% of electricity consumption, and 39.3% of chilled water utilization [11]. Therefore, this study enhances EVSM by integrating the Dotoli Matrix for quantitative waste prioritization to better identify critical energy and operational waste before determining improvement strategies.

To overcome these problems, an integrated approach is required to evaluate both process flow and energy utilization simultaneously. Energy Value Stream Mapping (EVSM) extends conventional Value Stream Mapping (VSM) by integrating energy consumption analysis into process mapping [12]. EVSM enables simultaneous visualization of process flow, material flow, information flow, and energy consumption to identify operational and energy waste systematically.

Several studies have applied EVSM in manufacturing industries. Müller et al. (2014) introduced EVSM by integrating time and energy into production analysis [1], while Schillig et al. (2015) and Verma & Sharma (2016) expanded its application for energy efficiency and green manufacturing [5], [6]. However, previous studies mainly focused on energy flow visualization in discrete manufacturing systems and did not explicitly incorporate heat duty (Q) analysis to capture thermal energy transfer and recovery potential in continuous processes. Therefore, this study extends EVSM by incorporating heat duty (Q) analysis to evaluate thermal losses in the Refinery unit, where heating and cooling utilities significantly affect energy consumption. EVSM was further integrated with the Dotoli Matrix and Root Cause Analysis (5 Whys) to identify critical waste, while improvement proposals were developed using Heat Exchanger Network (HEN) integration and automation-based lean improvement.

2. Methods

This study was conducted in the Refinery unit of a flavor enhancer manufacturing plant because this unit accounts for the highest utility and energy consumption among all production areas. The proposed framework integrates Energy Value Stream Mapping (EVSM), the Dotoli Matrix, Root Cause Analysis (5 Whys), and Heat Exchanger Network (HEN) to identify operational and energy waste, prioritize critical problems, determine their root causes, and develop improvement strategies. The methodology consists of five stages: (1) EVSM process mapping, (2) Dotoli Matrix analysis, (3) Root Cause Analysis, (4) improvement proposal development, and (5) performance evaluation.

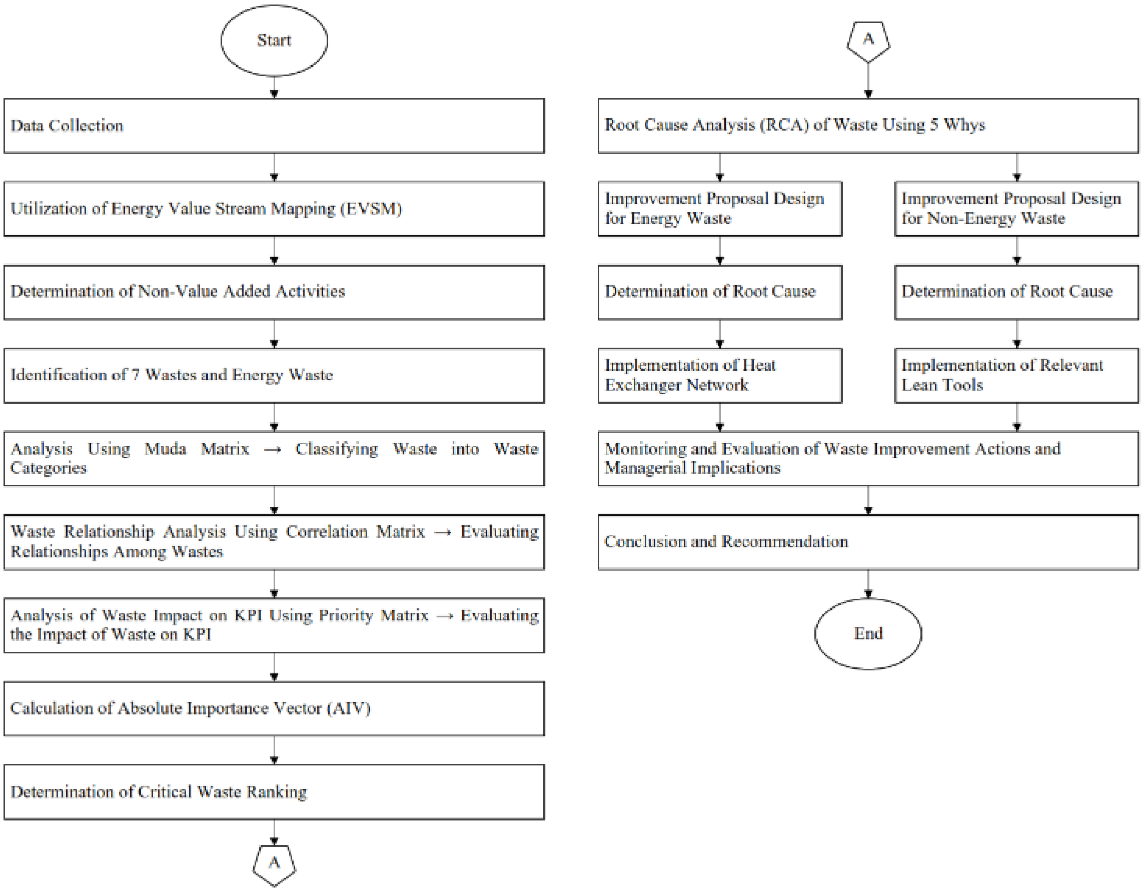

Figure 1. Flowchart of Methodology

2.1 Process Mapping Using Energy Value Stream Mapping (EVSM)

Process mapping was performed using the EVSM framework proposed by Müller et al. (2014) [1], adapted for the continuous production characteristics of the Refinery unit. The analysis covered the production flow from Thin Broth to Neutralizer Liquor [13]. Data were collected through Gemba Walk observations, production records, utility logs, and process measurements, including steam, electricity, chilled water, temperature, pressure, flow rate, cycle time, and production yield. The Current State EVSM was then developed to classify activities into Non-Value Added (NVA) and Energy Non-Value Added (ENVA) categories [14].

2.2 Critical Waste Analysis Using the Dotoli Matrix Method

Critical waste was prioritized using the Dotoli Matrix consisting of the Muda Matrix, Correlation Matrix, Priority Matrix, and Absolute Importance Vector (AIV). The assessment involved four experts representing the Production, Engineering, Utility, and Quality departments, each with more than five years of operational experience in the Refinery unit [15].

The Muda Matrix evaluated waste occurrence frequency based on field observations and EVSM results using a five-point scale (1 = very low occurrence, 5 = very high occurrence). The Correlation Matrix assessed the influence of one waste on another using a three-point scale (0 = no relationship, 1 = moderate relationship, 2 = strong relationship). The Priority Matrix evaluated the impact of each waste on four operational KPIs, namely Refinery Yield, Unit Energy Consumption, Production Target, and Losses Level, using a three-point scale (0 = low impact, 1 = moderate impact, 2 = high impact) [16]. These KPIs were selected because they directly represent production efficiency, energy performance, operational reliability, and production losses in the Refinery unit. Finally, the Absolute Importance Vector (AIV) was calculated by combining the Muda Vector (MV), Correlation Vector (CV), and Priority Vector (PV) to rank critical waste.

2.3 Root Cause Analysis Identification

Root Cause Analysis (RCA) was conducted using the 5 Whys method for the highest-ranked wastes identified by the Dotoli Matrix [17]. The identified root causes were validated through process observations, historical operating data, maintenance records, and verification meetings involving the same panel of Production, Engineering, Utility, and Quality experts. Only root causes reaching consensus among the experts and supported by operational evidence were used for improvement development.

2.4 Development of Improvement Proposals for Waste

Improvement proposals were developed based on EVSM findings, Dotoli Matrix prioritization, and validated RCA results . Non-energy waste was addressed using Lean Manufacturing principles, particularly Jidoka, whereas energy waste was addressed through Heat Exchanger Network (HEN) integration based on Pinch Analysis [18]. Technical feasibility was evaluated using heat balance and heat transfer calculations, while economic feasibility was assessed through annual cost savings and payback period.

2.5 Evaluation of Improvement Monitoring and Managerial Implications

Improvement performance was evaluated by comparing process efficiency, utility consumption, waiting time, defect rate, energy utilization, and production performance before and after implementation. Technical and economic indicators were used to assess the effectiveness of the proposed improvements.

3.Results and Discussion

This section presents the implementation of the proposed EVSM–Dotoli Matrix–RCA–HEN framework. The discussion covers process and energy mapping, critical waste prioritization, root cause identification, improvement development, and performance evaluation.

3.1 Development of Current State Energy Value Stream Map

The Current State EVSM was developed to visualize material flow, information flow, process activities, and energy consumption from the Fermentation Unit to the Neutralizer Liquor process. Based on the EVSM analysis, several Non-Value Added Activities (NVA) and Energy Non-Value Added Activities (ENVA) were identified as the basis for subsequent waste prioritization [19].

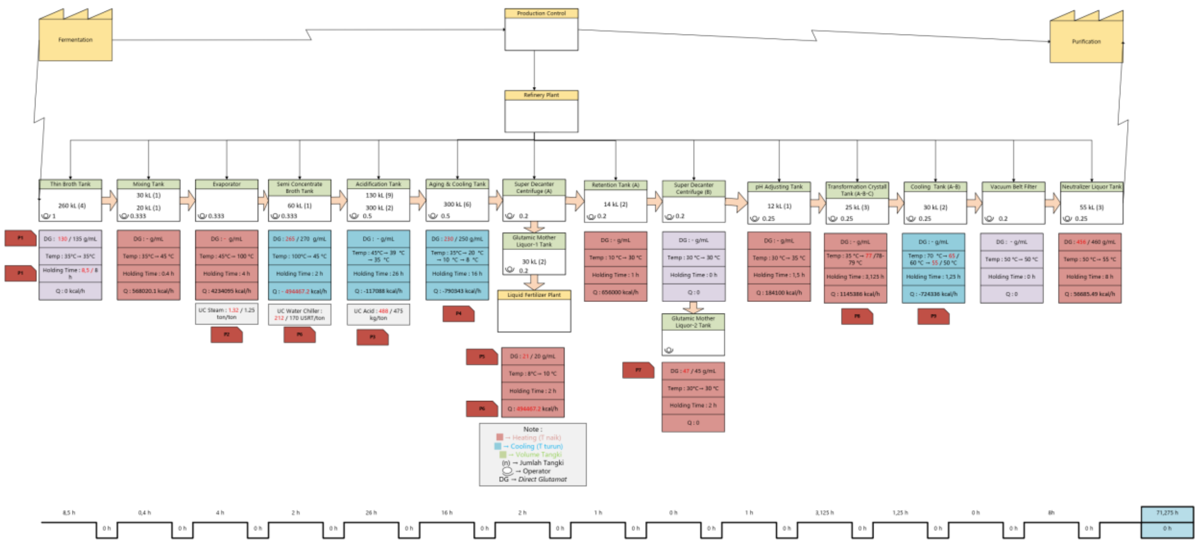

Figure 2. EVSM Current State

3.2 Waste Analysis Using Dotoli Matrix

The Dotoli Matrix ranked waste based on occurrence frequency (MV), interrelationship (CV), and operational impact (PV) [20]. P1 obtained the highest AIV score (8), followed by P6 (5), indicating that defect waste related to manual tank cleaning and energy waste associated with underutilized cooling energy were the most critical problems. These two wastes showed the strongest influence on operational KPIs and were therefore selected for Root Cause Analysis [21].

3.3 Root Cause Analysis of Critical Problems

Root Cause Analysis identified two dominant problems. Energy waste resulted from direct SCB cooling using a chiller without internal heat recovery, causing excessive chilled water and electricity consumption [22]. Meanwhile, defect waste originated from manual Thin Broth Tank cleaning, which prolonged holding time and increased product decomposition risk [23]. These findings became the basis for HEN integration and spray ball automation.

3.4 Proposed Improvements

HEN integration utilizes glutamic mother liquor-1 (GM-1) as an internal cooling medium to recover heat before SCB enters the chiller. The recovered heat duty was estimated using the steady-state energy balance,

$$Q = \dot{m}\, C_p\, (T_{in} - T_{out}) \tag{1}$$

Where Qis the recovered heat (kcal/h), m ̇is the mass flow rate (kg/h), C_pis the specific heat capacity (kcal/kg·°C), and (T_inⓜ-T_out)is the process temperature difference. Based on the operating conditions of the SCB stream (m ̇=34,920 kg/h, C_p=0.833 kcal/kg·^∘ C, T_in=47^∘ C, T_out=30^∘ C), the recoverable heat is approximately 494,467 kcal/h. Consequently, the chiller load decreases from 212 USRTH to 48 USRTH, generating annual savings of IDR 1.229 billion with a payback period of 2.4 years [24]. For non-energy waste, an automatic spray ball system reduces cleaning time from 49 to 19 min, minimizes operator dependency, and provides annual savings of approximately IDR 274 million [20].

3.5 Evaluation of Waste Reduction Monitoring and Management Implications

Performance evaluation confirmed that the proposed HEN significantly reduced cooling utility demand while improving overall energy efficiency. Similarly, the automatic spray ball system reduced cleaning time, water consumption, and defect losses, resulting in higher process stability and productivity [25]. Continuous monitoring of utility consumption, heat recovery, cleaning performance, and product quality is recommended to sustain the achieved improvements.

4. Conclusion

This study proposed an integrated EVSM–Dotoli Matrix–HEN framework to improve energy efficiency and reduce operational waste in the Refinery unit of a flavor enhancer manufacturing process. The framework systematically combined energy and process mapping, critical waste prioritization, root cause identification, and improvement development. The results identified manual Thin Broth Tank cleaning (P1) and underutilized cooling energy (P6) as the most critical wastes. Implementing Heat Exchanger Network (HEN) integration using glutamic mother liquor-1 and an automatic spray ball cleaning system reduced utility consumption, improved process efficiency, minimized product losses, and generated significant economic savings. Beyond this case study, the proposed framework can be applied to other energy-intensive continuous-process industries, such as food, chemical, petrochemical, and pharmaceutical manufacturing, where heating and cooling utilities represent major energy consumers. By integrating process improvement with energy recovery analysis, the framework provides a practical decision-support approach for identifying critical waste, prioritizing improvement actions, and enhancing sustainable manufacturing performance.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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