

Application of Lean Manufacturing Techniques to Low Density Polyethylene Recycling Processes: A Value Stream Mapping Approach

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ABSTRACT

Purpose: The aim of this study is reducing waste and improve process efficiency in the recycling of low-density polyethylene (LDPE) by applying lean manufacturing principles.

Method: Main stages in the production process Preliminary Preparation Line, Granule Extrusion Line, Film Extrusion Line, and Film Cutting Machine were examined. The current state was mapped using the Value Stream Mapping (VSM) technique. Identified wastes were addressed with lean tools, and a future state map was developed accordingly.

Findings: The analysis showed types of waste including waiting periods, unnecessary transportation, and overproduction. Improvement efforts led to reduced cycle time, fewer bottlenecks, and more efficient use of resources. The comparison between current and future states demonstrated a notable increase in overall performance and productivity.

Originality: This study offers a unique and sector-specific approach by implementing the VSM technique, which is rarely used in the plastic recycling industry. Its originality lies in adapting lean principles to recycling. Moreover, practical improvement suggestions based on actual field data provide guidance for similar businesses aiming to enhance operational effectiveness.

Keywords: Lean Manufacturing, Value Stream Mapping, Low Density Polyethylene, Process Improvement.

JEL Codes: D24, R15, Q55.

Düşük Yoğunluklu Polietilen Geri Dönüşüm Proseslerine Yalın Üretim Tekniklerinin Uygulanması: Değer Akış Haritalandırma Yaklaşımı

ÖZET

Amaç: Bu çalışmanın amacı, düşük yoğunluklu polietilen (LDPE) geri dönüşüm sürecinde yalın üretim yaklaşımıyla israfı azaltmak ve süreç verimliliğini artırmaktır.

Yöntem: Üretim sürecindeki ana faaliyetler olan Ön Hazırlık Hattı, Granül Ekstrüzyon Hattı, Film Ekstrüzyon Hattı ve Film Kesim Makinesi analiz edilmiştir. Değer Akış Haritalama (VSM) tekniğiyle mevcut durum haritası oluşturulmuş, süreçteki israflar tespit edilmiş ve yalın üretim araçları kullanılarak gelecekteki durum haritası tasarlanmıştır.

Bulgular: Analizler sonucunda; beklemler, gereksiz taşıma ve fazla üretim gibi israflar ortaya çıkmıştır. Uygulanan iyileştirme çalışmaları sayesinde üretim süresi kısalmış, darboğazlar azalmış ve kaynak kullanımı daha verimli hale gelmiştir. Mevcut ve gelecek durum haritaları karşılaştırıldığında performansta gözle görülür bir artış elde edilmiştir.

Özgünlük: Bu çalışma, plastik geri dönüşüm sektöründe nadiren uygulanan Değer Akış Haritalama yöntemini kullanarak sektöre özel ve yenilikçi bir çözüm sunmaktadır. Saha verilerine dayalı öneriler, benzer işletmelere yol gösterici niteliktedir.

Anahtar Kelimeler: Yalın Üretim; Değer Akış Haritalama, Düşük Yoğunluklu Polietilen, Süreç İyileştirme.

JEL Kodları: D24, R15, Q55.

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1. INTRODUCTION

Lean Thinking is a management and production philosophy that aims to eliminate or minimize waste in production processes. The concept of "Kaizen," which forms the basis of this approach, refers to continuous improvement and seeks to enhance quality, increase efficiency, and reduce costs within businesses (Papadopoulou and Özbayrak, 2005). Lean thinking is not merely a production method but also a management philosophy that shapes the entire organizational culture. It adopts a participatory and holistic approach where the ideas and opinions of every individual involved in the production process are valued. Accordingly, lean is an organizational culture that ensures continuous improvement through individual contributions (Nefes, 2019: 7). Lean production is based on identifying and eliminating or reducing all non-value-adding activities. This approach enables businesses to use their resources more efficiently, increases productivity, reduces costs, and enhances customer satisfaction (Aktaş, 2022: 6). With a strategic approach, the focus is on the development of the whole, not the parts. Value stream analysis is carried out by evaluating all steps, and this analysis can reveal that activities that do not create value for the customer may constitute a significant part of the process. Therefore, it is critical to see the big picture and determine the steps that create value in the entire process. The most important benefit of value stream analysis is that waste elements can be easily identified. By using lean production techniques, waste is eliminated, thus saving time and cost (Çelenk et al., 2019).

Value Stream Mapping (VSM) is a tool that connects the lean production approach and techniques. This method not only makes waste visible, but also shows the available resources and creates a general language for production processes. It allows analyzing all aspects of processes and aims to see more together with production processes such as welding, assembly, and painting. It shows the relationship between information and material flows and provides a detailed definition of how production should be run. It also allows finding solutions by examining the source of problems that may arise along with the processes on site (Meier and Liker, 2006: 22). VSM refers to the mapping of material and value flows for product materials and semi-finished products in a value flow starting from suppliers, covering the manufacturing process and including shipment to the buyer. This method shows each step in the material and information flow required for the completion of the product from order to delivery with a simple diagram. Value stream mapping includes the process of monitoring the current information and material process, summarizing them and creating a future situation aimed at achieving high-level goals (Rother and Shook, 1999: 17-19).

However, literature reviews show that VSM has not been adequately applied or studied in the recycling sector, particularly in the processes of waste collection, separation, and reprocessing. Yet, recycling processes are inherently complex, multi-step, and variable. This complexity makes process optimization difficult and leads to resource waste. At this point, evaluating the potential contributions of lean production techniques especially VSM in the recycling sector becomes critically important.

Low-Density Polyethylene (LDPE), widely used in the recycling industry and particularly preferred in packaging materials, is a type of plastic that plays a central role in sustainability policies due to its environmental impacts. The recycling process of LDPE includes several stages such as waste collection, sorting, washing, drying, pelletizing, and remanufacturing. These stages involve many elements that can lead to time, energy, and resource waste. At this point, using VSM to analyze each step of the process can help identify and eliminate non-value-adding activities. Thus, costs can be reduced, and environmental impacts can be minimized.

With growing environmental awareness and the rise of circular economy models, restructuring recycling processes with lean production techniques is becoming increasingly important. By integrating tools like VSM into these processes, the efficiency of recycling systems can be improved, resource usage in waste management can be optimized, and contributions can be made toward sustainable development goals.

Accordingly, the aim of this study is to apply the value stream mapping (VSM) approach one of the lean production techniques to the recycling processes of low-density polyethylene (LDPE), to analyze the current process, identify potential sources of waste, and propose improvement recommendations.

In the second section of the paper, the reflections of VSM applications in the literature are comprehensively analyzed. Studies conducted in various industrial sectors and the operational and strategic contributions they provide to businesses are presented with detailed data analysis. The evaluations show that applying the VSM approach to LDPE recycling processes could provide a high level of benefit when compared to examples in the literature. Moreover, the reviewed literature clearly demonstrates that VSM can be applied effectively and efficiently not only in the production sector but also in diverse fields such as healthcare, software, agriculture, and logistics.

The third section is dedicated to the research methodology. This section explains in detail the research design, data collection techniques, and analysis methods adopted in the study. Under the subheading

“Value Stream Mapping: A Method for Improvement and Efficiency Enhancement,” the theoretical foundations and practical applications of the VSM method are thoroughly discussed. In this context, explanations are provided on how VSM is used for identifying waste, improving processes, and increasing operational efficiency.

The fourth section, presented under the title Findings and Discussion, analyzes the current state of the LDPE recycling process using VSM. A detailed mapping of the current process flow was performed, and non-value-adding activities and sources of waste were identified. Then, a future ideal process map based on lean production principles was presented, and a comparative analysis with the current state was conducted. Based on the findings, process deficiencies and improvement potentials were discussed, and proposed solutions were detailed.

In the fifth section of the paper, the implementation of the value stream mapping (VSM) method in the production process, the comparison between the current and target future state maps, and the results of the implemented improvements are comprehensively addressed. In this section, using the VSM technique, takt time, cycle time, scrap rates, changeover times, and capacity values in the production processes were determined, and process performance was analyzed using numerical data. The positive impacts of these improvements on the production process were explained in detail based on the findings, and forward-looking recommendations to support the continuous improvement of the process were provided.

In the last section, the sixth section, a general evaluation is made in the conclusion section and suggestions for future studies are presented.

2. LITERATURE RESEARCH

This section presents a literature review on the applications of the Value Stream Mapping (VSM) method, one of the core tools of Lean Production, across various sectors. VSM enables a systematic analysis of value-adding and non-value-adding activities within production and service processes, aiming to reduce waste and enhance process efficiency.

Birgün et al. (2006), conducted a VSM study at UZEL A.Ş., identifying sources of waste in the current state and implementing Lean tools such as 5S, Kanban, and Kaizen to achieve process improvements. Maraşlı et al. (2016), applied VSM in an ice cream manufacturing facility to reduce excess inventory and mold changeover times, resulting in significant cost and time savings. Eser and Yıldız (2017), focused on the packaging process of a denim production firm, evaluating the applicability of Lean production and addressing encountered challenges and solutions.

Sarı (2018), aimed to streamline production processes by distinguishing between value-added and non-value-added activities. Similarly, Sevgili and Antmen (2019), analyzed the entire process from raw material intake to finished product delivery using VSM, revealing areas for improvement. Uygun et al. (2019) and Akin (2020), highlighted the contributions of VSM to process efficiency, while Çelebi and Yıldız (2020), employed the Analytic Hierarchy Process (AHP) to identify the most suitable Lean technique, offering a systematic approach to Lean transformation. Bilici and Kosanoğlu (2021), conducted a VSM application in the textile industry to identify bottlenecks and optimize operations. Büyükarıkan (2021), applied VSM in the agricultural sector to detect waste and enhance quality and efficiency. Kama and Doğan (2021), examined the applicability of VSM within supply chain processes, while Kuğu and Köse (2021), identified Kaizen opportunities in a heat exchanger flow using VSM. Oğuz and Gergin (2021), showcased the applicability of Lean approaches in a different industrial setting. Sarı (2022), explored the relationship between VSM and Industry 4.0 technologies, evaluating the impact of digital transformation on Lean production. Başak et al. (2019), transformed production processes into a pull system and utilized SMED (Single-Minute Exchange of Die) to reduce setup times. Coşkun and Özcan (2023), used ABC analysis for product family selection and employed VSM to reduce cycle times. Duzdar Argun and Çelik (2023), approached the process holistically through VSM in line with zero-inventory philosophy. Yurtseven et al. (2024), implemented an extensive VSM application in the automotive sector, successfully reducing delivery time by 52%.

VSM is also widely used in service industries. Khalilov and Gündebahar (2012), analyzed banking processes integrated with information technologies to identify optimization opportunities. Doğan and Ersoy (2016), applied VSM to streamline laboratory analysis processes at a university. Ömürgönülşen and Çatman (2018), identified sources of waste in public services and proposed improvements. Serdarasan and Ertek (2021), introduced a Lean production perspective into software development processes. Erdem (2023: 488-493), examined the benefits of VSM in software development within ASELSAN, while Alp and Akalın (2023), conducted a bibliometric analysis of Lean management-themed theses in the Turkish Council of Higher Education Thesis Center.

Applications in the healthcare sector also demonstrate VSM's impact on process improvement. Efe and Engin (2012), analyzed the current state of an emergency department process and proposed a future-state

map. Özkan et al. (2015), and Yıldız and Yalman (2015), assessed the implementation and outcomes of Lean techniques in healthcare settings. Bulut and Yıldız (2018), investigated healthcare workers' attitudes towards Lean practices, while Çavmak (2018), implemented 5S in a coronary intensive care unit. Doğan and Yağlı (2019), reviewed the literature on Lean healthcare, and Timurtaş (2020), analyzed the effects of Lean Six Sigma practices on process performance. Fidan and Toraman (2023), proposed improvements aimed at reducing paper usage in hospital outpatient services.

VSM has also been applied in other sectors such as energy, mining, and tourism. Gönen (2013: 101), investigated applications in the energy sector aimed at increasing efficiency and reducing inventory. Pekin (2015), explored the integration of Poka-Yoke and VSM to reduce human error in rubber production. Öztürk and Elevli (2017), evaluated Lean management in the mining sector, while Karlı and Tanyaş (2020), discussed the role of Lean practices in the context of smart logistics. Kapucugil et al. (2022), integrated Lean principles with ISO 14001 environmental management systems in the tourism sector to enhance environmental performance.

Bakhshayesh (2024: 27), examined the integration of Value Stream Mapping (VSM) and the Cut-to-Box systems in a shoe manufacturing facility in Istanbul. As a result of the implementation, delivery time was reduced by 21%, and the number of pre-production personnel decreased from 27 to 21. Coşkun (2023: 67-71), aimed to reduce non-value-added activities in the shoe sub-industry through VSM. As a result of analyses and improvements made in foam-based products, production time was reduced from 32.25 days to 23.5 days (27.1% reduction), and material circulation was decreased from 262.25 meters to 233.8 meters. Kökten (2021: 72-73), identified sources of waste in a cable reel manufacturing business using the VSM method and developed improvement proposals during the transition to lean production. After implementation, production flow time decreased by 44.44%, from 1.8 days to 1 day, and processing time decreased by 27.78%, from 368.23 seconds to 265.90 seconds. Kiriş (2021: 64-68), analyzed waste sources in a small-scale cable duct manufacturing company using Value Stream Mapping and proposed improvements through practices like SMED, 5S, Poka-yoke, and Kaizen. Production speed was aligned with takt time, and daily shipments were achieved with fewer shifts. Sheykhli (2024: 51-57), found that the current state map revealed the olive oil production facility could not meet the customer demand of 3473 kg per shift. Key issues included machine failures, long setup times of 40 minutes, and cleaning operations during production. Solutions proposed included reducing setup time to 24 minutes, autonomous maintenance, operator training, the Shu-Ha-Ri approach, standard work methods, Poka-Yoke, ERP integration, a supermarket system, and heijunka. Demir (2024: 36), analyzed the production processes of the TK product family in a paper manufacturing company producing cleaning products using Value Stream Mapping (VSM). Same time Alanyüz (2023: 62), in the study conducted in an olive oil production facility in İzmir, the process time was reduced from 529 minutes to 458.29 minutes (a 13.37% reduction) using the VSM method and further reduced to 406 minutes (23%) with the addition of a second operator for palletizing.

Aktaş (2022: 84), applied the VSM method in a company with a broad product range. Waste resulting from low-volume and irregular orders and a push system was identified. Duman (2019: 38), applied shipment-focused value stream mapping based on lean production principles in a project-based elevator installation process. Gür (2019: 33), conducted improvement studies with lean production and OEE analyses in the neutral soybean oil production process. Yılmaz (2019: 19-24) implemented fuzzy value stream mapping in a company producing folding boom cranes in Konya. Improvements increased assembly line efficiency by 50%, and daily production rose from 1 to 1.5 machines. Takt time dropped from 540 minutes to 360 minutes, and total processing time decreased from 1,965 minutes to 1,295 minutes (a 34% improvement). Çalışkan (2018: 70-71), carried out process improvements using VSM in a water fixture manufacturing facility. Total production time decreased from 79.83 days to 5 days, a 93.7% improvement. Kahrıman (2013: 69-73), used VSM in an injection molding facility and reduced cycle time by 29.1% and production flow time by 34.8%, while increasing value-added time by 35.8%. Başer (2011: 72-74), in a study at a household appliance manufacturing facility, VSM and Kaizen continuous improvement methods were applied to increase production efficiency. In the first phase, the number of operators required to produce 1,500 kettles decreased from 31 to 23, and per capita daily output increased from 48.4 to 65.2 units. Keskin et al. (2013) proposed the use of VSM in industrial processes to increase energy efficiency; VSM is a powerful tool not only for operational improvements but also for optimizing energy consumption. In this context, the application of VSM in the current study to make energy and resource losses in plastic recycling processes visible provides a parallel contribution to this potential stated in the literature.

These studies have been encountered in the literature as hybrid studies with VSM as the focal point. Bilici (2019: 39-43), integrated the VSM and Failure Modes and Effects Analysis (FMEA) methods for lean production. The highest RPN problems identified were uncontrolled intermediate stock (RPN: 288), long raw material procurement time (RPN: 192), and machine inefficiencies (RPN: 168). These were reduced to below 6, 12, and 100 respectively. Production efficiency increased by 2.5%, and daily output rose from

1,680 kg to 1,720 kg. Flow time decreased by 48% to 0.85 days, and cycle time dropped by 57% to 37.8 seconds. The study shows the effective results of integrating VSM and FMEA. On the other hand, Uzun (2024: 57-69) analyzed 13 defect categories using Value Stream Mapping and the Fuzzy Logic-supported FMEA method in the production of C9 model blank firing pistols at a defense industry company named CS. Kiliç (2025: 46), in the study conducted VSM, Simulation, and Spaghetti Diagram methods were integrated to improve process performance in a citrus packaging facility. Birol (2021: 62), investigated problems caused by improper material flow in oil pump production. In the current state, cycle time was 8.7 days, and processing time was 2044 seconds. The main issue was identified as the inability to procure defect-free materials from external suppliers. Improvement proposals prioritized via future state mapping and the TOPSIS method included computer-based recording systems, standardized error codes, rework instructions, part marking, material responsibility, 5S practices, and supplier development. Alaca (2010: 76-115), conducted a value chain analysis on the screen-printing process at BSH's washing machine factory. Sixteen losses were identified and prioritized based on cost. Transition to cellular manufacturing reduced stock from 4.62 days to 4.05 days (12.3%) and delivery time from 0.49 days to 0.36 days (26.5%). Duzdar and Asan (2024), applied VSM to a company producing building materials and evaluated the process performance with Bayesian analysis. This study shows that VSM can be integrated with different analysis methods in sectoral diversity. Demirci (2017: 49-50), applied VSM and MTM-UAS methods together in a sewing thread manufacturing plant, reducing delivery lead time by 56% and increasing value-added activity time by 57%.

Literature containing lean production techniques in sectors such as LDPE is developing as follows. Shalnev and Denisova (2023), HDPE production, the implementation of the "Just-in-Time" principle has led to improvements in process management; instead of the traditional KANBAN system, an automated information system adapted to chemical production has been proposed. This system automatically determines the amount of starting material, optimizes material flow through a pull-push model, and reduces the risk of emergency situations. Furthermore, the HDPE storage process is rationalized, significantly reducing the required warehouse space. Guillen et al. (2018), in a company producing PP, LDPE, and HDPE bags, the untimely delivery rate was recorded at 41.67% in 2016, leading to customer loss and additional costs. Identified issues included a 22% material shortage, defective products, and a 5% rework rate. Through the implementation of Jidoka, 5S, and a visual Kanban system, process improvements were achieved: the defective product rate decreased from 18% to 10%, rework rate from 7% to 3%, raw material replenishment efficiency increased from 65% to 90%, and delivery compliance rose from 58% to 95%. Collao-Diaz, et al. (2023), the implementation of Lean Manufacturing and Total Productive Maintenance (TPM) practices in the plastics industry increased the service level from 56% to 90.4%. The main problems identified were long delivery times (71%) and poor quality (22%). Through SMED, mold changeover time was reduced from 59.06 minutes to 43.07 minutes. Workplace organization was improved using 5S practices, resulting in a cycle time of 164.69 minutes. Penalty costs were reduced, yielding annual savings of 9,973 units, and the proposed model was validated through simulation with 90.13% efficiency. Rosnah and Othman (2012), lean manufacturing tools were systematically applied in a small-to-medium-sized enterprise focused on the plastic injection molding process. The objective was to eliminate waste on the shop floor and enhance process flow. As a result of integrating tools such as Value Stream Mapping (VSM), 5S, SMED, Heijunka, small batch production, Kanban, and milkrun, efficiency reached 94.1%, delivery performance achieved 100%, mold changeover time was reduced to 38.5 minutes, and total inventory levels were lowered to 2.86 days. The implemented methods were found to be effective and suitable for supporting continuous improvement. Quiroz Flores and Vega-Alvites (2022), with its versatile range of applications, plastic production reached 348 million tons in 2017, with Colombia showing the highest growth rate in Latin America at 4.8%, followed by Peru at 4.5%. In Peru, per capita plastic consumption is 30 kg, and the sector contributes 4% to the national GDP and 13% to tax revenues. However, companies operate at only 71.5% of their installed capacity, indicating inefficiencies. Through the implementation of Lean tools such as 5S, SMED, TPM, and Jidoka, Overall Equipment Effectiveness (OEE) increased by 13%, product losses decreased by 0.77%, and unplanned downtime was reduced by 37%. The model significantly improved delivery performance and serves as an example for the industry.

Overall, the literature reveals that VSM is widely and effectively used in diverse sectors including manufacturing, healthcare, software, public services, and agriculture. However, there appears to be a significant gap in studies focusing on the application of VSM in the recycling industry. Considering the potential benefits VSM can offer in processes such as waste collection, sorting, and reprocessing, this area represents a promising yet underexplored field in both academic and practical contexts. The complex and multi-stage nature of recycling operations makes systematic tools like VSM particularly valuable, and further research in this domain can contribute significantly to both the literature and industrial practice.

3. MATERIALS and METHODS

3.1. Value Stream Mapping

Value stream mapping is a method that aims to plan improvement efforts by identifying waste sources in production processes. It focuses on targets such as reducing raw material losses, preventing errors, reducing costs, preventing delivery delays and increasing quality. VSM analyzes all aspects of processes by making waste and available resources visible, and shows the relationships between information and material flows. It also contributes to the implementation of lean manufacturing techniques by providing the opportunity to examine problems on-site and find solutions (Meier and Liker, 2006: 40-44). In product or service production, some activities add value to the final product while others create waste. "Value stream mapping", one of the lean manufacturing techniques, aims to identify and eliminate waste, thus ensuring efficient use of resources, shortening delivery times, reducing costs and increasing profitability (Manos, 2006).

The first step to create a VSM starts with determining the product family. Then, the current situation is mapped and the current process is analyzed and the necessary information is provided to create the future situation. The current situation and changes in the future situation are considered as activities that affect each other. The last step is to prepare the plan to be implemented and start implementing it. Value stream mapping helps businesses achieve goals such as increasing efficiency in their processes and reducing costs, while also enabling them to develop strategies to increase customer satisfaction and gain competitive advantage. In VSM, various symbols are used to visualize the process. These symbols represent material and information flows, processes and other important elements (Kökten, 2021: 36-37; Demirci, 2017: 10-11).

The main purpose of this map is not to reduce the cost of a particular product, but to recognize systematic problems and develop systematic solutions for better performance of functions (Jones and Womack, 2002: 20). The main goal in the value stream perspective is to improve the whole from a broad perspective, not just limited to processes. The focus in this approach is to effectively analyze and optimize the value-creating flow (Rother and Shook, 1999: 17-19).

Table 1. Application steps of VSM method

<i>Steps</i>	<i>Applications</i>
1	A single product family is selected
2	A value stream manager is determined.
3	Mapping activities are initiated.
4	In the mapping drawing, information and material flow are monitored and planned together.
5	The VSM technique is applied to the current situation.
6	Process information such as mold change time, stock status, cycle time, number of operators, etc. are collected in the current situation value stream mapping process and recorded on the map.
7	A forward-looking situation value stream map is drawn using lean techniques in order to eliminate situations that cause waste and increase value for the consumer by utilizing the current situation value stream map.
8	An action plan is created for the future situation map.
9	The future situation is created with continuous improvement studies.

Reference: Rother and Shook (1999: 17-48)

VSM analysis is critical to increasing the efficiency of the business and eliminating waste. Mapping allows for effective analysis by visualizing all steps and relationships in the production flow. The company, which operates in a plastics plant, produces low-density polyethylene granules and garbage bags according to customer orders. Orders are received by the marketing department, recorded, and sent to the production department via e-mail. The production department prepares special work orders for each order and forwards these orders to production, purchasing, quality control, and relevant department managers.

While the purchasing department supplies the necessary raw materials according to the work orders, shift engineers perform quality controls during the production process. Department managers instruct their employees to ensure that the processes proceed smoothly. This system ensures that production is carried out in accordance with customer demands, raw materials are supplied on time, and quality standards are maintained. Thanks to this regular and integrated work, the company successfully produces granules and garbage bags while keeping customer satisfaction at the highest level.

4. FINDINGS

The information obtained has formed the basis for creating a map of the current status of the business. This map has enabled the identification of deficiencies and unnecessary stages in the processes and has allowed for the identification of improvement opportunities. The VSM technique not only determines the current problems of the business, but also helps to detect potential future problems in advance. In this way, a culture of continuous improvement has been adopted and quality has been increased in all processes of the business. Forward-looking plans and applications will strengthen the position of the business in the sector and contribute to it becoming a more successful business.

4.1. Current State Map

4.1.1. Product Family Selection

First, the variety of products available in the business and their classification are explained. Each of these products has different raw material properties. Since the production planning unit carries out production according to customer demands, there is no stock accumulation during the production process. The separation line is adjusted according to the incoming orders and the production process starts accordingly.

As a result of the observations, the Pre-Preparation Line and Granule Extrusion Line product family consisting of Pre-Preparation Line, Granule Extrusion Line, Film Extrusion Line and Film Cutting Machine sections were selected. The reason for this selection is due to the problems in the Granule Extrusion Line as a result of the observations. In addition, it was determined that the Pre-Preparation Line and Granule Extrusion Line were more suitable in terms of efficiency and product quality. This selection was made in order to improve the production process and increase customer satisfaction. The color types used in the production of low density polyethylene (LDPE) generally vary depending on the characteristics of the plastic waste obtained in recycling processes and customer demands. The colors commonly used in LDPE recycling are as follows:

- Natural (Clear/White): LDPE in its purest form, undyed or colorless. This is usually the highest purity and quality recycled LDPE.
- Black: LDPE obtained from black pigment or mixed color waste. It is usually produced and dyed from a mixture of plastic wastes of various colors.
- White: White colored LDPE obtained from pure or slightly colored waste.
- Colored (Mixed Colors): Mixed color LDPE produced from wastes of various colors. This category can include recycled LDPE in different colors such as blue, red, green, yellow.

Color variety may vary depending on the nature of the recycling process and the raw material used. Some recycling facilities can also produce special colors according to specific customer demands. The company's more efficient and sustainable production by taking into account this color variety and differences in the production process plays an important role in increasing customer satisfaction and reducing environmental impacts. VSM study provides a better understanding and improvement of all these processes. Detailed analyses performed in each of the production steps help identify bottlenecks and waste sources and offer various improvement suggestions to eliminate these problems. In this way, the company's overall production performance is increased and customer satisfaction is ensured.

As a result of measurements made in the factory, observations made on site and interviews with shift managers, data related to production were collected. Within the scope of this study, necessary information was obtained to evaluate the current status of the factory and the product family was determined. The current status map presented in Figure 1 shows each production stage (separation, crushing/washing, pool, extrusion, and packaging) in the LDPE recycling process and the cycle times, stocks, and types of waste in these processes. With this map, waiting times, intermediate stock accumulations, and bottlenecks that occur throughout the process are visualized; for example, quality problems due to human errors in the separation line and stoppages in the extrusion line are clearly defined on the map. Takt time was calculated in line with customer demands. In order to clearly transfer the current status to the map, basic questions need to be answered. The recovery process focused on by the study is a semi-automatic process. There are four employees who control all stages of the automatic line along the production line. These employees continue the flow of the process by intervening in problems that may occur on the line. During the observations made in the factory, time measurements were made at each stage repeatedly. The average completion time of each stage was calculated and determined as a result of these observations. The current status map helps us observe the entire process and see the wastes. In this section, a value stream map was drawn for the selected product family and in this direction, the value-creating and non-value-creating operations of the process

were examined and the necessary information was presented on the map. A current VSM study was conducted for a product of the plastic sector that produces granule raw materials in an industrial company. The VSM process begins with the production planning department informing the supplier of the required raw material according to the order quantity reported from the marketing department. The raw material required for the selected product family is supplied within a week and low density polyethylene production begins. The granules produced are tested for product quality. Bales are received from the supplier every Monday and packaged granule products are shipped to the customer on Mondays and Thursdays. The majority of transportation is carried out by road. In the current situation, cycle times, takt times and intermediate stocks have been mapped for a weekly production of 35 tons.

In this study, data were collected through a systematic, planned, and multidimensional observation process and production reports conducted directly on the production line. The data collection phase covered a 7-week period, including 6 working days per week and 3 shifts per day, totaling 42 shifts. This extensive observation process reflects both the temporal and operational diversity of the production environment and allows for evaluating the consistency and sustainability of the processes under varying production conditions. In the initial phase, a comprehensive current state analysis was conducted over 10 days to identify the main performance issues observed in the production line. Following this analysis, specific durations were allocated for the improvement of each production line. The sorting line was allotted 8 days, the crushing line 9 days, the washing pool 3 days, and the extrusion line 2 weeks. During these periods, operations in each line were directly observed on-site, operator workflows were monitored, and each step of the processes was recorded in detail. Additionally, the study incorporated not only quantitative but also qualitative data. Semi-structured interviews were conducted with a total of 33 personnel working across different production lines. Through these interviews, comprehensive qualitative data were obtained regarding operational challenges, bottlenecks, root causes of defects, and improvement opportunities. Thus, the data collection methodology was designed not only based on performance indicators but also with a worker-oriented perspective. Collected data included key performance indicators such as cycle times, breakdown and waiting durations, scrap amounts, production outputs, and OEE values. From each production station, 30 observations were recorded to represent the current state. Similarly, after the implementation of process improvements, another set of 30 observations per station was collected to represent the future state. This structure enables a comparative analysis between current and improved processes, ensuring that observed changes can be statistically evaluated with high reliability. The use of equal, consistent, and systematically gathered data from two different timeframes increases the validity and reliability of the study and supports its replicability in future applications. This integrated approach combining observational and analytical data offers a holistic evaluation of lean manufacturing practices and provides concrete insights into improving operational efficiency within the enterprise.

According to the data collected in the business, low density polyethylene production is transferred in line with the given production order. In the first stage of the process, the raw material in bale form is spoiled during the separation stage. An average bale weighs 500 kg. The entry of the bale into the separation section is carried out by the forklift operator or shift manager, and as a result of observations, the average time for the bale to be completely opened is 5 minutes. First, the bales delivered to the business by the suppliers are arranged in an orderly manner in the stock area. The storage area has a storage capacity of 100 bales (50,000 kg). While 2 workers place the dispersed bale on the belt, 4 workers separate the unwanted materials in the raw material on the moving belt. The completion of a bale has been measured as 105 minutes, meaning 1 kg of product is separated in 15 seconds. Unless there is any situation that prevents the production line, it is in continuous flow.

The separation line is the first process that enables the recovery of waste plastics and their reprocessability. Packaging wastes accepted in bales are sorted by manpower on the separation conveyor and unwanted products such as paper, metal, cardboard, glass, etc. are separated into scrap. During the separation process, each employee is assigned to separate a specific material, thus the process progresses faster and more efficiently. The separated plastics are checked by the quality control team before being subjected to the cleaning process. The quality control team prevents any disruptions in the production line by ensuring that the separation process is carried out correctly and completely. The separation section is the cornerstone of the recycling process. Effective and efficient work in this section directly affects the success of the overall production process. After the separation process is completed, the cleaned and separated plastics are sent to the next processing stage and the recycling process continues. This process ensures that the plastics are made suitable for later processes and can be used in the production line.

At the crushing machine stage, it reduces the size of the scrap by shredding the plastic material in the recycling line with the help of six rotating and four fixed blades depending on the screen diameter. It transmits the rotation direction of the electric motor to the rotor with the belt pulley. When the rotating blades connected to the rotor shaft start to rotate, the scrap passes between the moving blade and the fixed blade of the machine. At this time, the crushing process takes place. Water is sprayed from the upper chamber and the dirty product is washed in the crushing machine. It is carried to the beating with the crushing exit spiral located at the bottom of the crushing machine. In an average of 12 seconds, 1 kg of material is shredded and reduced. This process is repeated with the end of each bale.

The washing pool is the process of washing, cleaning and removing unseparated unwanted materials from the plastics coming from the crushing line. Since the materials transferred from the crushing line are generally dirty, a washing process is required. This stage is quite critical since the impurities in the incoming product affect the quality of the outgoing product. When the rotor, screen configuration and rotary speed in the turbo beating process are combined, the materials are cleaned and the residual moisture content of the product is removed. Contaminated particles and water are thrown out of the screen holes, and unwanted materials in the product are separated and purified.

This process is carried out effectively thanks to the centrifugal force created by the high-speed rotating rotor. The waste water comes out of the lower discharge hole of the dryer, thus minimizing the moisture content of the recovered plastics.

This method ensures that the materials are of higher quality in the subsequent processing stages and ensures that the final product complies with the standards. Turbo-beating process increases the efficiency of the production line, saving both time and energy costs. In addition, the efficient execution of this process is an important factor that increases the durability of the products and customer satisfaction. As a result, turbo-beating plays a critical role in recycling processes and also contributes to environmental sustainability. The squeezer dewateres the shredded product by applying mechanical torque and dries it by reducing the moisture content by 85%-90%. This process allows the materials to be dried efficiently and ensures that the product is of higher quality in the subsequent stages.

The squeezing machine increases the quality of the low-density recycled product, making it more durable and usable. This is an important step in the recycling process and provides a great advantage in using the materials as a final product. It is possible to minimize the waiting time in the granule extrusion line by increasing the speed of the crushing and washing line. In this way, we can continue production without stopping the line by gaining the time required for blade replacement. Eliminating the waiting waste in the granule extrusion line makes the production process more efficient and effective. This improvement both saves time and reduces overall production costs. Being able to continue production without stopping the line allows the company to meet customer demands more quickly and effectively by increasing its production capacity. Thus, the company's competitiveness increases and its market share expands.

After the pressing process is completed, the fan used during the transportation of the materials to the silo ensures that the product becomes even drier. This fan creates an additional drying effect during the transportation of the materials, helping to maintain the quality of the material.

The silo plays an important role in the storage of raw materials and intermediate products. Keeping stocks for use in the factory and having safety stocks ensures that production processes continue without interruption.

In the Granule Extrusion Line, plastic waste is melted in the extruder and turned into a homogeneous melt. During this process, the plastic material is brought to the desired temperature and pressure using heaters and screws. The extruder screws carry the material forward while also performing mixing and homogenization. This stage ensures that the plastics melt completely and create a homogeneous mixture. The molten plastic is passed through double head granule and head cutting molds in the next stage of the granule extrusion line. The mold allows the plastic to be brought to the desired shape and size. The molten plastic is subjected to a cooling process after exiting the mold. Plastic granules are quickly cooled and solidified using water cooling systems. This cooling process ensures that the granules maintain their shape and harden. The cooled plastic melt is converted into granules of the desired sizes with the help of cutting machines. These granules separate the plastic material into small, usable pieces and make it ready for storage. The granules are collected and stored by packaging units. During the storage process, the granules are made ready for use or sale.

There are situations that cause inefficiency and decrease in production speed in the production line. The first step that forms the basis of the current situation map is to determine takt time. Takt time is

defined as the frequency of customer demand for products. Businesses should manage their production activities by establishing a balance between takt time and current production speed. Takt time is calculated by dividing the net working time by an average order Equation 1.

$$\text{Takt Time} = \text{Available Work Time} / \text{Customer Demand} \quad (1)$$

$$\text{Takt Time} = 81000 / 5833.3 \text{ kg} = 13,88 \text{ sc/kg}$$

Raw material production takt time is calculated as 13.88 seconds in line with customer demands. As a result, it shows that overtime work is required due to product production below demand.

Table 2. Number of employees and cycle time by department

Section	Number of Employees	Cycle Time
Separation	6	15 sc
Crushing/Washing	1	12 sc
Pool	1	25 sc
Whipping/Squeezing	1	7.5 sc
Extrusion Line	1	14.4 sc
Package	1	14.4 sc

Addressing the efficiency and time management in the production process is critical to increasing the competitiveness of the business. All processes within the business were examined in detail in terms of the efficiency of different machines and operators, and as a result of these evaluations, production planning, flow times and all processes from order to delivery of the product to the customer were analyzed comprehensively. According to the performance of the machines and operators used in the recycling process, capacity, processing times and waste rates were determined and OEE (Overall Equipment Effectiveness) values were calculated using this data. OEE is a metric that measures how efficiently equipment is used and consists of three basic components: availability, performance and quality Equation 5. The overall efficiency of the business was evaluated by considering these components.

$$\text{Availability} = \text{Working Time} / \text{Planned Production Time} \quad (2)$$

Working Time is the time obtained by subtracting planned downtimes from planned production time. Planned Production Time is the total time planned for production.

$$\text{Performance} = [(\text{Total Number of Parts Produced} * \text{Cycle Time}) / \text{Working Time}] * 100 \quad (3)$$

$$\text{Quality} = \text{Acceptable Number of Parts} / \text{Total Number of Parts Produced} \quad (4)$$

Acceptable Number of Parts is the number of parts that passed quality control and were accepted. Total Number of Parts Produced is the total number of parts produced.

$$\text{OEE} = \text{Availability} * \text{Performance} * \text{Quality} \quad (5)$$

By considering the production flow times and total cycle time, operational efficiency in the company was calculated and improvement areas were determined in the light of these efficiency values. Cycle time is the total time it takes for a product to be completed on the production line and this time includes all production stages, waiting times and transportation. Cycle time is a factor that directly affects the efficiency and speed of the production process Equation 6. Therefore, optimizing the cycle time is important for identifying and eliminating bottlenecks in the production line.

$$\text{Cycle Time} = \text{Total Production Time} / \text{Total Number of Parts Produced} \quad (6)$$

In the production process, all processes from the order to the shipment of the product to the customer are carried out in a coordinated manner between the planning, production and logistics departments. This coordination allows each department to perform their duties in the most effective way and contributes to the smooth progress of the process. The planning department receives customer orders and creates a production program; the production department carries out production in accordance with this program and the logistics department ensures that the completed products are shipped to the customers on time and correctly. Optimizing each stage in this process increases the overall performance of the business and ensures customer satisfaction.

As a result of these calculations, in order to see the general situation comprehensively, the current situation map was calculated and visualized as in Figure 1.

In this study, a current state value stream map was developed for the LDPE (Low-Density Polyethylene) recycling process. The map details each process step from the supplier to the customer, visually illustrating key performance indicators such as cycle time (C/T), changeover time (C/O), scrap rate, and overall equipment effectiveness (OEE) for each station. In the current state, the production line consists of six main stations: Sorting, Crushing, Washing, Dewatering, Extrusion, and Packaging. It is assumed that each station operates across three shifts. The total cycle time of the production line was calculated as 88.3 seconds, and the total production lead time was estimated at 9.52 days. These durations reveal existing bottlenecks and inefficiencies within the production flow.

In particular, the sorting station demonstrates a significant loss, with a 15-second cycle time and a scrap rate of 4.6%. The extrusion station also shows a high scrap rate of 5.9% and an OEE value of only 54%. These low-performance figures limit the overall production capacity and result in the need for frequent overtime to meet customer demand. Against a weekly customer demand of 35,000 kg, the production line currently achieves only 32,400 kg per week due to capacity constraints, particularly with an average hourly production rate of 240 kg. This analysis highlights critical areas that require improvement and lays the groundwork for implementing lean manufacturing techniques in the next phase.

4.2. Future State Map

As a result of the current situation analysis, in this section where improvements in the production flow are specified and a future situation map is created, suggestions are presented for eliminating waste. As a result of determining the flow in the business by drawing the current situation value flow map, wastes and losses have been clearly revealed. With these improvements, value-added and non-value-added activities that are intended to be replaced with lean production have been identified. While aiming to minimize time losses and make the process more efficient in the future situation, the adoption of lean production has been encouraged with the suggested techniques and applications Figure 2.

The future state map in Figure 2 visually reflects the lean production-based improvement suggestions aimed at eliminating waste elements detected in the current process. The map shows in detail the interventions made in each of the main processes in the production line such as separation, crushing/washing, pool, squeezing, granule extrusion and packaging and the effects of these interventions on the process. As a result of the integration of Andon systems and the provision of ergonomic training in order to increase employee performance in the separation line, the cycle time was reduced from 15 seconds to 10.3 seconds and quality losses were reduced. In the crushing unit, blade change times were shortened with the SMED method and stoppages were reduced thanks to the use of more durable materials. Overflow and blockage problems were prevented in the washing line by using automatic water level control sensors, and product quality was increased by applying disinfectant against bad odor problems. In the granule extrusion line, the cycle time was shortened and production quality was increased thanks to the improvement of vacuum covers, operator training and the creation of standard work instructions. In line with all these arrangements, it is seen on the map that the production flow is more balanced, unnecessary stocks are eliminated and a system that works at a speed suitable for customer demand is designed. Thus, the production process has been reduced to a sustainable structure, with increased efficiency and reduced waste. Detailed information is provided under the subheadings.

The push system currently applied in the business has been addressed because it can lead to inefficiency and a decrease in speed in production. The first step in the future state map was to determine takt time; that is, to determine the production speed appropriate to customer demands, so that new customer demands can be met. Businesses should align production with customer demands by using takt time.

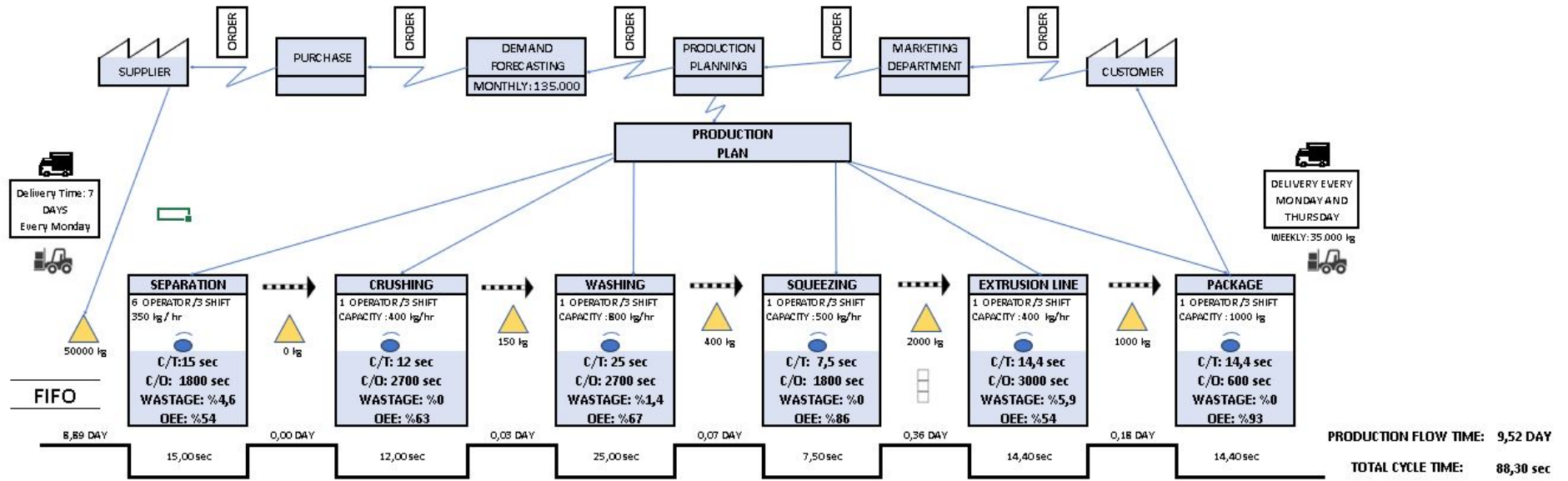


Figure 1. Current state map

Application of Lean Manufacturing Techniques to Low Density Polyethylene Recycling Processes: A Value Stream Mapping Approach

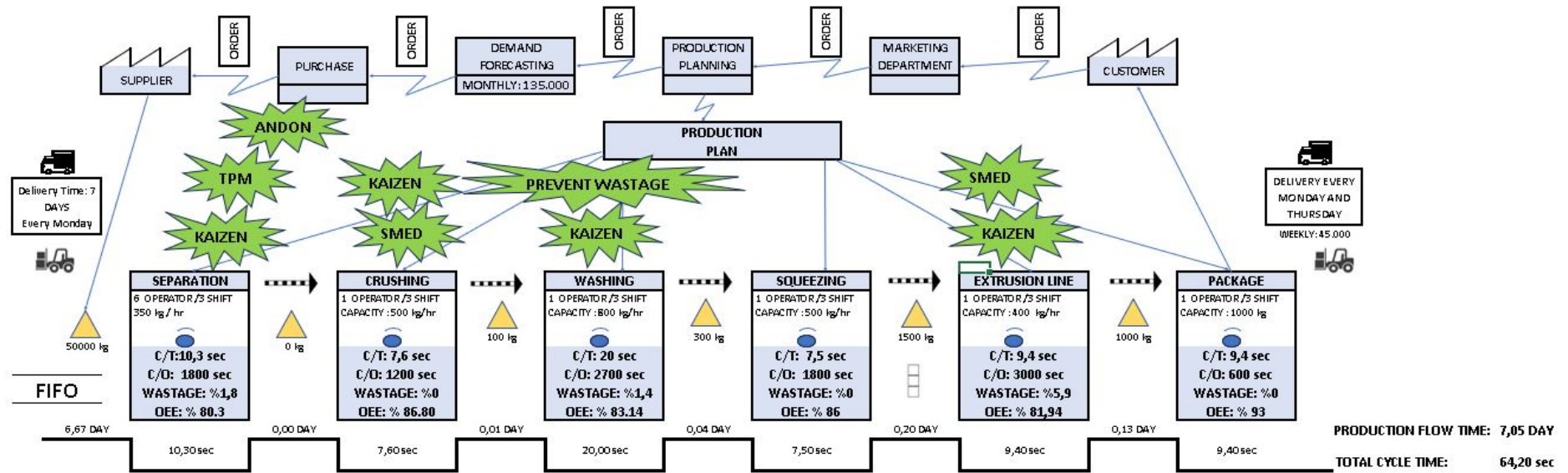


Figure 2. Future state map

5. RESULTS AND DISCUSSIONS

5.1. Separation Line

It has been determined that the most important factor that negatively affects the efficiency of the separation line is the human factor. Operating the belt at a speed that will strain the employees causes the personnel to lose their attention because they cannot keep up, and unwanted metal pieces damage the crushing blades and conveying spirals. This situation results in the replacement of the blades and the pause of production, which increases costs and decreases efficiency. In order to solve the problem, analyses were conducted to optimize the belt speed and regular training programs and ergonomic arrangements were planned to be implemented to increase the performance of the employees. As part of the training programs, employees were guided to adapt to the belt speed and work in a balanced and ergonomic manner without losing focus. They were taught correct working postures and methods to avoid errors caused by excessive physical effort. Additionally, awareness was raised about the damage that metal or foreign objects can cause to equipment during the production process, and the basic rules for the safe and careful use of equipment were explained. Quality control awareness was enhanced through topics such as detecting scrap contamination, effective use of Andon systems, and early reporting of quality issues. Furthermore, to boost employee motivation and strengthen team communication, topics such as feedback techniques and setting performance targets were addressed. Along with Kaizen and a culture of continuous improvement, employees were also encouraged to actively participate in the improvement processes.

As a result of the cause-cause analysis, the current status of the process was evaluated, wastes were identified and improvement suggestions were developed. It was suggested that entry controls be tightened to prevent scrap contamination, quality control equipment be strengthened and suppliers be regularly inspected. In addition, it was planned to make agreements with suppliers that determine quality standards and to ensure the continuity of these agreements. It was emphasized that targets should be realistically determined and the belt speed should be adjusted in accordance with the capacity of the employees in order for the personnel to adapt to the speed problem in the production line. In order to eliminate imbalances in raw material quality, it was envisaged to improve supplier selection processes and separate scraps from different sources. With all these arrangements, it is aimed for the company to operate with higher efficiency in the short and long term and to gain cost advantage.

Table 3. Paired samples statistics of the separation line

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	CT_Before	15.0333	30	0.73781	0.13471
	CT_After	10.304	30	0.21418	0.0391
Pair 2	Waste_Before	4.6027	30	2.129	0.3887
	Waste_After	1.908	30	0.36488	0.06662
Pair 3	OEE_Before	53.6453	30	2.91039	0.53136
	OEE_After	80.3233	30	1.68772	0.30813

As a result of the improvements implemented, significant advancements were achieved in the separation line in terms of cycle time, waste amount, and equipment effectiveness. The average cycle time, which was 15.03 seconds before the improvement, decreased to 10.30 seconds afterward representing an approximate reduction of 31.5%. This reduction indicates a notable increase in production efficiency (Table 3). In terms of waste, the initial rate of 4.60% dropped to 1.91% following the improvements. This corresponds to a 60% reduction in waste and reflects a more efficient approach to resource utilization. Similarly, a substantial improvement was observed in OEE. The average OEE increased from 53.64% before the intervention to 80.32% afterward, marking a rise of approximately 49.7%. This improvement demonstrates that the separation line operated with fewer stoppages, higher performance, and better quality rates.

Table 4. Paired samples correlations of the separation line

		N	Correlation	Sig.
Pair 1	CT_Before & CT_After	30	0.971	< 0.01
Pair 2	Waste_Before & Waste_After	30	0.949	< 0.01
Pair 3	OEE_Before & OEE_After	30	0.965	< 0.01

The correlation coefficient between the variables CT_Before and CT_After was calculated as 0.971, with a p-value of < 0.001 (Table 4). This result indicates a strong and statistically significant positive relationship between the two variables, suggesting a high level of linear association between the pre- and post-improvement cycle time data. Similarly, the correlation coefficient between Waste_Before and Waste_After was found to be 0.949, with a p-value of < 0.001 . This also demonstrates a strong and meaningful relationship between the waste amounts before and after the improvement, indicating a consistent and parallel change in waste levels. For OEE_Before and OEE_After, the correlation coefficient was calculated as 0.965, with a p-value of < 0.001 . This reflects a high degree of alignment and linear relationship between the equipment effectiveness measurements taken before and after the improvement.

Overall, the correlation analysis reveals strong and statistically significant associations across all measured parameters before and after the improvement efforts. These findings confirm that the improvements implemented in the separation line have had a direct and effective impact on process performance, leading to substantial advancements in key indicators such as cycle time, waste reduction, and overall equipment effectiveness (OEE).

5.2. Crushing Machine

Regular maintenance and cleaning are important for the efficient operation of the crushing machine. Keeping the blades sharp and the moving parts working smoothly increases the efficiency of the crushing process. Operators should receive regular training and comply with safety protocols to ensure the correct operation of the machine. In addition, it is important for occupational health and safety to keep the noise level generated during the operation of the crushing machine under control. The factors that affect the efficiency of production in crushing are as follows:

- Sieve Diameter
- Blade Quality
- Water Intensity

5.2.1. Sieve Diameter

A six-day analysis was carried out by testing three different sieves: 100 mm, 80 mm and 60 mm sieve diameters were tested.

In Table 5, when a 100 mm screen diameter is used, the semi-finished product particles passing through the screen without being crushed are relatively large, resulting in an increase in line speed. However, these larger particles tend to wrap around the transport augers, leading to issues such as motor overload, motor burnout, and belt breakage, which ultimately cause line stoppages.

When a 60 mm screen diameter is used, the semi-finished product particles passing through are smaller, which leads the system to further reduce their size, thereby slowing down the line and decreasing overall efficiency. It was determined that using an 80 mm screen diameter provides the most optimal line efficiency, balancing throughput while reducing breakdowns and stoppages by approximately 50%.

Table 5. Optimum sieve diameter root causes analysis

<i>Process</i>	<i>Potential Root Causes</i>						<i>Solution</i>
	<i>Why?</i>	<i>Why?</i>	<i>Why?</i>	<i>Why?</i>	<i>Why?</i>	<i>Root Cause</i>	
Sieve diameter	Low production efficiency in crushing.	Using a sieve diameter of 100 mm.	The large diameter causes semi-finished products to be wrapped in spirals.	Engines straining, burning out and belts breaking.	It causes the line to stop.	Inappropriate sieve diameter.	80 mm sieve diameter: provides the most optimum line efficiency.
		Using a sieve diameter of 60 mm.	Small diameter slows line speed.	Products need further processing to become thinner.	Efficiency is decreasing.		
		Using a sieve diameter of 80 mm.	Speed and failure rate are balanced.		Faults and postures decreased by 34 %		

Table 6. Blade quality root causes analysis

<i>Process</i>	<i>Potential Root Causes</i>				<i>Root Cause</i>	<i>Solution</i>
	<i>Why?</i>	<i>Why?</i>	<i>Why?</i>	<i>Why?</i>		
Blade Quality	Crushing knives become dull quickly.	The material used is not hard enough.	Plain carbon steel is used.	Insufficient blade quality.		With the use of Hardox 500 hardened steel, 60% efficiency in production downtimes has been achieved.
	Hand tools and materials to be used are not ready.	No preparation has been made for blade replacement.	Due to shift change, crushing knives that need to be sharpened are left for the next shift.	Blade change times are long (30 minutes).		In order to minimize tool change times, spare tools must be preprocessed. Must be viewed and made ready for use. In addition, a specific place and bench should be arranged so that hand tools can be easily found.

5.2.2. Blade Quality

A root cause analysis regarding the impact of blade quality on production was conducted and presented in Table 6. Upon reviewing the production reports, it was found that crushing blades dull quickly, requiring replacement three times per day, with each replacement taking approximately 30 minutes.

The root cause analysis revealed that the main issue was the rapid dulling of the blades, primarily due to the insufficient hardness of in-house manufactured blades.

To address this problem, Hardox 500 hardened steel was used instead of plain carbon steel to increase blade durability, and the impact on production downtime was monitored. As a result, the frequency of blade replacements was reduced from three times to twice per day.

In addition, by applying the SMED (Single-Minute Exchange of Die) method, several improvements were made:

- The positions of hand tools used for blade replacement were standardized,
- Tools were prepared and made ready before the replacement process,
- Blades were pre-sharpened in advance.

These steps collectively reduced the blade replacement time from 90 minutes to 40 minutes. These improvements enabled a more continuous and efficient production process. By reducing both the frequency and duration of blade changes, the overall performance of the production line improved, resulting in a more productive operational environment.

Table 7. Water intensity root causes analysis

Process	Potential Root Causes			Root Cause	Solution
	Why?	Why?	Why?		
Water Intensity	The line stops due to blockages.	When there is insufficient water, the product remains in the breaking state. When the water intensity is high, it accumulates in the spiral.	When the water intensity is low, the product after crushing does not fall into the spiral. Excess water causes the product to accumulate in the screw.	Incorrect adjustment of water intensity.	The intensity of the water was adjusted to the optimum level. Loss of time and decrease in production efficiency were minimized.

5.2.3. Water Intensity

Based on data obtained from production reports, various analyses were conducted on downtimes in order to improve production efficiency. It was observed that insufficient water pressure from the top chamber causes the crushed material to fail to move toward the screw conveyor, resulting in accumulation within the crusher. On the other hand, excessive water pressure leads to accumulation in the screw conveyor, causing blockages that require the line to be stopped and emptied (Table 7). In both scenarios, time loss and a decrease in production efficiency were identified as significant issues.

Various improvements have been made in the crushing and washing processes to increase the efficiency of the production line. By determining the sieve diameter as 80 mm, optimum balance has been achieved in line speed, and the strain on the motors and stoppages have been reduced by 50%. Hardox 500 steel has been preferred to prevent rapid dulling of the crushing blades, and the blade change time has been reduced from 90 minutes to 40 minutes with the SMED method. In addition, the frequency of blade changes has been reduced from three to two per day, reducing production interruptions. Automatic water leveling sensors have been used in the washing basin to prevent overflow and blockage problems, and line efficiency has been increased. In order to prevent bad odor problems in the raw material, disinfection has been provided with NaOCl and solid caustic, and the final product quality has been improved. By ensuring the trouble-free operation of the washing basin with periodic maintenance and filter cleaning, customer satisfaction has been increased.

Table 8. Paired samples statistics of the crushing machine

		<i>Mean</i>	<i>N</i>	<i>Std. Deviation</i>	<i>Std. Error Mean</i>
Pair 1	CT_Before	12.0207	30	0.51520	0.09406
	CT_After	7.6000	30	0.93070	0.01699
Pair 2	Waste_Before	0	30	0	0
	Waste_After	0	30	0	0
Pair 3	OEE_Before	62.4757	30	2.51880	0.45987
	OEE_After	82.2480	30	0.99771	0.18216

Before the improvement, the average cycle time was 12.02 seconds, which decreased to 7.60 seconds after the improvement. This represents a reduction of approximately 36.8%. Such a decrease indicates an acceleration in the production process and a reduction in time losses (Table 8). When pre- and post-improvement measurements are examined, the waste amount was reported as 0.00 in both cases. The OEE (Overall Equipment Effectiveness) value increased from 62.48% before the improvement to 82.25% afterward, corresponding to an improvement of approximately 31.6%. This rise in OEE suggests enhancements in equipment availability, performance, and quality rates.

Table 9. Paired samples statistics of the crushing machine

		<i>N</i>	<i>Correlation</i>	<i>Sig.</i>
Pair 1	CT_Before & CT_After	30	0.884	<0.01
Pair 3	OEE_Before & OEE_After	30	0.910	<0.01

The results of the correlation analysis (Table 9) show that the correlation coefficient between CT_Before and CT_After was calculated as 0.884, indicating a strong and positive relationship between the two variables ($p < 0.001$). This finding suggests that the improvements had a systematic and consistent impact on cycle time, contributing to enhanced process efficiency. The correlation coefficient between OEE_Before and OEE_After was found to be 0.910, which also reflects a strong and statistically significant positive relationship ($p < 0.001$). This result indicates that the observed increase in OEE was not due to random variation, but rather a direct and effective outcome of the improvement initiatives on overall process performance.

5.2. Washing

The water level in the washing tanks must be maintained at an optimal level. When the water level is too low, the movement of raw materials slows down, which in turn reduces the line speed. On the other hand, when the water level is too high, the tanks overflow, leading to material loss. Instead of manually adjusting the water level, the use of an automatic water level control sensor has allowed for consistent regulation, increasing line efficiency and preventing overflow outside the tank.

Additionally, semi-finished materials in the washing tank that are dirty and emit unpleasant odors can cause the raw material from the granule extrusion line to also smell bad, negatively impacting product quality and customer satisfaction. To address this issue, sodium hypochlorite (NaOCl) and caustic soda were used in the washing tank to eliminate bad odors from the material and to disinfect the water. This improvement has led to a noticeable increase in final product quality and has enhanced customer satisfaction.

Table 10. Paired samples statistics of the washing

		<i>Mean</i>	<i>N</i>	<i>Std. Deviation</i>	<i>Std. Error Mean</i>
Pair 1	CT_Before	12.5653	30	0.95797	0.1749
	CT_After	10.0033	30	0.17691	0.323
Pair 2	Waste_Before	1.4303	30	0.4565	0.8335
	Waste_After	1.3947	30	0.22491	0.4106
Pair 3	OEE_Before	66.5157	30	4.98047	0.90931
	OEE_After	83.1163	30	1.43645	0.26226

The average Cycle Time before the process was 12.57, while the post-process average was measured at 10.00. This indicates a reduction of approximately 20.4% in cycle time, demonstrating that the production process has accelerated and a significant improvement in the operational efficiency of the line has been achieved (Table 10). Regarding the amount of waste, the pre-process average was 1.43, while the post-process average was measured at 1.39. Although this appears to be only a 2.8%

reduction in percentage terms, the increase in production volume after the intervention makes this improvement more meaningful. The fact that waste decreased despite higher output indicates that the process has become more efficient and that waste is being managed more effectively. Therefore, it is reasonable to conclude that there has been a significant improvement in waste reduction. In terms of OEE (Overall Equipment Effectiveness), the average increased from 66.52% before the process to 83.12% afterward. This approximate 24.9% increase shows that substantial improvements have been made in components such as machine availability, performance, and quality on the production line.

Table 11. Paired samples correlations of the washing

	<i>N</i>	<i>Correlation</i>	<i>Sig.</i>
Pair 1 CT_Before & CT_After	30	0.876	< 0.01
Pair 2 Waste_Before & Waste_After	30	0.898	< 0.01
Pair 3 OEE_Before & OEE_After	30	0.921	< 0.01

The calculated correlation coefficient for the change in Cycle Time is $r = 0.876$, and this relationship is statistically significant ($p < 0.001$). This finding indicates a strong and consistent relationship between the pre- and post-improvement cycle times. For waste data, the correlation coefficient was found to be $r = 0.898$, which is also highly significant ($p < 0.001$). This result shows that the change in waste levels is not random but occurred systematically, supporting the reliability of the measurements. The correlation coefficient for changes in OEE was calculated as $r = 0.921$, indicating a very strong linear relationship ($p < 0.001$). This suggests a strong connection between the pre- and post-improvement OEE values (Table 11). The high correlation coefficients for Cycle Time, waste, and OEE parameters demonstrate that the improvements made are not only operationally effective but also statistically reliable and consistent. These findings show that the process improvement initiatives were implemented effectively and contributed positively to overall system performance.

5.3. Granule Extrusion Line

In order to prevent speed losses and increase efficiency in the granule extrusion line, machine, method, environment, material and human factors were analyzed. In this analysis, the origins of the errors and solutions were determined using fishbone diagram and Kaizen methods.

Among the problems originating from the machine and method, there is no original silicone used in the vacuum cover and the lack of an automatic speed control system. In addition, the lack of procedures for changing the sieve and the lack of standard work instructions lead to disruptions in production. In the material category, foreign substances in the products cause equipment damage and stoppages. Among the human factors, the fact that the operators have different competencies and that the transfer settings are made incorrectly stood out as important problems. Damage to vacuum equipment due to personnel carelessness also negatively affects line speed.

In order to solve these problems, the Kaizen approach has been adopted (Table 12). The use of original silicone in the vacuum cover and standardization of cover opening methods have been ensured. Steps such as the establishment of an automatic speed control system, development of procedures for screen replacement and training of operators have been taken. Controls have been increased to prevent foreign substances, and measures have been taken to support personnel motivation. These improvement efforts have increased performance by minimizing line speed drops, and an uninterrupted flow has been achieved in production.

The analysis results of the Granule Extrusion Line reveal that significant improvements have been achieved in the production process. First, when examining the Cycle Time data, the average cycle time decreased from 14.41 seconds before the improvement to 9.40 seconds after the improvement. This represents a reduction of approximately 34.7%, indicating an acceleration in the production process and a substantial advancement in time management (Table 13). In terms of waste amount, the average value prior to the improvement was 5.91, and it slightly decreased to 5.90 afterward. This difference is minimal and suggests that there was no statistically significant change in waste levels. Therefore, no notable improvement was achieved in terms of waste reduction on the Granule Extrusion Line.

Table 12. Granule extrusion line root causes analysis

Step No	Process	Potential Root Causes		
		Why?	Why?	Why?
1	Raw Material Dosing	The film being shot is gassy	The granule is gassy	Vacuum dehumidification unit not working effectively
2	Raw Material Dosing	The film being shot is gassy	The granule is gassy	Vacuum dehumidification unit not working effectively
3	Raw Material Dosing	The film being shot is gassy	The granule is gassy	Vacuum dehumidification unit not working effectively
4	Raw Material Dosing	The film being shot is gassy	The granule is moist and the granules are not dried sufficiently	Drying unit not operating at full capacity
5	Raw Material Dosing	Burnt granule	Problem caused by screw sleeve	Foreign (metal) objects entering the screw barrel
6	Raw Material Dosing	Burnt granule	When the granule sieve becomes clogged, the operator increases the resistance temperature or changes the melt pressure instead of changing the sieve, which allows the material to pass through the sieve but deteriorates the quality of the melt material.	
7	Melting of Raw Materials in Granule Extruder	The operator reduces the machine speed on his own initiative		
8	Melting of Raw Materials in Granule Extruder	The operator reduces the machine speed on his own initiative		
9	Melting of Raw Materials in Granule Extruder	Each operator adjusts the granulating machine differently		
10	Melting of Raw Materials in Granule Extruder	Each operator adjusts the granulating machine differently		
		<i>Why?</i>	<i>Why?</i>	<i>Final Root Cause</i>
		Vacuum cover leaking		A different material was used instead of the original silicone
		Vacuum cover leaking		It has been determined that the correct method is not used when opening and closing the vacuum lid.
		The vacuum clock is faulty and gives incorrect data		Vacuum clock was damaged due to personnel error
		The drying screen strainer gets clogged frequently	Dandruff formed during cutting blocks the screens	The operator is not adjusting the flow setting properly.
				There are foreign substances that cannot be separated in the purchased semi-finished product.
		Not changing the sieve at the right time		There is no standard for sieve replacement in the granule line. Granule extruder settings are made differently by each operator. There is no automatic speed control system in the granule extruder line.

Table 13. Paired samples statistics of the granule extrusion line

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	CT_Before	14.4093	30	0.3578	0.06532
	CT_After	9.4013	30	0.15449	0.02821
Pair 2	Waste_Before	5.908	30	0.47623	0.08695
	Waste_After	5.9003	30	0.39521	0.07215
Pair 3	OEE_Before	53.5177	30	1.46375	0.26724
	OEE_After	81.9913	30	1.39923	0.25546

In contrast, a considerable increase was observed in the Overall Equipment Effectiveness (OEE) rate. The average OEE increased from 53.52% before the improvement to 81.99% after the improvement, reflecting an approximate increase of 53.2%. This improvement indicates that the production line operated more efficiently, equipment performance was enhanced, and overall production quality improved.

Table 14. Paired samples correlations of the granule extrusion line

		N	Correlation	Sig.
Pair 1	CT_Before & CT_After	30	0.985	< 0.01
Pair 2	Waste_Before & Waste_After	30	0.969	< 0.01
Pair 3	OEE_Before & OEE_After	30	0.985	< 0.01

The correlation analysis results for the Granule Extrusion Line indicate that there are highly strong relationships between the pre- and post-improvement data (Table 14). The correlation coefficient for Cycle Time is $r = 0.985$, which points to an exceptionally strong positive relationship. This suggests that the changes in cycle time before and after the intervention were consistent, demonstrating that the improvements were implemented in a systematic manner. For waste amounts, the correlation coefficient was found to be $r = 0.969$. This value indicates that the small changes observed in post-intervention waste levels were not random but rather the result of planned and structured actions. Similarly, a very strong linear relationship was observed for OEE, with a correlation coefficient of $r = 0.985$. This confirms that efficiency levels before and after the improvements changed in a consistent and regular pattern, highlighting the effectiveness of the interventions. All correlation values are statistically significant ($p < 0.001$), confirming the reliability of the findings and supporting the validity of the improvement process.

This study has shown that significant improvements in production efficiency and process quality have been achieved by applying lean production techniques to the LDPE recycling process. The findings, when compared to similar applications in different sectors in the literature, offer both parallel trends and sector-specific contributions. First of all, the reduction of the waste rate in the separation line from 4.6% to 1.8% shows how quality losses can be minimized with lean production tools, as in the studies of Bilici (2019: 39-43) and Kökten (2021: 72-73). In Bilici's study, high-risk problems were identified with the FMEA method and the factors causing waste were brought under control, and production efficiency was increased by 2.5%. Similarly, Sheykhli (2024: 61:63) has shown that production in line with demand can be achieved by eliminating the causes of waste, such as malfunctions and cleaning in machines in food production. Bakhshayesh (2024: 41-43), also minimized waste and wastage in shoe production, resulting in a 21% decrease in production costs and an increase in efficiency. In our study, in-process observation and standardization for waste control provided improvements at similar rates.

The 44% reduction in blade change time with SMED application is similar to the study of Demir (2024: 43), where the roll change time was reduced by 28% in the paper production facility and an increase of approximately 1 million boxes in annual production was achieved. The effective application of SMED not only shortened the time but also directly increased the production capacity. This situation was also emphasized by Kiriş (2021: 71), and it was stated that a 61% improvement in production time was achieved with methods such as 5S and Kaizen applied together with SMED.

When evaluated in terms of cycle time, a decrease from 12 seconds to 7.6 seconds (approximately 37%) was achieved in our study and from 88 seconds to 64 seconds (27%) in the extrusion line. These rates are highly consistent with examples such as Yılmaz (2019) reducing cycle time by 34% in crane production, Demirci (2017: 49-50) providing a 57% increase in time that adds value in yarn production, and Birol (2021: 64) reducing cycle time by 60% in oil pump production.

Increasing shift capacity and increasing it to a level that meets customer demand is similar to Kahrıman (2013: 69-73) reducing cycle and flow time by over 30% in injection mold production, thus increasing capacity. It is also consistent with efficiency-oriented transformations such as Başer (2011: 72-74)

increasing production per person by reducing the number of operators in white goods production. The target of increasing capacity to 349 kg/h by eliminating the bottleneck in the separation line shows the direct impact of identifying and removing constraints in the system on output. This approach has a similar strategic perspective to Uzun (2024: 61) reducing flow time by 63% as a result of analyzing bottlenecks in the defense industry with Fuzzy FMEA.

The study also suggests that developing water recovery systems can be used not only in terms of operational but also environmental sustainability. In this context, it is consistent with the studies of Kapucugil et al. (2022) in which they achieved an increase in environmental performance with the integration of Lean and ISO 14001 in the tourism sector. It is also seen that Gür (2019: 27) established a balance between efficiency and sustainability by switching to the CIP system in oil production. As a result, this study has provided successful improvements that coincide with many studies in the literature, but it has also made an original contribution due to the small number of applications in the recycling sector. With the systematic application of lean tools, both efficiency has been increased and sustainability goals have been contributed. This reveals the applicability of lean production even in sectors that are inherently variable and energy-intensive, such as the LDPE recycling process.

Table 15. Comparison of current state and future state

Section	Cycle Time		Setup Time		Wastage		OEE	
	Current State	Future State	Current State	Future State	Current State	Future State	Current State	Future State
Separation	15 sc	10.3 sc	1800 sc	1800 sc	4.60%	1.80%	54.00%	80.30%
Crushing	12 sc	7.6 sc	2700 sc	1200 sc	0%	0%	63%	86.80%
Washing	25 sc	20 sc	2700 sc	2700 sc	1.40%	1.40%	67.00%	83.10%
Squeezing	7.5 sc	7.5 sc	1800 sc	1800 sc	0%	0%	86%	86%
Extrusion Line	14.4 sc	9.4 sc	3000 sc	3000 sc	5.90%	5.90%	54.00%	81.90%
Package	14.4 sc	9.4 sc	600 sc	600 sc	0%	0%	93%	93%

Table 16. Production flow time and total cycle time

Production Flow Time		Total Cycle Time	
Current State	Future State	Current State	Future State
9.52 days	7.5 days	88.3 sc	64.2 sc

In Table 15 and Table 16, LDPE recycling process, six main operational steps have been analyzed: Separation, Crushing, Washing, Squeezing, Extrusion Line, and Packaging. These steps have been compared in terms of key performance indicators such as cycle time, setup time, waste rate, and overall equipment effectiveness (OEE), considering both the current and future states. This comparison demonstrates that the integration of lean manufacturing techniques into the LDPE recycling process has led to accelerated processes, increased efficiency, reduced waste, and significant improvements in machine and equipment effectiveness.

6. CONCLUSION

In order to gain competitive advantage and increase sustainability, businesses focus on eliminating hidden waste in their production processes, increasing efficiency and adopting continuous improvement principles. When past studies are observed, it is seen that in VSM studies in general, the absence of a rational planning decision in the production process causes an increase in setup time and intermediate stocks, production of faulty products, waste of movement, loss of raw materials and an extension of production time. As a solution to the problems, it is aimed to create a future state value stream map that will represent the point to be reached with the returns of the studies.

LDPE is produced in plastic recycling raw material manufacturing. It is aimed to analyze the current situation with VSM and implement improvements in recycling processes. In line with the information obtained from the company, the product family was determined first and the current situation map was drawn as a result of the observations. When this map was examined, it was determined that the company was insufficient to meet customer demands at the end of the day and that overtime was constantly being worked because the current production line could not produce products. It was observed that this situation caused customer loss. It was also determined that unnecessary stops occurred in processes where there was continuous flow. The map helped determine the necessary improvements to increase the performance of the company by revealing the deficiencies and bottlenecks observed at every stage of the process. Elimination of these disruptions in the production line will increase customer satisfaction and increase the competitive power of the company. In addition, reducing

overtime will reduce labor costs and increase employee satisfaction. In this direction, steps will be taken to increase the efficiency of the company with the analyzes and improvement suggestions made.

When the current status of the business is examined, it is determined that it cannot respond to customer demands on time and needs overtime. Due to these problems, customer loss is experienced and employee satisfaction decreases. The Andon system was implemented to prevent unnecessary stops in the production line, and efficiency was increased by using a siren system to control the line speed during the separation process. In addition, TPM (Total Productive Maintenance) studies increased employee motivation and made production processes more fluid. With the improvement of inspections in the supply chain, the waste rate was reduced from 4.6% to 1.8% and quality standards were increased.

Failures caused by the blades not being hard enough were detected in the crushing lines. As a result of the root cause analysis, it was decided to use Hardox 500 hardened steel blades and failures were reduced by 36.7%. Blade change times were shortened by 44% and the cycle time was reduced from 12 seconds to 7.6 seconds with SMED (Single-Minute Exchange of Die) studies. With the Kaizen improvements applied in the washing pools, the amount of water was optimized, automatic sensors prevented overflow problems and bad odors were eliminated with sodium hypochlorite. In addition, the cycle time was reduced from 88 seconds to 64 seconds with the arrangements made in the granule extrusion line. It was also suggested to develop a system that will enable the reuse of dirty water for cleaning recycled plastics. From a production capacity perspective, the current bottleneck was identified in the separation line, which limits production to an average of 240 kg per hour, corresponding to approximately 32,400 kg per week. With the improvements planned for the future state, this constraint is expected to be overcome, increasing the hourly capacity to approximately 349 kg and the weekly output to 47,182 kg. Production efficiency was tried to be increased by aiming to minimize losses caused by mold or product changes in the processes. As a result of all these improvements, the operational efficiency and customer satisfaction of the business were increased and a significant increase in competitiveness was achieved.

In this study, the results obtained by applying lean manufacturing techniques to low-density polyethylene (LDPE) recycling processes indicate that the model can be adapted to other types of recycling. In particular, the visualization of processes with the VSM technique, the detection of waste types and the planning of continuous improvement steps can be integrated into the recycling processes of different types of waste such as paper, metal, glass and electronic waste. Considering the different process steps of each material group, the analysis and improvement approach developed within the scope of this study can be modified. In addition, the applicability of this model to businesses of different sizes (SMEs and large-scale companies) or in different geographical and economic contexts can be tested.

In further research, the integration of lean manufacturing techniques with Industry 4.0 technologies (e.g. IoT-based sensors, digital twins or artificial intelligence-supported planning systems) can offer significant opportunities for real-time monitoring and further optimization of dynamic data in recycling processes. However, integrating environmental impact analysis tools such as life cycle assessment (LCA) with VSM will enable the measurement of not only operational but also ecological benefits. Future studies can develop more comprehensive frameworks to address these aspects and increase both sustainability performance and resource efficiency in a multidimensional manner.

Another suggested area for development in the study is focused on water recovery systems. Treatment solutions to reprocess dirty but recyclable plastics are of strategic importance for both environmental sustainability and reducing operating costs. This recommendation can serve as a guide for future studies and is considered a development area that contributes to the circular economy.

In conclusion, this study demonstrates that lean production techniques can be successfully applied in sectors that directly contribute to environmental sustainability, such as waste management and recycling. The results obtained will serve as an example for other similar production facilities and provide guidance on strategic steps to be taken in the lean transformation process.

When lean production is considered not only as a system that enhances operational efficiency but also as a framework that contributes to environmental performance, it becomes possible to position the study within a broader sustainability perspective. In this context, the implementation of SMED and TPM practices leads to reduced energy and resource consumption; optimization of water usage contributes to the conservation of natural resources. Moreover, the reduction of the waste rate from 4.6% to 1.8% increases raw material efficiency, while the recommendation to reuse recovered water aligns directly with the principles of the circular economy. These aspects demonstrate that lean production practices offer significant benefits not only from an economic standpoint but also in terms of ecological sustainability.

This study demonstrates that lean manufacturing techniques can be successfully integrated into LDPE recycling processes. However, assessing the performance of this model across different organizational structures and production scales would contribute meaningfully to the literature at both theoretical and practical levels. Testing the implemented lean transformation model in enterprises with low, medium, and high production capacities would reveal how the outcomes of improvement initiatives vary depending on production volume. Such an analysis would enhance the understanding of the conditions under which performance indicators such as cycle time, scrap rate, and Overall Equipment Effectiveness (OEE) yield more effective results.

Adapting the model to SMEs operating in different sectors such as packaging, textiles, or rubber recycling would be particularly valuable in evaluating the model's sensitivity to process variability. This approach could serve as a transition guide for SMEs engaged in recycling activities aiming to adopt lean production principles. Moreover, such an assessment would enable the study to transcend the scope of a single case application, transforming it into a scalable transformation model applicable across diverse industrial contexts. Especially in sectors like recycling that directly contribute to environmental sustainability, conducting comprehensive analyses on the applicability of lean production practices at the SME level would provide significant guidance for both academics and practitioners, including policymakers and industry stakeholders.

In conclusion, evaluating the scalability and adaptability of the proposed model by testing it in enterprises with varying production capacities and structural characteristics would enhance the academic rigor of the study and address a notable gap in the lean production literature within the recycling industry.

Author Contributions

Emre Can Temiz: Literature Review, Methodology, Data Curation, Analysis, Modelling, Writing-original draft
Emel Yontar: Conceptualization, Methodology, Modelling, Writing-review and editing

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Compliance with Ethical Standards

It was declared by the authors that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement

It was declared by the authors that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.



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