APPLICATION OF THE LEAN SIX SIGMA METHODOLOGY FOR IMPROVING LONG TERM MAINTENANCE PLANNING – CASE STUDY

MERVE IŞIK EROĞLU

Thesis for the Master's Program in Industrial Engineering

Graduate School
Izmir University of Economics
Izmir
2023

APPLICATION OF THE LEAN SIX SIGMA METHODOLOGY FOR IMPROVING LONG TERM MAINTENANCE PLANNING – CASE STUDY

MERVE IŞIK EROĞLU

THESIS ADVISOR: PROF. DR. AHMET SERMET ANAGÜN

A Master's Thesis
Submitted to
the Graduate School of Izmir University of Economics
the Department of Industrial Engineering

Izmir
2023

ETHICAL DECLARATION

I hereby declare that I am the sole author of this thesis and that I have conducted my work in accordance with academic rules and ethical behaviour at every stage from the planning of the thesis to its defence. I confirm that I have cited all ideas, information and findings that are not specific to my study, as required by the code of ethical behaviour, and that all statements not cited are my own.

Name, Surname: Merve Işık Eroğlu

Date: January, 2023

Signature:

ABSTRACT

APPLICATION OF THE LEAN SIX SIGMA METHODOLOGY FOR IMPROVING LONG TERM MAINTENANCE PLANNING – CASE STUDY

Işık Eroğlu, Merve

Master's Program in Industrial Engineering

Advisor: Prof. Dr. Ahmet Sermet Anagün

January, 2023

In today's competitive world, all efforts focus on meeting production targets at the lowest possible cost, highlighting the need for maximum benefits from existing machinery/equipment. In this context, effective maintenance strategies have become the main tool to be used to meet this goal. In this thesis, a wheel company maintenance data is used to perform lifetime analysis of CNC machines and components. The decision-making process in maintenance was supported by the application of the Lean Six Sigma Methodlogy. In actual practice, the DMAIC steps define, measure, analyze, improve, and control were used. The goal of the study is to identify potential improvement areas and to create a substructure and where decision-making assistance for maintenance operations is provided by performing lifetime analysis of machines. As a result, this analysis is carried out for the 30 CNC machines using information on failure time and frequency over a time span of about two years.

Keywords: Maintenance Process, Lifetime Analysis, DMAIC, Lean Six Sigma, Decision Support Analysis.

ÖZET

UZUN DÖNEM BAKIM PLANLAMALARI İÇİN YALIN 6 SİGMA METODOLOJİSİNİN UYGULANMASI – ÖRNEK UYGULAMA

Işık Eroğlu, Merve

Endüstri Mühendisliği Yüksek Lisans Programı

Tez Danışmanı: Prof. Dr. Ahmet Sermet Anagün

Ocak, 2023

Günümüzün rekabetçi dünyasında, tüm çabalar mümkün olan en düşük maliyetle üretim hedeflerine ulaşmaya odaklanır ve mevcut makine/ekipmanlardan maksimum fayda sağlama ihtiyacını vurgular. Bu bağlamda etkili bakım stratejileri, bu amaca ulaşmak için kullanılacak ana araç haline gelmiştir. Bu çalışmada, CNC makinelerinin ve bileşenlerinin ömür analizini yapmak için bir jant şirketinin bakım verileri kullanılmıştır. Bakımda karar verme süreçleri Yalın Altı Sigma Metodolojisi uygulamaları ile desteklenmiştir. Örnek uygulamada, TÖAİK adımları tanımla, ölç, analiz et, iyileştir ve kontrol kullanılmıştır. Çalışmanın amacı, makinelerin tezgah ömür kaynaklı etki analizlerinin yapılarak, potansiyel iyileştirme alanlarının belirlenmesi ve bakım operasyonları için karar verme desteğinin sağlandığı bir alt yapı oluşturmaktır. Sonuç olarak, bu analiz, yaklaşık iki yıllık bir zaman diliminde arıza süresi ve sıklığına ilişkin bilgiler kullanılarak 30 CNC makinesi için gerçekleştirilmiştir.

Anahtar Kelimeler: Bakım Süreci, Ömür Etki Analizi, TÖAİK, Yalın 6 Sigma, Karar Destek Analizi.

Dedicated to my family

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to Prof. Dr. Ahmet Sermet Anagün for his guidance and insight, advice and kindness throughout the research,
I would like to thanks my family for their support during the course of this thesis,
Lastly, I would like to thanks Sinan Eroğlu for always being there to support me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

TPM: Total Productive Maintenance

Cp: Process capability

Cpk: Process capability ındex

DPMO: Defects Per Million Opportunities

MTBF: Mean Time Between Failures

DMAIC: Define, Measure, Analyze, Improve, Control

TÖAİK: Tanımla, Ölç, Analiz, İyileştir, Kontrol

DMADV: Define, Measure, Analyze, Design, Verify

RAM: Reliability, Availability, and Maintainability

HSE: Health, Safety, Environment

SIPOC: Suppliers, inputs, process, outputs, customers

CTQ: Critical to Quality

CNC: Computer numerical control

ANOVA: Analysis of Variance

MES: Manufacturing Execution System

SAP: System Analysis and Program Development

KPI: Key Performance Indicator

OEE: Overall Equipment Effectiveness

CHAPTER 1: INTRODUCTION

1.1. The Concept of Lean 6 Sigma

The objectives of the Lean Six Sigma methodology are to increase quality, decrease variability, and eliminate waste within an organization. Lean Six Sigma is based on the Lean and Six Sigma methodologies. The goals of Six Sigma are to decrease variability, measure errors, and enhance the quality of goods, processes, and services. Six Sigma is also a quality management philosophy. Early in the 1980s, Motorola Corporation created the Six Sigma idea. The concept was popularized in the late 1990s when it was implemented by General Electric Company and its CEO, Jack Welch. Lean Business is an approach focused on minimizing total processing time and eliminating process waste. The approach first emerged as the Toyota Production system at Toyota Motor Company, and following the 1973 energy crisis, its popularity increased. In the literary works Lean Thinking by James P. Womack and Daniel T. Jones, the phrase "Lean Thinking" was first used (Womack and Jones, 1996). The concept of “Lean Business” expands the field of Lean program to include the whole organization from production (Alukal, 2003). The DMAIC approach to problem solving is one of many quality problem solving strategies used in the Six Sigma Methodology. Depending on the kind of process being investigated and the issues encountered, several methodologies are employed. Similar to this, the Lean Approach employs a variety of Lean Techniques to streamline, organize, and reduce waste in business operations.

Six Sigma can be described in various ways. Six Sigma is a process measurement method. At the Six Sigma level, there are 3.4 defects for every million opportunities (3.4 DPMO). It is a method to transforming an organization's culture. According to another definition, Six Sigma is a disciplined and data-driven approach that aims to reduce errors in all processes from service to production. The main goal of the Six Sigma methodology is to establish a strategy based on measurements and focused on reducing variability and process development through Six Sigma improvement projects within the company (Pyzdek, 2001). Another definition for Six Sigma as a performance level; expressed as an outcome rather than a methodology or tool: “Six

Sigma is an optimized level of performance that approaches zero error in a process that produces a product or service. It indicates the achievement and maintenance of a world-class performance. Six Sigma is a result, not a methodology or tool" (Wilson, 1999). In its most correct form, Six Sigma should be defined as a broad and comprehensive system that aims to achieve and retain business performance, success, and leadership. (Pande et al., 2003). In other words, Six Sigma is an environment where you can combine many valuable "best practices" with concepts such as system design, continuous improvement, quality management, total productive maintenance**.**

1.2. The Development and Principles of Lean 6 Sigma Management

Six Sigma is an evolutionary development that incorporates the best elements of past quality initiatives in the science of improvement. While certain Six Sigma tools, such quality function deployment (QFD), are relatively new, the majority of tools, like the fishbone diagram, have been around for at least 50 years.

Statistical process control systems, which were brought to the agenda by Deming and Juran in the 1950s, were carried to an advanced stage with the Toyota Production System in the 1960s. In the 1980s, Just-in-Time Production and Total Quality Management came to the fore as new approaches. While Lean Thinking and Lean Production first came to the fore in the 1990s with the book "The Machine That Changed the World" by James P.Womack, inspired by the Toyota Production System, the Six Sigma approach was first recognized in the world by Motorola and then General Electric (Womack and Jones, 1996).

Motorola, like many American and European industries, lost market share to Japanese competitors in the 1980s and early 1990s. Motorola, like many organizations at the time, ran not just one but several "quality" programs. In 1987, however, Motorola Communications Group, led by George Fisher, introduced a new concept of improvement called "Six Sigma" (Pande et al., 2003). The executives of Motorola blended the ideas of "process capability" and "product specifications". Process performance was compared to these requirements using Cp and Cpk measurements. Capacity calculations were expressed in defects per million opportunities (DPMO).

Motorola awarded the Malcolm Baldrige National Quality Award just two years after implementing Six Sigma.

In the ten-year period between 1987 and 1997, when Six Sigma was launched, the following achievements were obtained:

- Sales would increase by five times, and profits would grow by about 20% a year.
- A total of $14 billion in savings from Six Sigma projects.

Motorola has implemented Six Sigma beyond a set of tools as a way of restatement business, built on communication, training, leadership, teamwork, measurement and customer focus. As Alan Larson, one of the first Six Sigma consultants at Motorola, said: “Six Sigma is indeed a cultural phenomenon; It is a form of behavior.” (Pande et al., 2003)

The Lean Six Sigma approach has emerged since the 2000s, by combining the different advantages of lean production and Six Sigma in the production and service sector. Although Lean Six Sigma is a new method in the quality journey, the method is still under development. Lean is to reduce all kinds of unnecessary waste and control resources based on customer requirements Anything that increases costs without improving the consumer experience is waste. Lean is a methodical technique to locating and removing waste to guarantee flawless product flow to customers in the pursuit of continuous improvement. Within the context of process optimization, the lean methodology emphasizes cost reduction (Öztürk, 2009). Six Sigma focuses on decreasing errors and increasing quality through minimizing variability. An strategy called Lean Six Sigma integrates these two techniques in a balanced way. (Hostetler, 2010).

Lean Six Sigma provides standardization in both quality improvement and cost reduction, and has a methodical impact on lowering waste and cost (Polk, 2011).This approach, which simplifies manufacturing processes and improves product quality with a maximum of 3.4 defects per million, has been developed by General Electric Co., Dell Inc., Xerox Corp. and Johnson & Johnson, many companies have realized major benefits and cost reductions (Guarraia, Carey, Corbett and Neuhaus, 2008). The objective is to reduce error rates, enhance productivity, perfect all organizational operations, and steadily improve customer satisfaction. The Lean Six Sigma approach is not content with detecting and correcting errors, but also restructuring the business function in a way that prevents errors from the start. Activities that cause critical quality issues to the customer and cause long delays in all processes; it offers great opportunities to improve cost, quality and delivery times (Dumitrescu, Tent and Dumitrescu, 2010). The primary driver of Lean Manufacturing is the reduction of waste. Lean Manufacturing focuses on identifying and eliminating the seven wastes involved in each process, using the Just-in-Time Manufacturing system.

1.3. Importance and Aim of Lean 6 Sigma

The following is a list of the principal advantages of Lean Six Sigma: Cost reduction, improved productivity, increase market share and customer satisfaction, cycle-time reductions, quality increase, positive cultural transformation, service development.

In addition, looking at the Motorola example and the experiences of other companies applying Lean Six Sigma and the high earnings, we can define the attractive aspects of Six Sigma to companies as follows:

It leads to lasting success: The general concern of many companies in the market is the possibility of being deleted from the market in a certain time or losing some of the existing market share by not following the innovations. Only ongoing innovation and reorganization can maintain the existing growth rate and a share in shifting marketplaces. Lean Six Sigma develops the capabilities and corporate culture necessary for continuous improvement.

Establishes a performance goal for everyone: In international corporations, it can be quite challenging to make sure that everyone is moving in the same direction and pursuing the same objectives. Expectations and goals vary by department, study group, and person.

Increases the customer value added work: Due to competitive conditions in every industry, offering only good products or services will not be enough for success.

Customer focus is fundamental to Lean Six Sigma and includes understanding what value is for current and potential customers as well as strategizing how to offer that value to them financially.

Increases improvement percentage: Standing out from potential competitors is possible by performing the fastest improvement. Lean Six Sigma enables a company not just to improve its performance, also to develop its improvement, thanks to the tools and ideas it incorporates from many disciplines.

It supports learning and deployment of knowledge: Six Sigma is an approach that can increase and accelerate development and the sharing of new ideas by the entire organization. Personnel who specialize in processes and how to manage and develop them can be transferred from one department to another as needed. For this reason, it is easier to share ideas and compare performance.

Realizes the strategic change: Introducing new products, taking new risks, opening up to new markets, buying new companies are the applications that many companies frequently apply today. Having a good comprehension of the company's operations and procedures will assist in making decisions for minor changes that will bring success, as well as making larger strategic decisions. (Pande et al., 2003)

1.4. Maintanence Types

In today’s competitive world, all efforts focus on meeting production targets at the lowest possible cost, highlighting the need for maximum benefits from existing machinery/equipment. In this context, efficient and reliable maintenance policies have become the main tool to be used to meet this goal. With the development of technology and modern system complexity, organizations require reliable maintenance plans to remain competitive. Maintenance planning defined as planning of the tasks to be performed in order to guarantee that the machinery and facilities of a factory are in continuous operation.

Purposes of Maintenance Activities:

- To minimize production costs while increasing product quality and productivity,
- To prevent machine failures and downtime for ensure production flow
- Increasing the efficiency of the capital invested in these assets by extending the lifetimes of all types of facilities, machinery, and equipment,
- To guarantee the security of employees operating all types of equipment for machines,
- Reduce the cost of maintenance and repairs.

Maintenance actions can be separated into two groups: planned maintenance and unplanned maintenance (Wireman, 2013) in Figure 1.

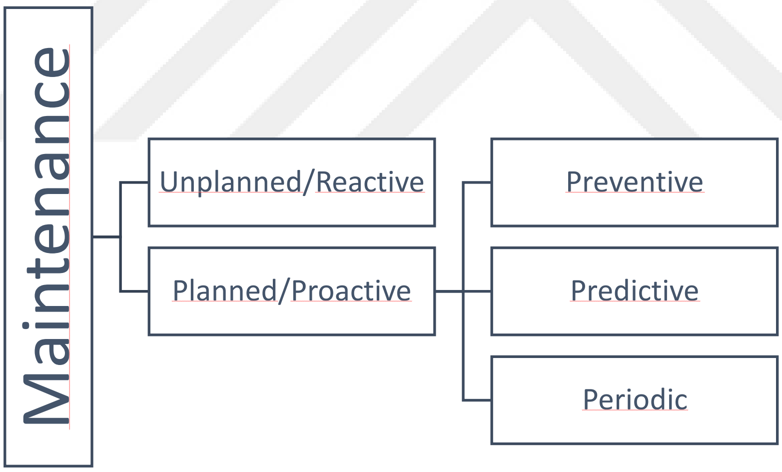

Figure 1. Maintenance Types

1.4.1. Unplanned Maintenance

Unplanned Maintenance is performed at the when the equipment breakdowns or malfunctions in the machine or facility. Low labor expenses and fewer people are required for maintenance and repair. Unplanned maintenance is used in factories that use equipment that can be quickly maintained, has a large number of spare parts, and is not highly expensive. Since maintenance is performed when something breaks down, there is a significant production loss while the problem is being fixed.

Disadvantages of Unplanned Maintenance:

- Breakdown might happen at any time.
- Safety risk: When a component of the machine breakdown, it might create dangers that could result in control loss, machine failure, or even operator injury. While examining and fixing the error, there is a possibility that injuries will occur.
- Unexpected machine failures could occur. If the failure can not be anticipated, it may happen quickly for unexpected causes that conflict with the production schedule.
- Capacity losses and delay: If there is no spare machine or spare parts for a machine, either production can be delayed or production can be stopped completely. Breakdowns, if neglected, cause greater stoppages.

1.4.2. Planned Maintenance

When faults and failures are identified along planned maintenance, errors can often be quickly fixed at low expense. Each component of a machine must be fully under control in order to do planned maintenance work and to achieve the intended results.

The following are some advantages of planned maintenance:

- It minimizes stoppages, lowers potential breakdowns, and lowers production costs,
- It ensures safe working conditions and the execution of previously planned production programs,
- It boosts an enterprise's yield and lowers energy costs,
- It contributes to the extending of machine life,
- It reduces material and spare part inventories,
- It decreases the need for personnel

1.4.2.1. Periodic Maintenance

Periodic maintenance is a form of planned maintenance that is carried out on both factory and equipment in order to increase equipment life and decrease unplanned stoppage. With periodic maintenance, downtimes that are not predicted and potential breakdowns are avoided due to the system maintenance that was previously carried out on a regular basis. Based on the experience of the maintenance personnel and the performance and working conditions of the machines in the past, it will be decided at what intervals the machine will be stopped and taken into maintenance. The machine is put into maintenance after the inspection, at which point it is decided which parts need to be changed; these parts are then stored in stock.

Disadvantages of Periodic Maintenance:

- Replacement of parts that have not failed in the system in order to meet the demand for a longer period of time and avoid stopping the production flow unnecessarily.
- Employing a large number of maintenance personnel.
- During the periodic maintenance, the parts that are planned to be changed based on both statistics and experience will have to be replaced before the end of their life, and many parts will have to be kept in stock. This will increase the cost of spare parts as well as create a stocking problem.
- After the periodic maintenance, it will take a while for the machine to become ideal due to friction and wear on both the adjustment and new parts. Good working conditions will be restored after new adjustments and initial wear, but in the meantime, there will be a decrease in production quality and quantity.

Advantages of Periodic Maintenance:

- Downtimes can be better controlled, and machine availability increased, as failures will be reduced. As a result, production increases and more reliable repair times can be determined.
- Since the adjustments required by the machines will be made on time,

efficiency and quality will increase, and the rate of defective products will decrease. The unit cost of production decreases.

- Repair costs are reduced. Because longer stoppages due to replaced parts will be avoided as a result of the control, maintenance costs will be reduced. It prevents the machines from wearing out earlier than their normal life and ensures that the replacement costs are reduced. It provides better control of spare parts.

1.4.2.2. Predictive Maintenance

The entire effort is focused on quantifying the physical parameter trends of the equipment, comparing them to specified engineering limitations, analyzing and interpreting the data, making issues that could lead to failures that are economically fixable but ineffective (Topaz and Sümen, 2003).

Predictive maintenance application prevents the occurrence of breakdowns and is made according to specific methods of measurement and evaluation, based on the physical characteristics and uses of materials or mobile systems.
Machines or equipment are tracked from specific locations during predictive maintenance. Using measurement device, data collected over a predetermined period of time is reviewed. Even when the machine is in good working condition, system breakdowns may be predicted by looking at the trend of the measurement result obtained.

Before problems develop into serious failures and more expensive complications, are fixed. This technology avoids the system pausing and changing needless parts since it monitors the functioning system for potential problems. By examining the trends in the measurement values, a planned maintenance program is created, and also the system is taken into maintenance.

Benefits of Predictive Maintenance:

- For predictive maintenance activities, real data is used, which is an indication of the actual mechanical condition of the equipment or machine. Maintenance plans are carried out and updated in the light of real data.

- Predictive maintenance not only prevents unplanned failures to a great extent but also prevents future failures from wearing down other systems and also provides real data about the situation after repair.
- Machine-critical breakdowns can be minimized.
- Maintenance time, hence machine downtime, can be minimized. It is not necessary to interrupt operating, well-maintained machines. The amount of resources and time required are minimized in this method.

Predictive maintenance can be applied in four ways:

- The measurement devices and the computer program are purchased by the company, and the measurements, analyses, and planning are made by the internal resources,
- After the company purchases measurement devices, measurements are taken by maintenance personnel, collected data is sent to the consulting firm, and analyses are performed.
- Obtaining measurement analysis services from outside sources without purchasing a device or program
- Application for predictive maintenance with automatic trip-measurement analysis and online fixed sensors

Predictive Maintenance Methods:

- Failure Early Warning System
- Analysis of Vibration
- Analysis of Oil
- Analysis of Temperature Analysis
- Acoustic Emission
- Analysis of Particle
- Monitoring of Corrosion
- Performance Monitoring

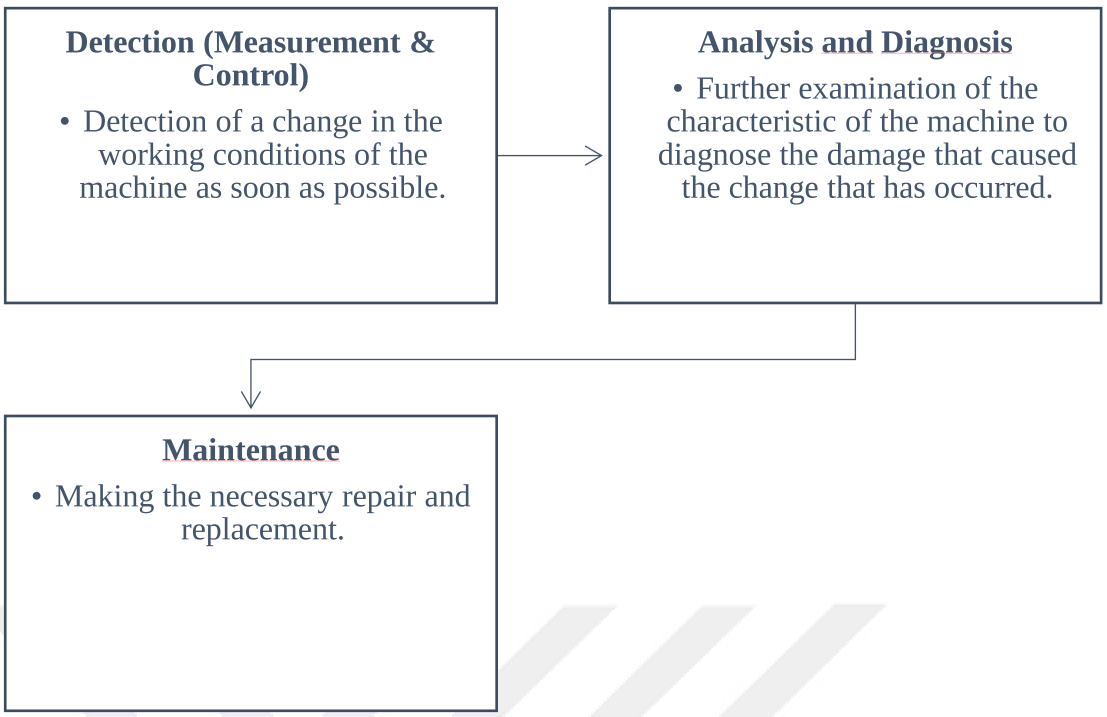

Figure 2. Stages of a Predictive Maintenance Program

1.4.2.3. Preventive Maintenance

Preventive maintenance, which is a planned maintenance activity, is a maintenance policy based on assessing whether a functional unit will fail in the future period and taking the necessary measures to prevent this failure. Preventive maintenance aims to avoid problems from occurring in the first place rather than identifying existing problems with the machines. Changes to the design, lubrication system, and operating conditions can eliminate the causes of failure.

Benefits of Preventive Maintenance:

- Reducing production downtime due to less machine breakdown.
- Prevention of premature replacement of machinery and equipment.
- Timely routine repairs reduce the number of large-scale repairs.
- When parts breakdown during operation, they often damage other parts. By reducing secondary failures, repair costs are reduced.
- The company's occupational safety and quality conditions increase.

The structure of this thesis is organized into five sections. The next section discusses literature review on maintenance strategies and activities, and Lean 6 Sigma principles and practices within the maintenance process. The third section demonstrates the research methodology. The fourth section includes Case Study. This includes DMAIC steps and its applications. The fifth section and last section contains a conclusion and proposals for future research.

CHAPTER 2: LITERATURE RESEARCH

2.1. Lean 6 Sigma Maintenance Applications

Years ago, maintenance was primarily considered a wasteful process. Today, the maintenance activity is accepted as a crucial operation function that helps the company meet the challenges of the economic, environmental, and social spheres. This is related to how maintenance affects various business operations (such as logistics, occupational health and safety management, production and environment). (Karuppiah et al., 2021; Hami et al., 2020; Saihi et al., 2022).

The economic, environmental, and social performance of a company is positively impacted by the control of manufacturing equipment and maintenance, but poorly planned maintenance activities result in a number of difficulties (Jasiulewicz-Kaczmarek et al., 2021). Insufficient maintenance procedures have a negative economic impact on prices, downtime, breakdowns, defects, excess inventory, and other factors that have an impact on product quality and an overall performance of the company (Zonta et al., 2020). Therefore, by lowering the equipment's failure rate, efficient and effective maintenance operations would enable not just the improvement of the equipment's situation but also the reduction of operating cost by increasing the equipment's lifecycle.

Inaccurately planned and carried out maintenance procedures and activities have a number of negative effects on the environment, including toxic emissions, wasteful resource consumption, and inefficient energy use.

To address economic, environmental, and social problems, manufacturers employ a variety of techniques to improve business operations, including Six Sigma, Lean Management, Theory of Constraints (TOC), and Total Quality Management (Sreedharan and Sunder, 2018).

Several approaches, including Total Quality Maintenance, Lean Maintenance, and Six Sigma, are suggested in the literature for process improvement in maintenance

(Thomas et al., 2008)

Nowadays, a greater number of companies are recognizing Six Sigma's potential (SS). Motorola created and introduced the Six Sigma technique in 1987. Six Sigma can be characterized as an improvement program that focuses on ongoing and creative improvement in order to reduce unpredictability. Customer satisfaction is the primary objective of eliminating variation in the service or production method.

Design Improvement (DMADV) and Process Improvement (DMAIC) are two subcategories of the Six Sigma approach. The deployment of a wide range of tools and technologies based on the procedure, the available resources, and the skills of the team members at various levels of the Six Sigma approach. It is also recommended to enhance maintenance procedures using the Six Sigma technique. Some of these recommendations integrate the Total Productive Maintenance (TPM) concept with the Six Sigma approach. The model created by Sharma and Sharma (2014) is based on the Six Sigma and TPM concept and focuses on increasing MTBF (mean-time-between-failures), improving quality and productivity.

According to Pophaley and Vyas (2015), the maintenance of production equipment can be improved by utilizing the TPM and Six Sigma ideas, particularly through the Autonomous Maintenance pillar of TPM. The goal of the TPM concept is to find ways to drastically reduce of resource waste and significantly improve how facilities and equipment are used, shifting responsibility for the proper operation and performance of technical systems to the personnel who utilize them on a regular basis. The TPM model and Six Sigma concept are combined to create an improved maintenance process model that makes use of all the advantages of the TPM approach. Also combination of these methods is enable to reduction of variations in the process, eliminating the occurrence of errors, and shortening the time cycle of the maintenance process through concurrent application of Six Sigma concept.

Recent research has demonstrated the value of the Six Sigma technique and reliability, availability and maintainability (RAM) analysis for choosing the optimum maintenance strategy, planning maintenance intervals, and scheduling maintenance tasks (Tsarouhas, 2022). Seow and Liu (2006) add that "businesses need to consider allowing the integration of Six Sigma-TPM as an accelerator for business sustainability".

To improve the maintenance process with the Six Sigma concept can be applied as a straightforward method for increasing performance.

Table 1. DMAIC Model for Maintenance Process

Improvement Steps of Lean Six Sigma		
Activity descriptions	Improvement	Design and Redesign of steps
Describe the activity aims for improvement	Determine requirements Set the desired outcome	Identify Issues. Describe the desired result.
Measure the existing system by setting reliable metrics for supervision of progress toward a goal and use information analysis	Verify the issue or process Problem/planned outcome filter Track important steps	Measure outputs against requirements. Assemble data on process effectiveness
Analyze the system to close any performance gaps between the current system or process and the anticipated outcome. Analyze data using statistical tools	Create hypothese about the cause Identify vital minority of the root of cause Verify hypotheses	Choose the best practice. Review the process design Filter the requirements
Improve the system, by using project management and other tools of management and planning, as well as statistic methods, to validate improvements	Create concepts for eradicating the underlying cause. Test response Standardize approaches and evaluate outcomes	Create a new procedure (check assumptions, apply creativity) Implement new procedures, organizations, and systems
Check the new system. By altering the system of rewards, policies, procedures, budget, etc., institutionalize the improved system	Create standardized benchmarks to sustain performance Fix problems as needed	Measurements are established and reviewed to ensure performance Fix issues as necessary

Lean Six Sigma is a advance approach to quality control and improvement process at the moment. The DMAIC methodology is used to enhance the production process, successfully reducing the quantity of non-compliant outputs and minimizing production costs. Similar to how the production process is characterized using indicators, the maintenance process also contains inputs, outputs, customers, and suppliers.

The prior searches only briefly examined how Lean Six Sigma principles might be applied to maintenance. The need for additional research on the implementation of lean manufacturing principles in maintenance operations was emphasized by Davies and Greenough (2010). Several research have made an effort to link maintenance practices to Lean Six Sigma methodology. With the use of the Lean Six Sigma concept, Ghayebloo and Shahanaghi (2010) developed a model to determine the minimal degree of maintenance requirement and acceptable reliability level. Tendayi and Fourie (2013) evaluated the significance of a set of maintenance excellence criteria and prioritized the Lean Six Sigma tools in relation to these criteria using a combined technique of Quality Function Deployment (QFD) and Analytic Hierarchy Process (AHP). A framework for monitoring maintenance methods based on Lean Six Sigma and agile components, i.e. waste elimination and responsiveness, was proposed by Soltan and Mostafa (2015). Nevertheless, the maintenance operations are still lacking a completely developed integrative framework of Lean Six Sigma thinking (e.g., principles, methods, waste identification). The output of this paper is a proposed roadmap for Lean Six Sigma integration into the maintenance process.

Unexpected failures of machines are extremely important in manufacturing systems. Due to high numbers of failure and thereby, long repair times in a line, line capacity decreases and the delivery time of orders is subject to a delay and as a result, there is an increase concerning prices. In this sense, lifetime analysis by using failure and repair data in the machines provide guidance in improving the efficiency.

In the highly competitive world of today, every effort is directed toward achieving production goals at the lowest cost, emphasizing the necessity to get the most out of the technology and equipment already in place. Effective maintenance strategies have become the primary method for achieving this objective in this scenario. In this study, lifetime analysis of CNC machines and components is carried out using maintenance data from a wheel company.

CHAPTER 3: METHODOLOGY

3.1. Lean Six Sigma Improvement Processes (DMAIC Approach)

Six Sigma focuses on process improvement, design, and management by using the DMAIC (Define, Measure, Analyze, Improve, Control) paradigm. The most important feature that distinguishes Six Sigma from other quality approaches is that it has a "process improvement strategy" like DMAIC. The concept of Six Sigma can be used to any process. This process can be a product design and production, as well as processing orders or creating financial statements. The basic steps mentioned here are measurement and analysis, “process characterization”; improvement and control is called “process optimization”. DMAIC is a cyclical process and each step of this cyclical process is desired to give the best results (Gursakal, 2005).

Table 2. DMAIC Phases and Specific Tasks

CHARACTERIZATION	Define	Defining the problem with its output and potential inputs
	Measure	Select critical quality features Define performance standards Create the data collection plan. Test the validity and reliability of the measurement system and collect data.
	Analyze	Build process capability. Define performance goals Identify sources of variability
OPTIMIZATION	Improve	Optimization of key factors Review potential causes Identify relationships between variables Create a pilot solution

3.1.1. Define Phase

In order to reach a higher sigma level, the define phase identifies the project goals and diagnoses the problems that need to be addressed. In the define phase, the tasks of focusing on the customer, developing the team statement and drawing the process maps are performed (Gürsakal, 2005).

The define phase is based on the “customer's voice” to define the need for learning and change (Mahantı, 2005). It is the step of selecting the project that will provide the most benefit in the case of identifying and listing the products or processes that need improvement (Pande and Holpp, 2001). In the definition step, the scope, objectives, inputs and outputs of the project are determined (Türkan et al., 2003).

Essential points to be considered at this stage are (Engin, 2006):

- The selected project is suitable for the possibilities and capabilities,
- Creating high probability with higher quality and reducing costs,
- Definition of problems as clearly and numerically as possible.

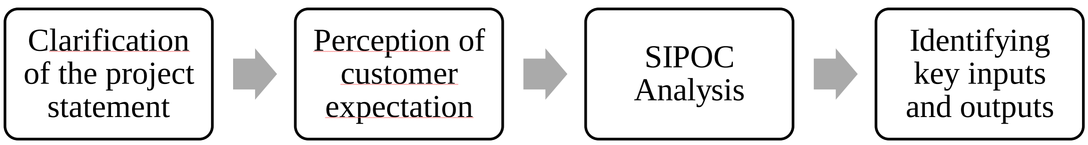

Figure 3. Define Phase Steps

3.1.2. Measure Phase

The purpose of the measurement phase is to indicate the existing process situations and problems in a factual understanding and to determine the source or cause of the problems. This information helps us limit the areas of potential causes that we should investigate during the “Analysis” phase. The performances of basic processes are measured in order to develop a data collection plan for processes, to identify failure types, measures and deficiencies of customer scanning results from various sources, and to compare them (Gürsakal, 2005).

Basic statistical concepts like mean, standard deviation, and probability distributions (normal distribution, Poisson distribution) during data analysis are crucial for comprehending the variation in the process (Gupta, 2004).

The results of the measurement phase can be listed as follows (Polat et al., 2005):

• It shows the differences between what actually happens and what we think.
• It allows us to validate previous experiences.
• Shows initial performance.
• Shows the past status of the problem.
• It shows whether the changes made in the process work or not.
• It enables us to capture the relationships that create variability.
• It ensures to stay away from approaches that will not solve the real problem.

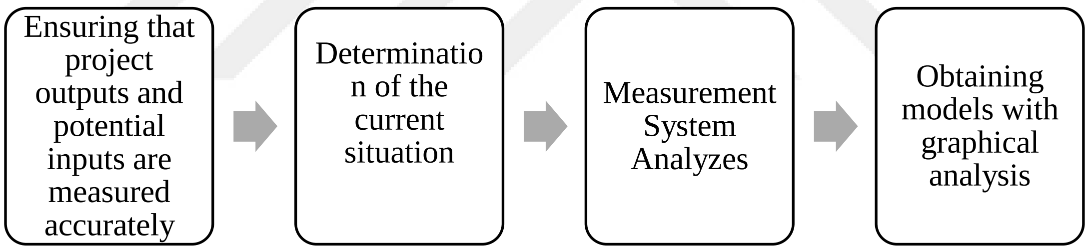

Figure 4. Measure Phase Steps

3.1.3. Analyze Phase

At this point, the primary goals are to identify the factors that contribute to process variability and to evaluate the levels of variability (Polat et al., 2005).

Various analyses are made at this stage to determine the process maps of the collected data and processes, to determine opportunities and root causes of errors for improvement, to identify the difference between current performance and target performance, to prioritize opportunities for improvement, and to determine sources of variability. Confidence intervals are calculated for the population parameters, and significance tests are performed using descriptive statistical analyses such as mean,

standard deviation, median, and ratio (Gürsakal, 2005)
The statistical analysis of the problem starts with the analysis step. Analysis is in the form of statistical acceptance or rejection of a problem with hypothesis tests. Thus, the variations that most affect the critical success factor are determined.
Statistical analysis of the problem identified in the previous stages begins at Analyze stage.

The data collected during the measurement stage is used as input at this stage. Because long-term data has the potential to explain long-term variations in the process, the root causes of problems are indicated by X, and the problem is indicated by Y. The most important root causes are found statistically, thus creating a basis for the improvement phase.

The step in which the main cause of the problem is determined, thanks to the transformation of the data into meaningful information, is analysis (Jiju et al., 2005).

3.1.4. Improve Phase

At this stage, the aim is to determine and test (verify) at what levels the important inputs that create the variability of the process will be adjusted (Polat et al., 2005). In the improvement phase, solutions aiming to eliminate the causes are developed, implemented, and evaluated. Using data, it is to show that your solution solves the problem and leads the way for improvement.
After the analysis and interpretation of the measurement results, improvement suggestions should be evaluated and implemented. The purpose of the improvement phase is to create solution proposals that will eliminate the problem that emerged during the analysis phase. The project team's established criteria are used to analyze and select the potential solution offers. Options such as time, cost, and simplicity of implementation are typically included in the criteria. With the action plan to be prepared, it should be determined how and which process will be intervened. It is necessary to make planning such as responsibilities, budget, time plan. Evaluation of the application is another important issue when the application is implemented. It should be evaluated whether statistically significant improvements have been made by collecting data on the results (Mansourian and Toomanian, 2009).

Improvements can be measured by making measurements before and after the implementations. Inferences should be made from the measurement results and the effect of the improvement application should be calculated. An application should not be considered the final recommendation. The principle of continuous improvement should be adopted. The stability and adequacy of the processes should be revealed in the cause-and-effect analysis.

3.1.5. Control Phase

The control phase goal is to develop the executed plan by requesting its documentation and implementation without allowing the process to revert (Gurukul, 2005). The accuracy of the measurement system is verified, and process capability is reassessed to ensure improvement is achieved. Efforts are made to ensure that the improvements are permanent and continuous at the 6 sigma level. Also, at this stage, the new process is documented so that the success is permanent (Atmaca and Girenes, 2001). Moreover, additional potential solutions are generated for future work.

Once progress is noticed, the aim is to check the process and continue the Six Sigma initiative. Keeping the Six Sigma initiative alive is the goal (Gupta, 2004). At this stage, a pilot application is made. A pilot is a low-scale trial of part or all of the considered design. The basic methodology behind the pilot is the Plan-Do-Check-Act approach. The first use of the pilot application in the cycle aids in the development of a better plan, allowing the solution to be implemented and the results to be improved (Işılgan, 2006).

Pilot applications create an opportunity to define the cause-and-effect relationship between root causes and solutions and allow to experience the solution without involving the whole organization. Pilots are necessary and beneficial investments for all Six Sigma projects. These practices allow for a better understanding of impacts and provide feedback from the process, customer, suppliers, organization/employees, and internal technology/existing systems. Pilot practices that enable the identification of potential failure points and the reduction of the risk of failure also increase the benefits of the organization. It allows the evaluation of the effectiveness of the measures taken in order to observe the improvement and enables the validity of the solution to be tested (Işılgan, 2006).

Implementation of the solution; This includes changing people's behavior, processes, measurement systems and possibly the way they create added value for customers. Implementing solutions has much greater meaning than implementing a pilot study and is one of the key milestones of a project. A project will be successful if it has well-defined goals and objectives, leader support, efficient teamwork, a plan agreed by all participants, evaluated in a timely manner and well-controlled. The next step will be procedures and standards. After the integration of the process is ensured, the solution is replicated and standardized; thus, the continuity of the gains is ensured (Işılgan, 2006).

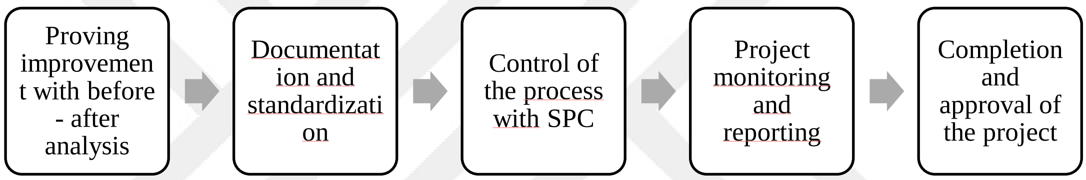

Figure 5. Conrol Phase Steps

CHAPTER 4: CASE STUDY

The goal of the study is to identify potential improvement areas and to create a substructure and where decision-making assistance for maintenance operations is provided by performing lifetime analysis of machines. As a result, case study is carried out for the 30 CNC machines using information on failure times and frequencies over a time span of about two years.

4.1. Company Identification

Maxion Wheels is the largest division of Iochpe-Maxion, a publicly traded company in Brazil formed in 1918 and today a leading manufacturer of both auto parts and railway equipment.

The Maxion Wheels division was responsible for 76% of the total company revenue in 2021. Maxion Wheels is the largest wheel producer in the world with more than 10,000 employees and 23 plants producing more than 50 million car, truck, trailer and specialty vehicle wheels a year. Plants produce aluminum and steel wheels for light vehicles, and steel wheels for commercial vehicles and specialty applications such as buses, trailers, and off-road vehicles for agriculture, mining, and construction.

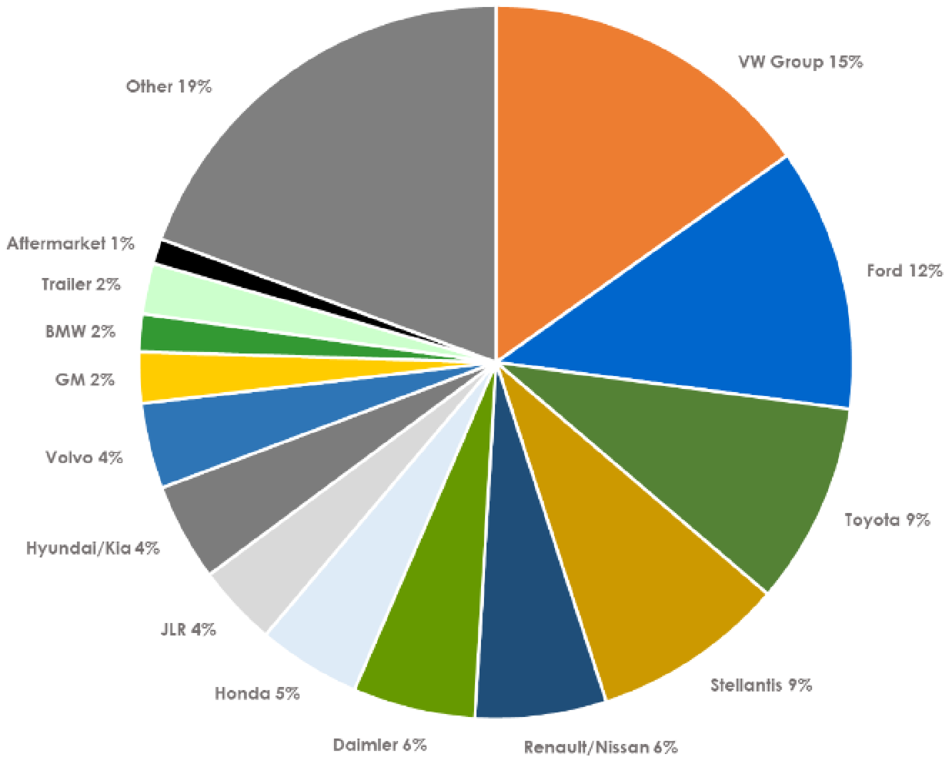

Figure 6. 2021 Sales by Customer

4.1.1 Maxion İnci Wheel Group (Turkey Operations)

Maxion Wheel factories are located in three locations in Turkey. These are the Maxion Jantaş Factory for truck wheels, Maxion İnci Steel Factory for passenger cars and Maxion İnci Aluminum Factory.

Figure 7. Maxion İnci Wheel Group

1.800 employees	13 million wheel production capacity	5 plants, 1 Logistics base in Manisa Industrial Park (MIP)
Export to more than 60 countries and 5 continents	300 million USD Export	400 million USD Turnover
İstanbul Chamber of Industry (İSO 500) Ranking: Maxion İnci Jant San. A.Ş. 153rd & Maxion Jantaş Jant San. ve Tic. A.Ş. 338th	Turkish Exporters Assembly (TEA 1000) Ranking: Maxion İnci Jant San. A.Ş. 107th & Maxion Jantaş Jant San. ve Tic. A.Ş. 250th	Automotive Industry Exporters' Association (OIB 50) Ranking: Maxion İnci Jant San. A.Ş. 18th & Maxion Jantaş Jant San. ve Tic. A.Ş. 31st

Figure 8. Maxion İnci Wheel Group at a Glance

4.1.2 Maxion İnci Aluminium Wheels Plant

Maxion İnci Aluminum Plant produces Passenger and Light Vehicle Wheels. Maxion İnci Aluminum was founded in Manisa in 2006 and currently operates 3 facilities, with 2 production areas and one logistics center that launched in 2016. These facilities comprise 100,000 square meters in space.

It has a 4 million 500 thousand capability to produce aluminum wheels. Plant has 940 employees. Together with Maxion İnci Steel, it is ranked 153rd on the İSO 500 list.

Audi, BMW, Dacia, Daimler, Fiat, Ford, Honda, Hyundai, Ineos, Isuzu, Iveco, J&LR, Karsan, Lexus, Mini, Nissan, PSA, Renault, Seat, Skoda, Toyota, and VW are some of the brands that the company serves as customers.

4.2. Wheel Production

Aluminum wheel production starts with melting aluminum ingots in melting furnaces, then it becomes the first gross wheel on casting machines in molds specially designed according to the design of the wheels. After the wheels go through quality control on

X-ray devices, heat treatment is applied to the wheels for increased durability. Afterwards, the excess metal on the gross wheel is removed in the machining cells, and the wheels are turned into net wheels. Finally, after being painted with the cosmetic features requested by the customer, the wheels are ready for packaging. The many machines of production, in order to complete all these processes, increase the need for well-planned and strategic maintenance activities.

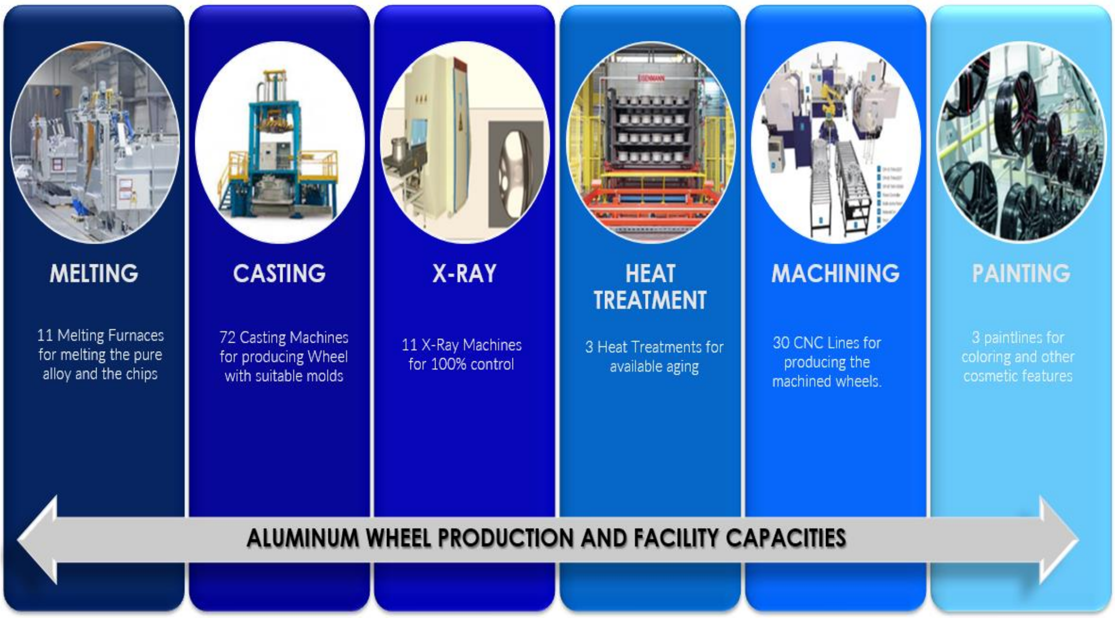

Figure 9. Aluminum Wheel Production and Facility Capacities

4.3. Description of the Company's Maintenance Process

The maintenance departments at the case study company perform all activities related to machine and equipment maintenance. The company uses planned maintenance practices like preventive, predictive, periodic, and, when necessary, corrective maintenance (CM) strategy for its machinery.

For Predictive Maintenance Activities Oil Analysis, Thermal Control, Belt Tension Controls, Vibration Analysis are performed.

Within the scope of preventive maintenance, periods, oil type, amount of use, responsibilities and machine parts have been determined for lubrication activities.

The Maintenance Department's Vision can be summarized as follows:

- Zero Downtime
- Zero Leakage
- Minimum Energy
- Minimum Maintenance Cost

The Maintenance Department's Vision can be summarized as follows:

- Eliminate breakdowns by analyzing root causes
- Prevent potential breakdowns by implementing predictive and periodical maintenance activities
- Monitoring Energy consumption continuously and implementing energy activities

For the machine investments, “New Equipment Risk Analysis” are performed and determined actions must be closed before equipment is in use. In Figure 10, the process map is presented.

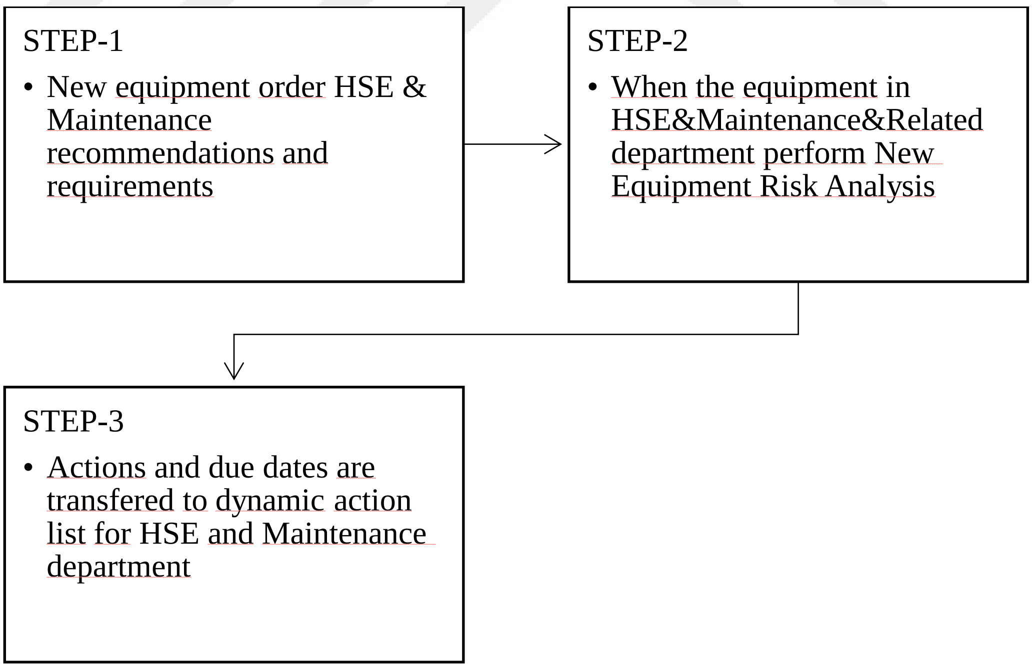

Figure 10. New Equipment Risk Analysis

4.3.1 Maintenance Organization

- Shift Organizations
    - 24.00-08.00
    - 08.00-16.00
    - 16.00-24.00
- Utilities
    - 1 Mechanical Engineer
- Periodical Maintenance
    - 5 Mechanical Technicians
    - 2 Electrical Technicians
- Support And Plannıng Team
    - 3 Supervisor
    - 4 Electrical Technicians
    - 5 Mechanical Technicians
- Documentation
    - 1 Technician

4.3.2. Troubleshooting Process Map

Using information gathered from the production and maintenance staff, an overview of the procedure for identifying and repairing machine breakdowns was developed. In Figure 11, the troubleshooting process map is presented.

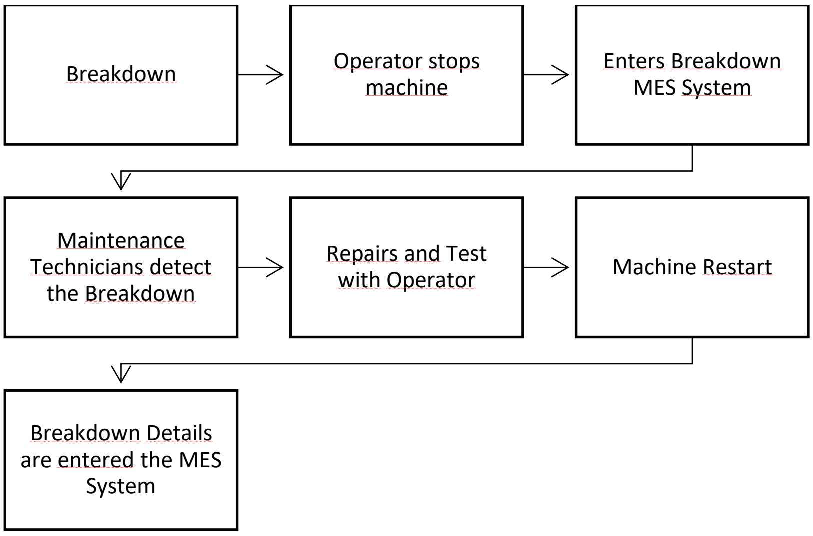

Figure 11. Maintenance Process

4.3.3 Energy Management

The company's energy management strategy can be visualized as a three-tiered pyramid. The first level is to monitor data online and on a regular basis. The second level is periodic checks and corrections. Finally, at the top of the pyramid, there are improvement studies and innovation projects with 6 Sigma and TPM methodology. All projects and activities are carried out according to the systematic approach of discovering, planning, building, deployment, and managing. Energy studies are managed by monitoring and controlling all outputs from the projects.

The first level of energy management consists of monitoring and reporting. Each machine has data readers, these signals are recorded in the MES system. With these systems, all energy metrics such as kWh/wheel, kWh/model and kWh/shift/day are tracked for all machines, all models and all cycle times. In addition, daily consumption values are followed and compared with target consumption values. The daily energy consumption is theoretically prepared according to the daily production plan. These target values are compared to the daily actual values. Daily energy consumption is compared with target consumption data per wheel/piece and kilogram. If there is a value above the target, the reason is investigated, and action is planned if necessary. In addition, natural gas and electrical energy consumptions are monitored based on factories and departments, and energy trends are analyzed.

The second layer of the energy management pyramid is periodic controls and actions to correct anomalies. This energy management pyramid is considered as two phases. The first is the energy consumption of serial production and the second is the energy consumption during the factory opening and closing periods. Energy consumption data is collected for mass production with the MES. However, since there is a more complicated process and more control area in opening and closing operations, measurements are made manually. Energy consumption controls and measurements are monitored during serial production and opening and closing periods of areas where the most energy is consumed such as melting, casting, heat treatment and the paintline.

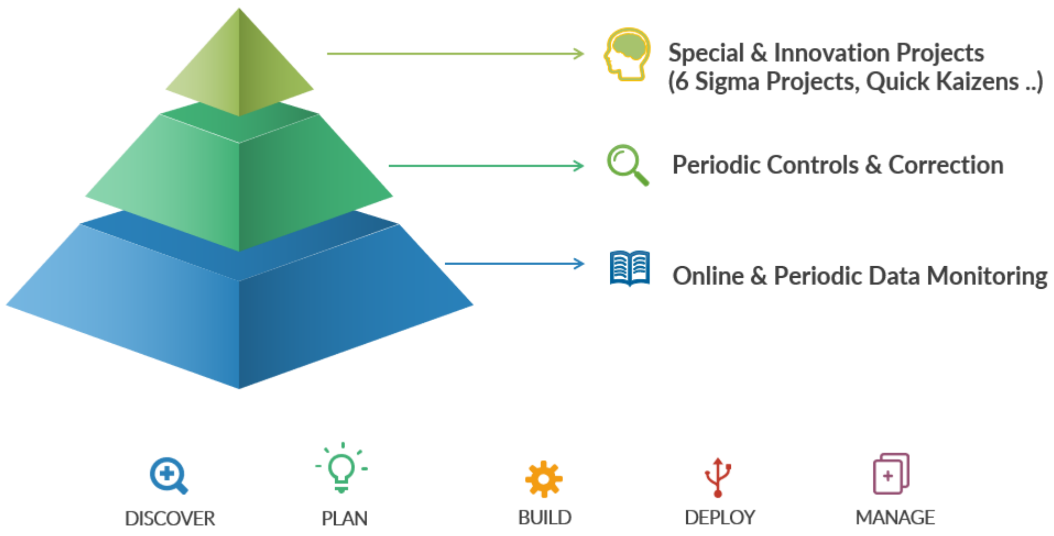

Figure 12. Energy Management

4.4. Six Sigma Project with DMAIC Improvement Model Steps

4.4.1. Define & Research Problem

In today's competitive world, all efforts focus on meeting production targets at the lowest possible cost, highlighting the need for maximum benefits from existing machinery / equipment. In this context, developing effective maintenance strategies has become the main requirement to meet this goal.

The company works five days a week, three shifts, for a total of 24 hours. During breaks and lunch times, the operators work alternately, so the machines do not stop.

The main production departments of the company that is the topic of this study are Foundry, Machining, and Painting. In light of this, breakdown duration and frequency of 2 years period between are included in the study. The machine stoppage records on the lines of the company were taken.

Selection of machines for studies was determined by ABC and Pareto Analysis. The entire breakdown time and types of all machines for 2021 and 2022 years are considered.
According to ABC Analysis, the Machining department has 11 of the 12 machines rated A+A+ in terms of downtime and frequency.

The main objectives of study are to increase system productivity, increase the overall profit as well as reduce the total life cycle costs by creating effective maintenance plans.

Table 3. ABC Analysis for Machine Prioritization

Machine	Department	Total Breakdown Duration (min)	Breakdown Frequency	Average Breakdown Duration (min)	Duration_ ABC	Frequency	Frequency_ ABC	ABC
102MBH201	Machining	7741,1	188	41,18	A+	1,6%	A+	A+A+
112MBH1201	Machining	7957,7	180	44,21	A+	1,5%	A+	A+A+
113MBH1301	Machining	8208,4	144	57,00	A+	1,2%	A+	A+A+
207MBH701	Machining	6277,8	142	44,21	A+	1,2%	A+	A+A+
109MBH901	Machining	8541,8	133	64,22	A+	1,1%	A+	A+A+
111MBH1101	Machining	10310,3	116	88,88	A+	1,0%	A+	A+A+
102MMC201	Foundry	11376,1	106	107,32	A+	0,9%	A+	A+A+
106MBH601	Machining	6319	105	60,18	A+	0,9%	A+	A+A+
210MBH1001	Machining	6669,6	102	65,39	A+	0,9%	A+	A+A+
103MBH301	Machining	12368	154	80,31	A+	1,0%	A+	A+A+
102MMC201	Machining	13028	192	67,85	A+	1,3%	A+	A+A+
101MBH101	Machining	10159	159	63,89	A+	1,1%	A+	A+A+
212MBH1201	Machining	7011,3	95	73,80	A+	0,8%	A	A+A
101MBH101	Machining	7246,3	87	83,29	A+	0,7%	A	A+A
105MBH501	Machining	6035,4	85	71,00	A+	0,7%	A	A+A
103MMC301	Foundry	9593,2	81	118,43	A+	0,7%	A	A+A
105MBH501	Machining	13067	132	98,99	A+	0,9%	A	A+A
113MBH1301	Machining	10635	140	75,96	A+	0,9%	A	A+A
104MBH401	Machining	4971,6	96	51,79	A	0,8%	A	AA
MCT125	Foundry	3354,1	96	34,94	A	0,8%	A	AA
209MBH901	Machining	3523,9	85	41,46	A	0,7%	A	AA
2MCT116	Foundry	2906,8	83	35,02	A	0,7%	A	AA
209MMC901	Foundry	3013,7	82	36,75	A	0,7%	A	AA
107MBH701	Machining	3942,8	82	48,08	A	0,7%	A	AA
108MBH801	Machining	3056,4	81	37,73	A	0,7%	A	AA
MCT114	Foundry	3053,9	79	38,66	A	0,7%	A	AA
2MCT123	Foundry	3590,1	77	46,62	A	0,7%	A	AA
MCT102	Foundry	2603,1	75	34,71	A	0,6%	A	AA

4.4.1.1. Project Team

Top management's support for the project was received; the factory director was involved in the project as the project's sponsor. The schematic representation of the project team is given in Figure 13.

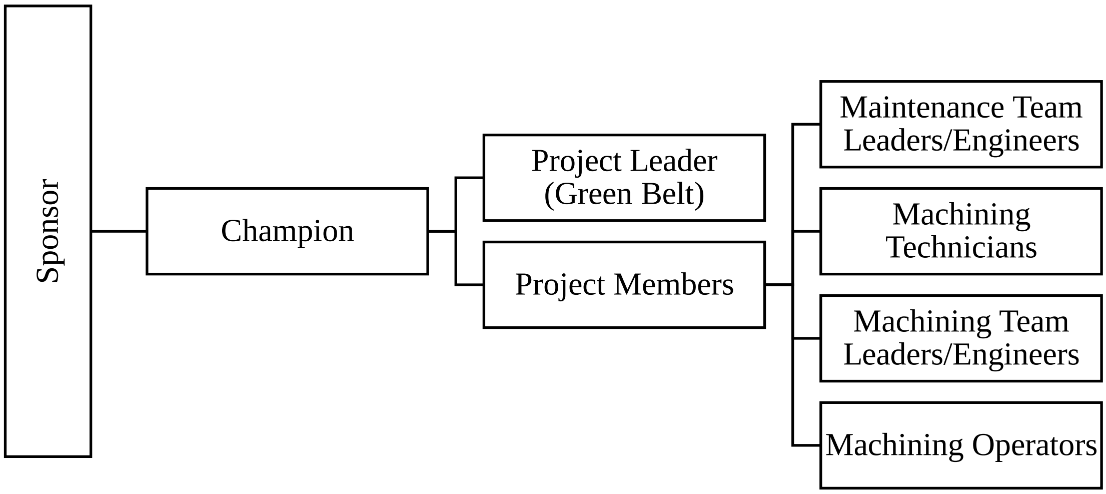

Figure 13. Project Team

After the team members are defined, it is required to create CTQ diagram for translating broad customer needs into specific, actionable and measurable performance requirements.

A Critical to Quality (CTQ) Tree is a schematic tool that can use to better understand the specific, quantitative performance requirements for accomplish to fulfil the expectations of customers. CTQ determines the characteristics of the product or service determined by internal or external customers. These characteristics play an important role in determining the lower and upper limits of the specification limits for the product or service, as well as determining other factors related to the product or service.

Table 4. CTQ Diagram of Project

Requirement	Key Point	CTQ	Metric
Increasing Machining Productivity by Reducing Breakdowns	Breakdown Duration	Life-Time Related Impact of CNC Machines Analysis for Improving Maintenance Strategy	Minutes
	Breakdown Frequecy		Amount
	Life Cycle Cost of Machine		Euro
	Revision Needs		OK/NOK

One of the most popular and effective diagrams for process management and improvement is the SIPOC model. In order to pinpoint the key actions that form each core process, a process map is constructed.

SIPOC is used to present a "one-shot" view of the process flow. This name is an abbreviation for the five steps in the diagram:

Supplier: An individual or group who provides critical information, materials, or other resources for the process.

Input: Data or material to be processed in the process.

Process: Activities to meet customer requests.

Output: The end product or data of the process.

Customer: The individual, team, or procedure that receives the output.

SIPOC assists people in seeing things from a process standpoint. Some of its advantages include (Pande et al., 2003):

• Using a single, simple diagram, depicts a series of cross-functional activities.

• Employs a framework that can be applied to any size process or even the entire organization.

• Helps provide a "big picture" viewpoint to which other details can be added.

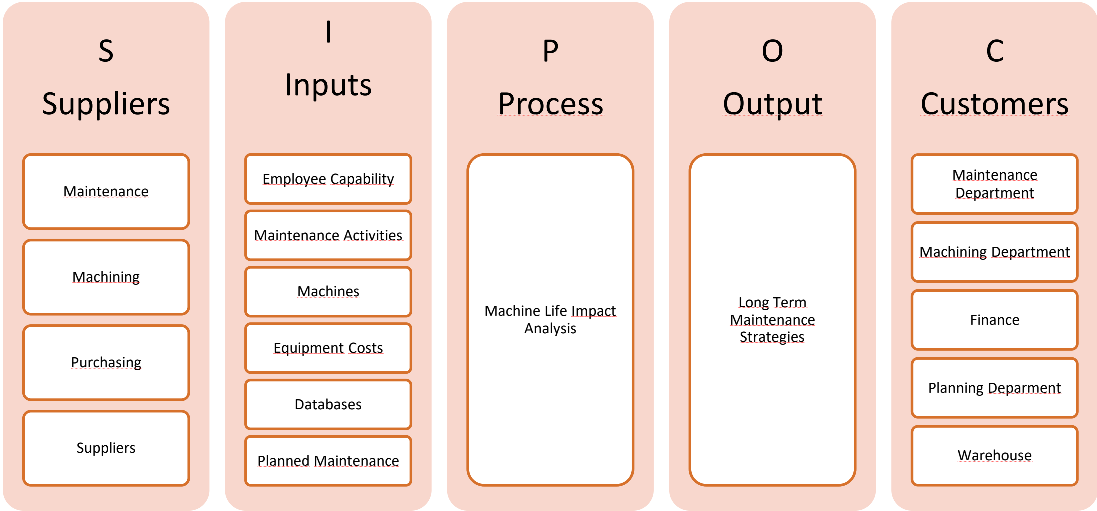

Figure 14. SIPOC Analysis

4.4.2. Measure

The data from the machining process was gathered in the second stage of the Six Sigma project. There are 30 CNC machine lines spread across two production areas. Each production area has 15 CNC machines, and each CNC machine has three cells: Lathe1, Bolt, and Lathe2. The machines differ as robotic, semi-automatic and manual. Since there are machines that perform two operations together, there are 86 cells/benches, since each of the CNC machine is thought to consist of three operations.

Between 2021 and 2022, 119,952 inputs were recorded. Data is collected via Manufacturing Execution System (MES) from the production area in real-time.

In Measure Phase, Data Collection Plan is determined. In Figure 15, the requirement map is presented.

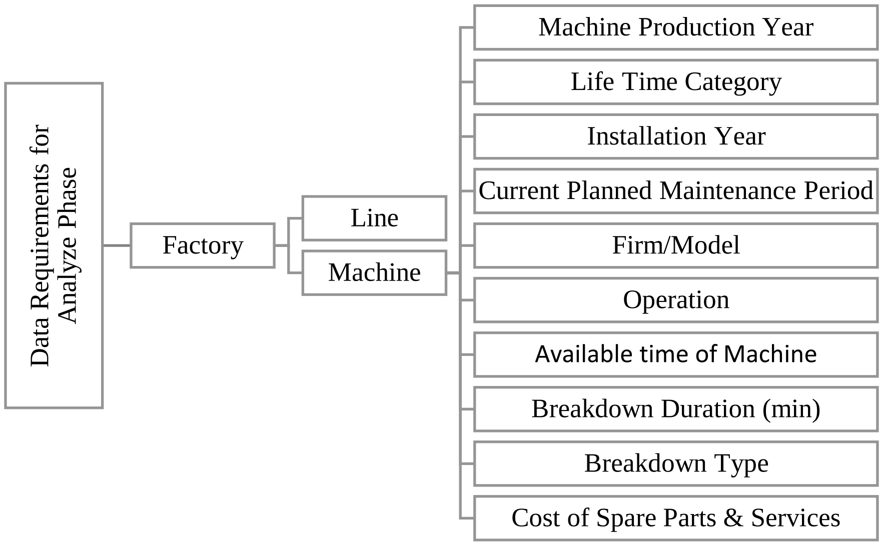

Figure 15. Data Collection Plan

4.4.3. Analyze

For Analyse Phase, machines are grouped according to their ages in Table 5.

Table 5. Machine Age Category

Machine Production Year	Category	Number Of Machines
1993	Old Machines	1
1996	Old Machines	1
1997	Old Machines	4
1999	Old Machines	1
2000	Old Machines	3
2002	Middle Aged	1
2003	Middle Aged	1
2004	Middle Aged	1
2005	Middle Aged	1
2006	Middle Aged	9
2007	Middle Aged	3
2010	Middle Aged	4
2011	Middle Aged	4
2012	Middle Aged	23
2013	New Machines	5
2014	New Machines	1
2015	New Machines	11
2016	New Machines	5
2018	New Machines	7

The data determined in the Measurement phase for the years 2021 and 2022 were analyzed with the help of the Tableau program. When the machines are grouped according to their lifetime for a total of 20 months data, it is observed that the average downtime of the old machines is longer than the new machines. Average downtime per machine is calculated with the following formula.

$$\text{Average downtime per machine} = \text{Total Breakdown Time/Machine number}$$

Average downtime for old machines is calculated as 14.222 minutes per machine, for middle-aged machines 7.662 and for new machines 6.243 minutes and depicted in Figure 16.

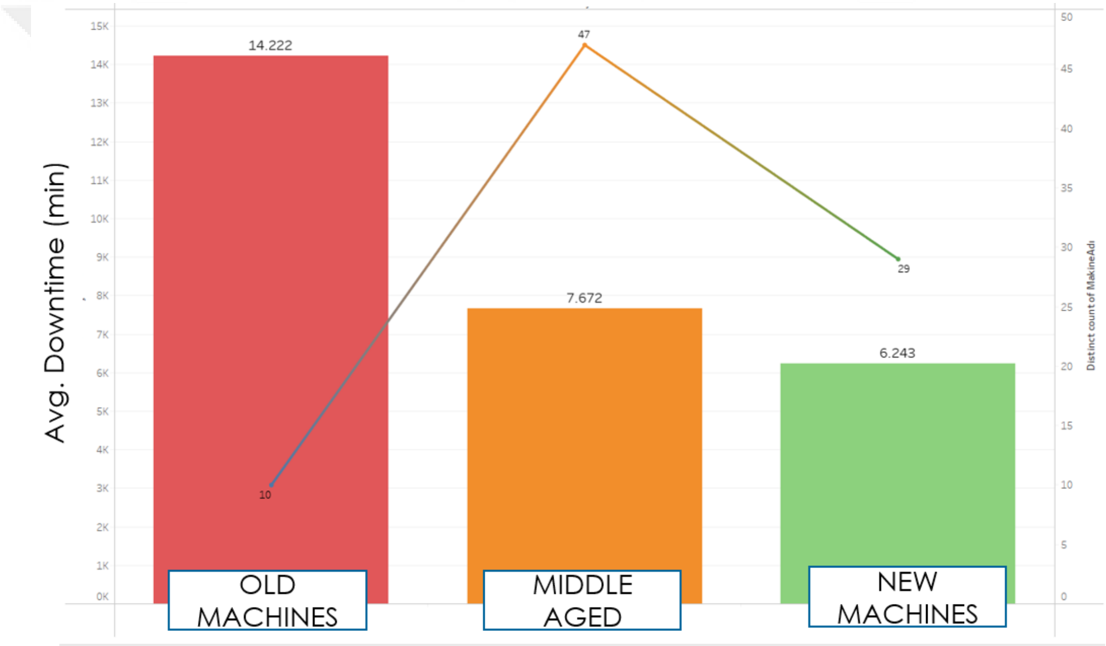

Figure 16. Average downtime per machine according to machine age

When the breakdown times are examined in detail according to the age of the machines, there was a 17-day shutdown in September of 2021, which was experienced in the wheel bolt machine produced in 2004. The reason for this instance is the Angle Table Spiral Head Failure and it was fixed with the support of the authorized service.

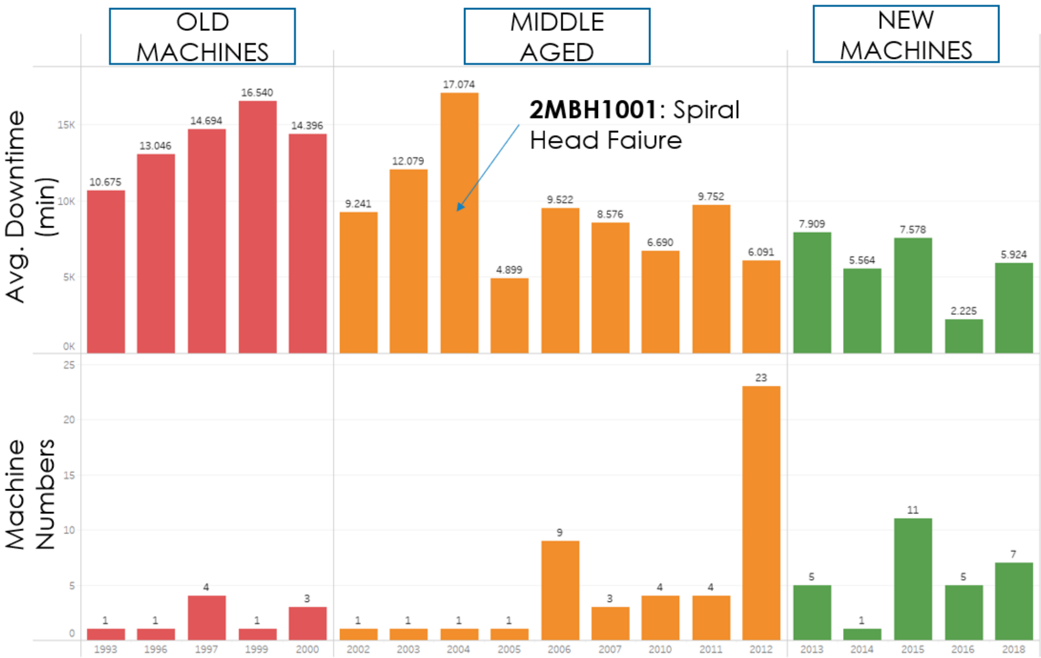

Figure 17. Average Downtime with respect to age and numbers of the Machine

The distribution of the downtime types in % on all machines, is given in Figure 18. As seen in Figure 18, the waiting time for the maintenance resources is approximately 25%. To perform maintenance tasks, the production department is waiting for maintenance resources. It includes waiting for tools, obtaining parts from the warehouse, completing documentation, and purchasing extra tools.

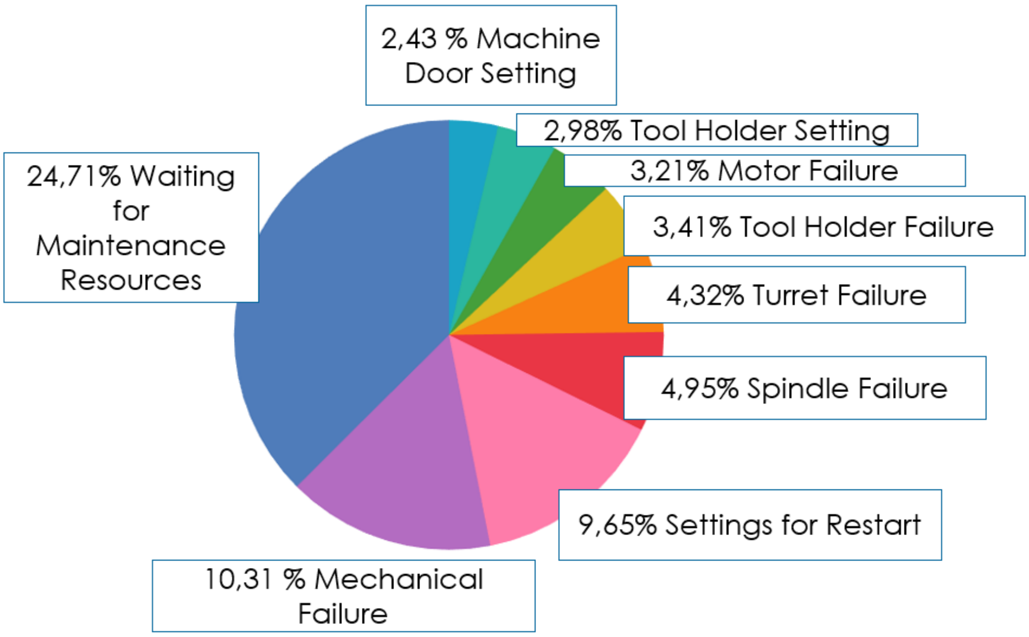

Figure 18. The distribution of the downtime types

4.4.3.1 Bolt Hole Drilling Operation Machines

As mentioned in the Measure phase, each CNC machine has three cells: Lathe1, Bolt, and Lathe2. Each CNC machine processes the gross wheel by completing two different operations. In this analysis, machines are grouped as Lathe and Bolt. When examined according to the types of failures, motor failure, switch failure, tool arm failures cause longer downtime that perform the bolt drilling operation. The Figure 19 represents the monthly average downtime per Bolt machine as minutes. A second project has been studied on Spindle and Tool Arm Failures, which will be mentioned in the Conclusions and Future Work section.

Table 6. Breakdown Types and Colour Indicator

Breakdown Types	
	Encoder Failure
	Cable Failure
	Contactor Failure
	Motor Failure
	Spindle Failure
	Driver Failure
	Switch Failure
	Tool Arm Failure
	Tool Arm Setting
	Turret Setting
	Sensor Failure

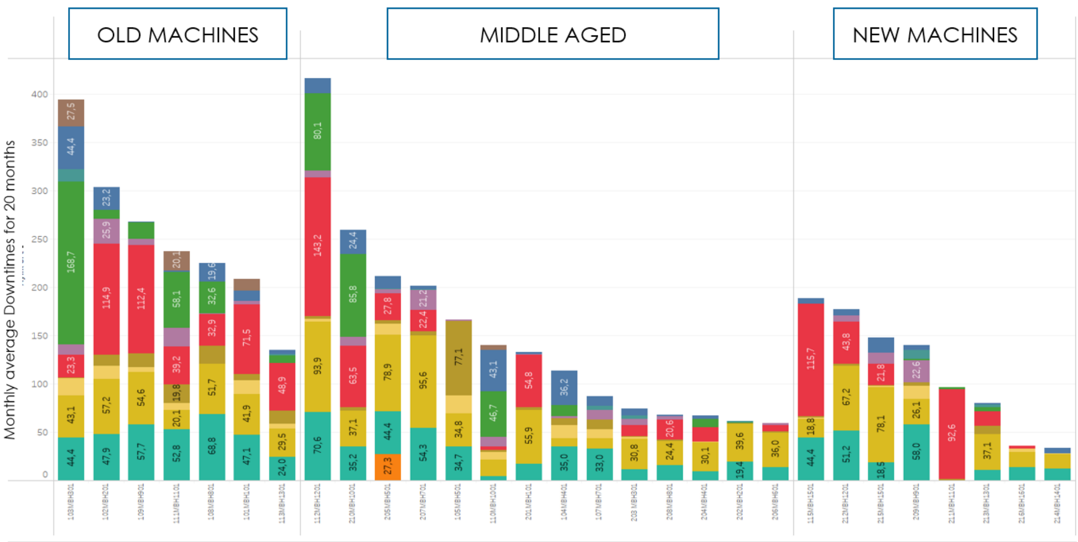

Figure 19. Monthly average downtime per Bolt machine as minutes

Monthly average breakdown frequencies for each Bolt machine indicate that tool arm related breakdowns have a higher impact for productivity losses in Figure 20.

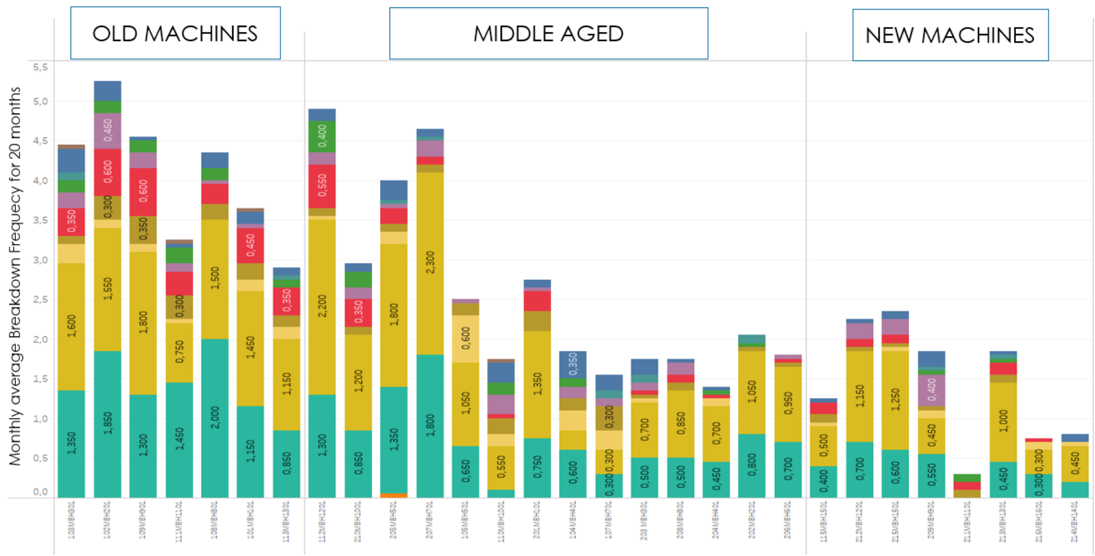

Figure 20. Monthly average breakdown frequency

4.4.3.2 Lathe Operation Machines

When examined according to the types of failures, turret failure, sensor failure, spindle failure cause longer downtime that perform the Lathe operation in Figure 21. Since Lathe operation is different from bolt operation, turret failures take the first place instead of tool arm failures. Mechanical, Pneumatic and Hydraulic Turrets are used. During the Improve phase, this situation was evaluated, and actions were taken separately.

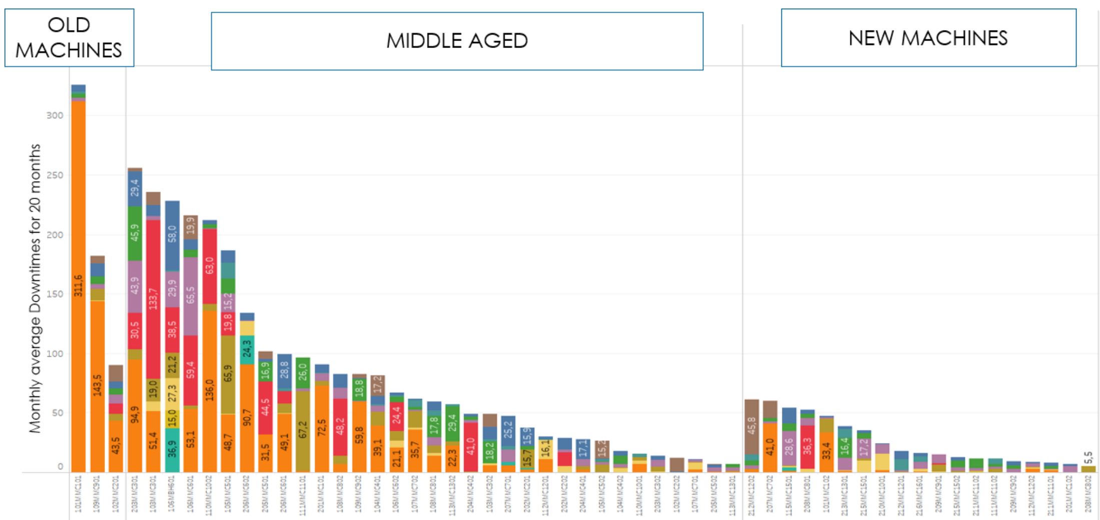

Figure 21. Monthly average downtime per Lathe machine as minutes

Monthly average breakdown frequencies for each Lathe machine indicate that Turret failure related breakdowns have a higher impact for productivity losses in Figure 22.

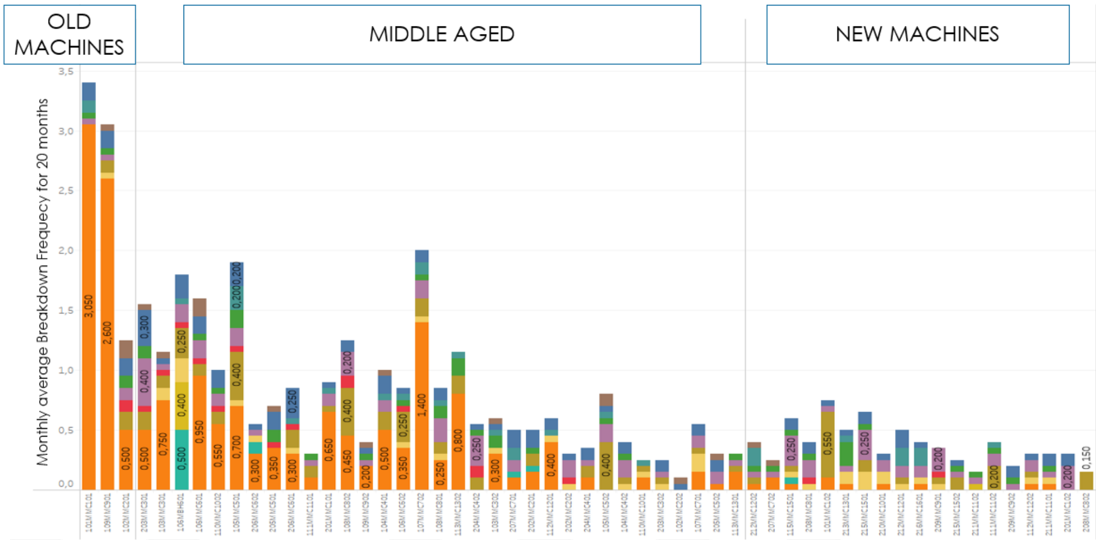

Figure 22. Monthly average breakdown frequency

4.4.3.3 Productivity Effects of Failures:

In order to explain the efficiency effect of these failures more clearly, the effect of the failures in terms of wheel amounts has been calculated**.** It has been determined that old machines cause more capacity loss than middle-aged and new machines in Figure 23.

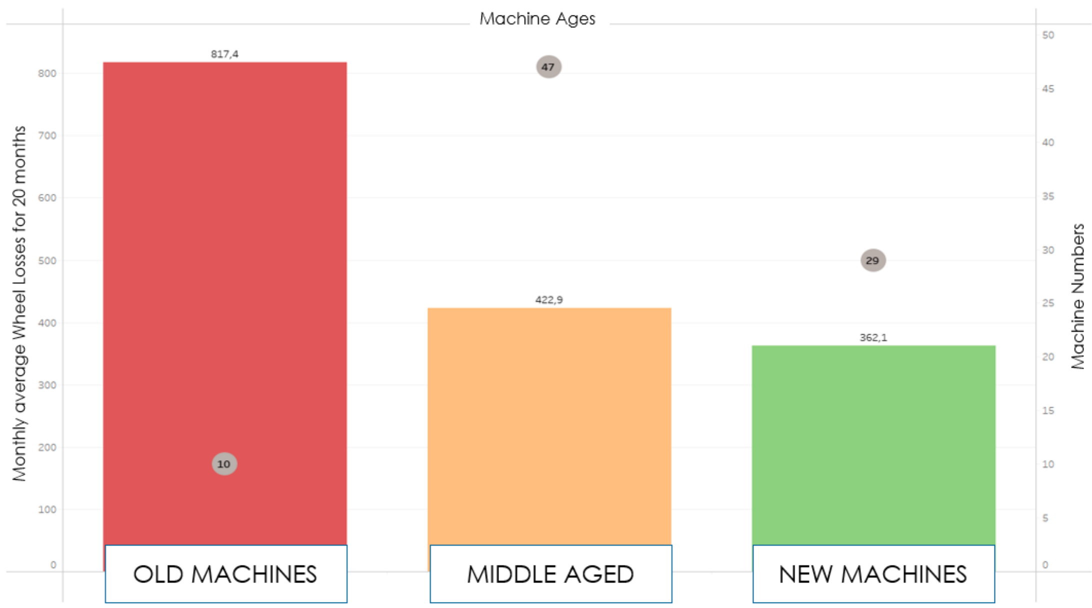

Figure 23. Productivity Effects of Machine Age

4.4.3.4 Cost Loss Analysis of Failures:

The 2-year warehouse spare parts usage amount of the machines determined within the scope of the study and the costs of these parts were evaluated. Spare parts and service cost data are taken from the SAP system. Old machines need revision or renewal. The average costs of old machines are 85% of the total cost of new and middle-aged machines in Figure 24. Table 7 shows the Cost Types and Colour Indicator.

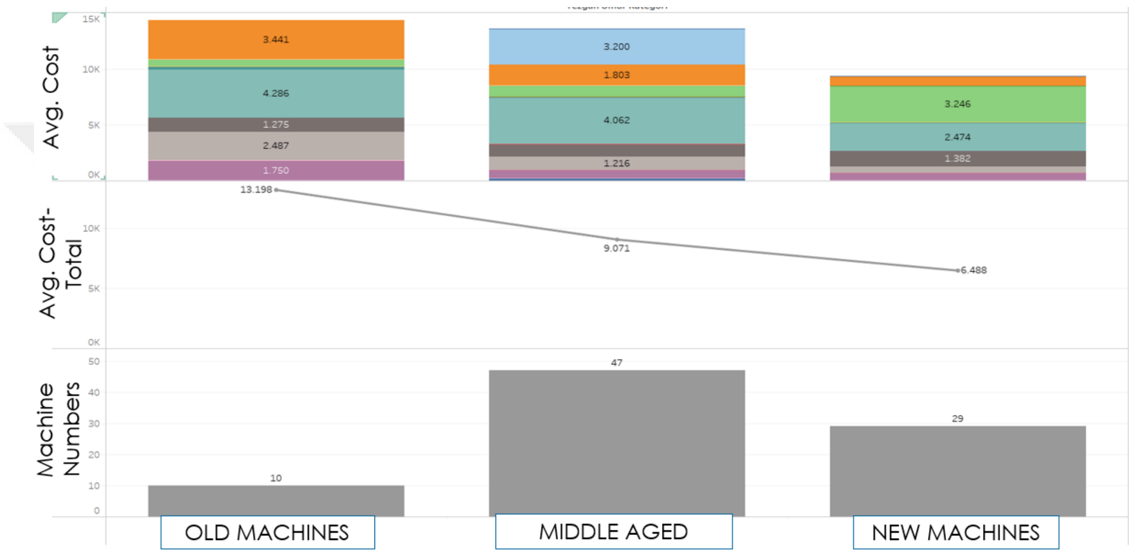

Figure 24. Cost Loss Analysis of Failures

Table 7 Cost Types and Colour Indicator

Cost Types	
	Electronical Parts
	Service
	Lubricating grease & Mineral Oil
	Supply Spends
	Bearing
	Abrasive & Sandpaper

4.4.3.5 Planned Maintenance Effect Analysis

Currently, machining machines are taken into planned maintenance after every 45,000 wheel production. This period can be expressed as 140 days in Figure 25. However, this planned maintenance period varies due to production planning, demand situations, lack of spare parts, disruptions due to unplanned downtime, lack of material, lack of labor, spare parts material supply time.

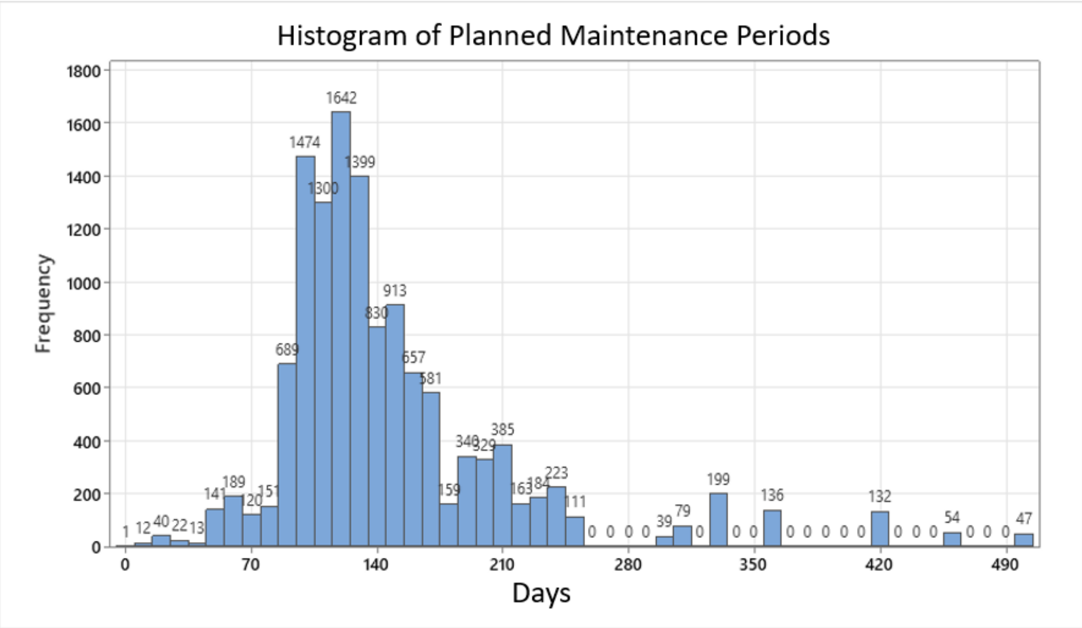

Figure 25. Current Planned Maintenance Periods

In Figure 26, the planned maintenance periods applied over 140 days are colored in red via Minitab.

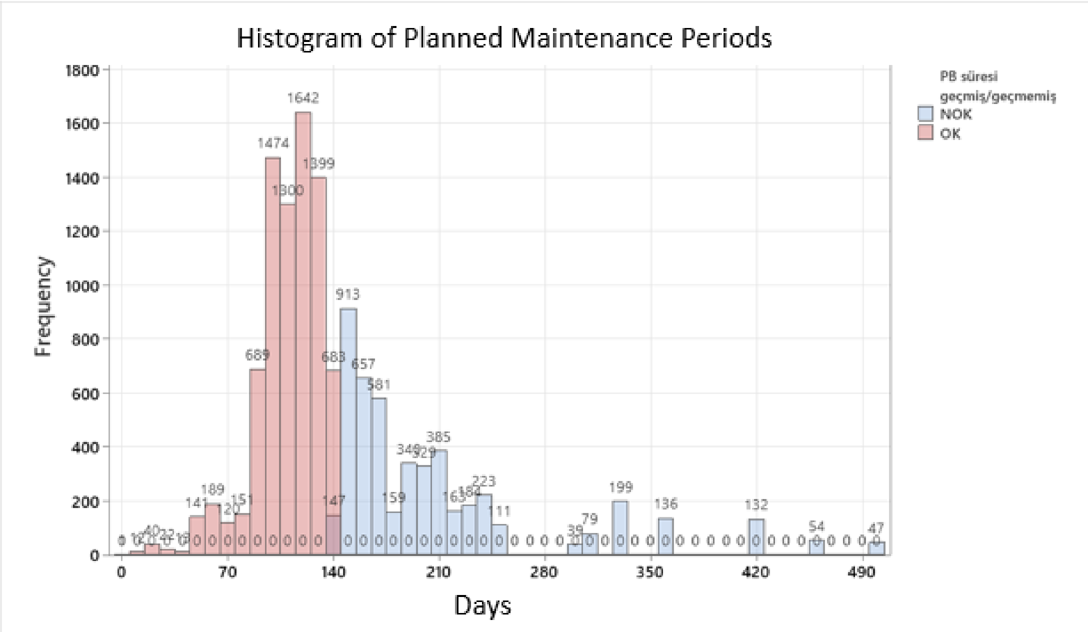

Figure 26. Situation of Planned Maintenance Period

When the planned maintenance periods of 4 years are examined (2017 to 2021). It is observed that the average is realized approximately every 147 days, similar to the target in Figure 27.

Statistics

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3
Bakım Periyodu(gün) (2 PB Arası	12754	0	147,14	0,610	68,88	3,00	107,00	128,00	164,00

Variable	Maximum
Bakım Periyodu(gün) (2 PB Arası	498,00

Figure 27. Statistics of Planned Maintenance Period

4-year failure data and machine-based planned maintenance periods are combined with Phyton software. The purpose of this analysis is to investigate the effect of the current planned maintenance period applied and the frequency of failures and downtime. A new need-oriented data set was created by combining 2 different reports in the company's database. The screenshot of the data set obtained in this way is given in Appendix A and Appendix B. According to the frequency of failure and downtime, the first 20 downtime types experienced in the 4-year data were examined.

Accordingly, the data were categorized according to the machine model, machine type, shift, planned maintenance time, and the time period in which the planned maintenance was applied on the downtime.

Model 1 for the machine model has a 14 minute longer downtime than Model 2, according to analysis of variance. With manual lines, downtime is greater. Downtime takes around 12 minutes longer for the first shift, or the night shift, than it does for the second and third shifts. The average downtime for planned maintenance in the 0-30 day period is 150 minutes. Longer downtime results from doing the planned maintenance throughout the 0-30 day period. The average downtime decreases to 79-85 minutes when the planned maintenance period is carried out between 120-150 or 60-90 days.

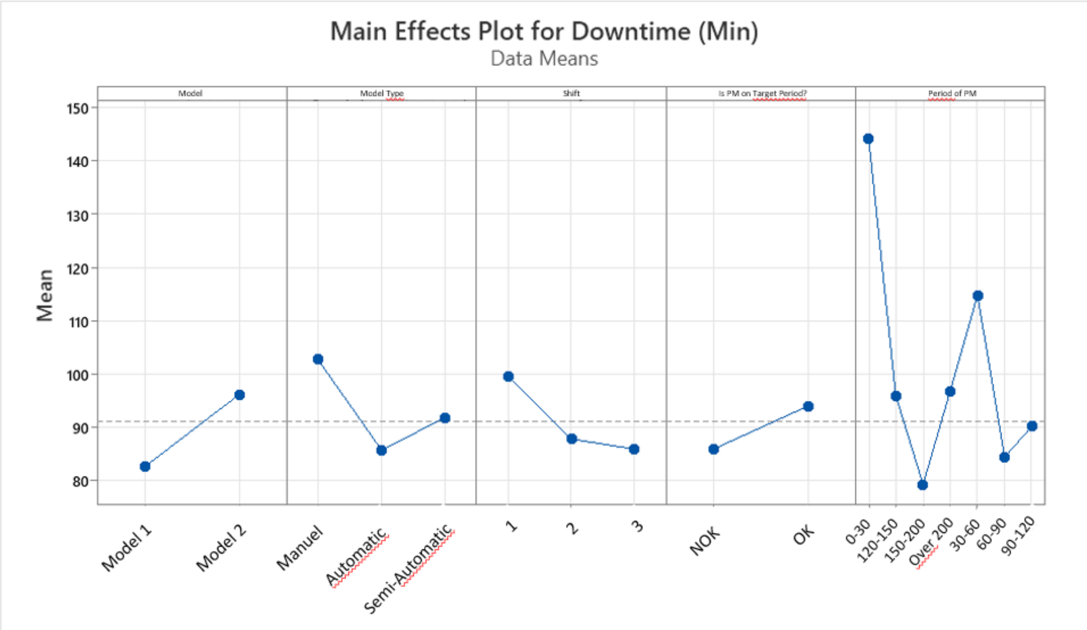

Figure 28. ANOVA-Main Effect Plot for Downtimes (min)

When the first failure is investigated in terms of how many days have passed since the planned maintenance, it is seen from the analysis of variance that there is a failure after 8 days for the 0–30 day planned maintenance period. Similar to the impact on downtime, performing planned maintenance in 0–30 day intervals accelerates failure rates. Similar to the impact on downtime, performing planned maintenance in 0–30 day intervals leads to faster failures. The best planned maintenance interval is thought to be between 150 and 200 days, preferably more. The machine model, machine type, and shift categories have been found to be less effective during the first failure time than during the downtime.

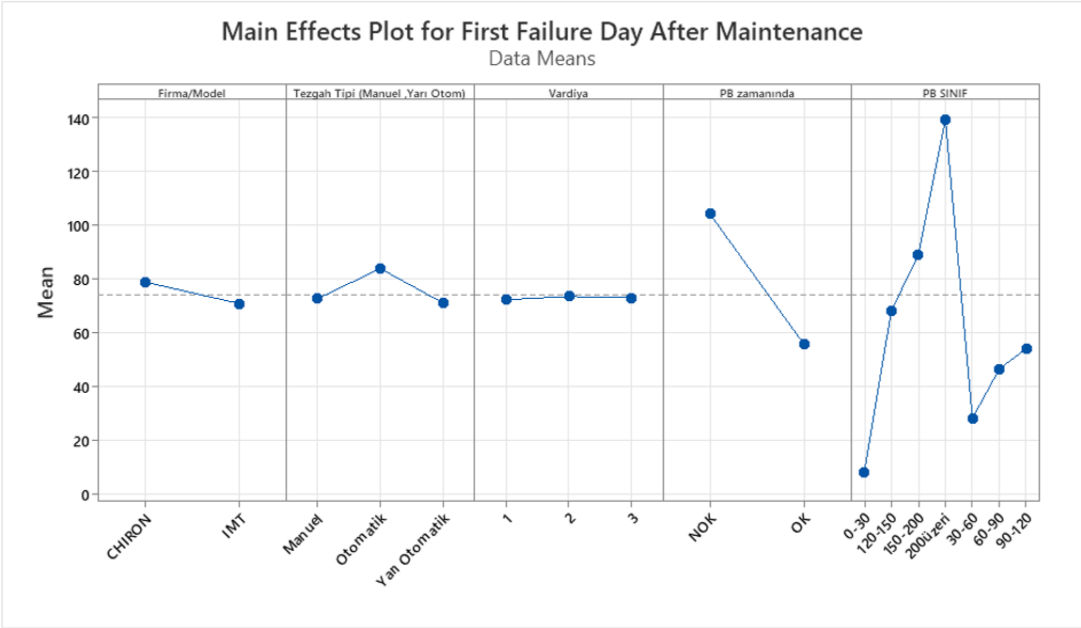

Figure 29. ANOVA Main Effects Plot for First Failure Day After Planned Maintenance

4.4.4. Improve

It has been decided to implement the following actions for the critical process steps determined during the Improve Phase:

Spare Parts Studies:

- For critical spare parts, the spare part status has been updated with suppliers.
- Spiral head belonging to automatic lines has been taken into warehouse stock.
- Orders have been opened for the critical spare parts of the Bolt machines.
- All existing spindles were sent to the supplier company and equipment were assembled by the after-maintenance service.
- New tool arms orders are opened.

Training and Standardization Studies:

- The training for Spindle assembly and adjustment has been completed for the maintenance team.
- Training for tool arms assembly and adjustment has been completed.
- Ordered to supply special tools that must be used for correct assembly and at

one time adjustment.

- An evaluation has been made for the revisions of the machines of the old system, and work has been started for the investment of new machines.
- Trainings were provided for the correct definition of MES data and its entry into the system.

Maintenance Activities:

- Predictive maintenance work was initiated to minimize spindle failures. Factors such as abnormal vibrations have negatively affected the spindle life. As a result, vibration measurements are taken in order to prevent damage to the spindle.
- Negotiations with the supplier have begun for the complete revisions of the Bolt machines. Preliminary work has been completed.
- Mechanical turrets, in particular, cause issues in lathes. Investment was planned for old type lathes. There is difficulty in maintenance activities due to the fact that the old control units had a spare part problem. There was a spare part problem. It has been decided that the replacement of all these machines is appropriate.
- In addition, 5S, one of the lean techniques, was reactivated in the maintenance warehouse area with this project.

The actions determined in this phase were implemented by prioritizing according to the time and resource plan.

4.4.5. Control

The results of the changes were monitored for 4 months. As a result of the changes made, the failure rate decreased in Figure 30.

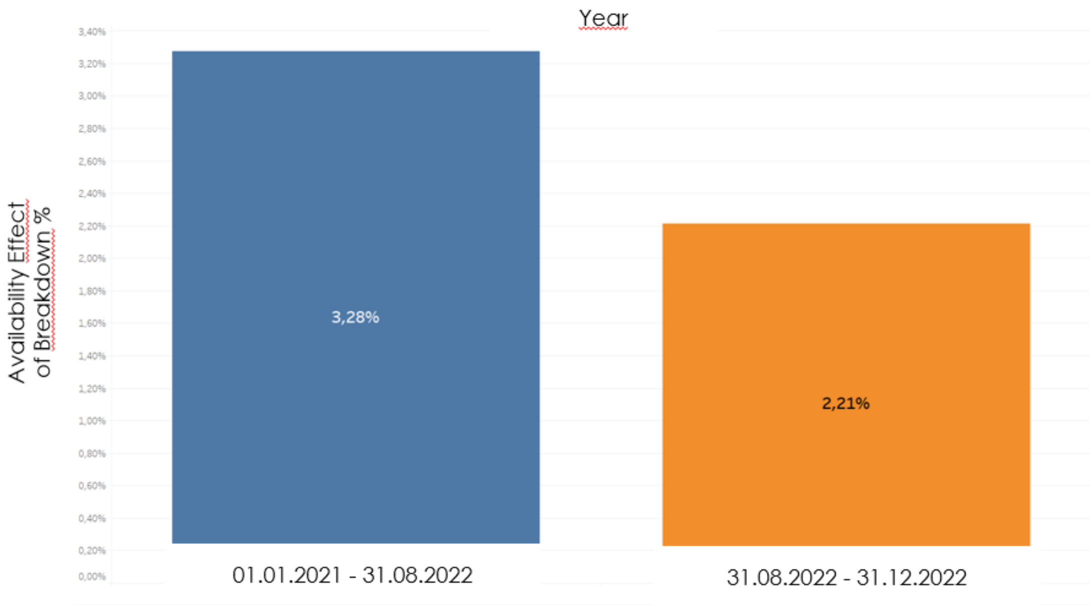

Figure 30. Availabilty Effect of Breakdown % After Improvement

Both the availability percentage and downtime have improved for the top five biggest failures in Figure 31.

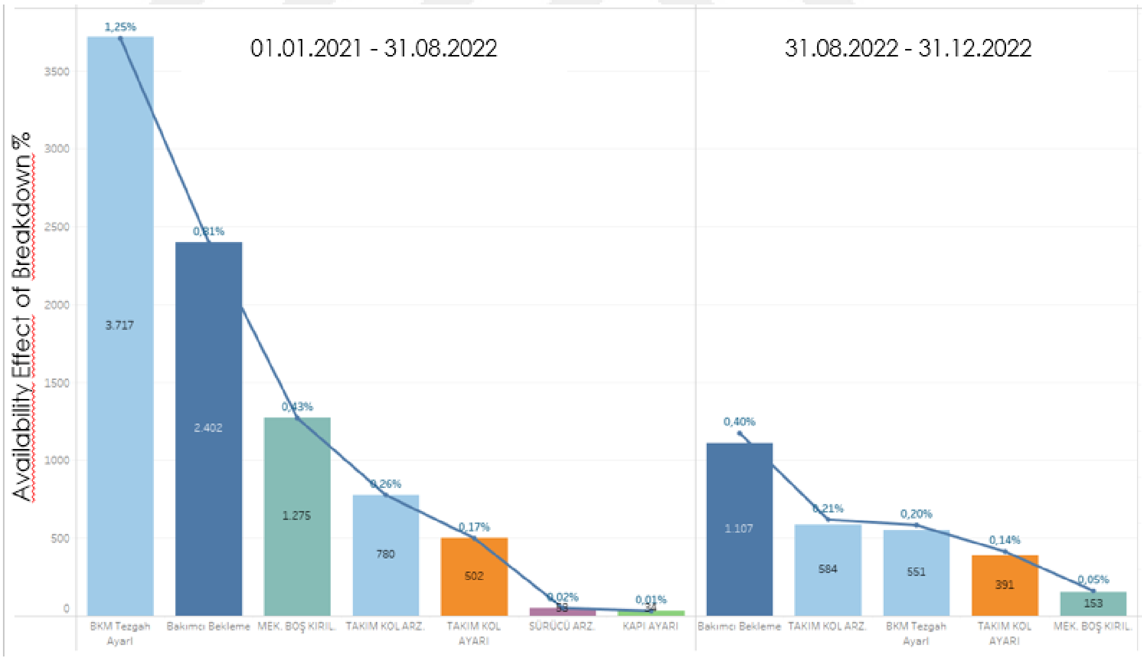

Figure 31. Availabilty Effect of Top 5 Breakdown Ratio % After Improvement

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

In today's increasingly competitive environment, there is only one way for businesses to survive: by improving their processes or services. At this point, Six Sigma is an effective methodology. Thanks to Six Sigma, companies have the opportunity to review, reorganize, or switch to a much better process based on their customers' needs. As a result of the improvements realized step by step with the help of Six Sigma, the company creates a structure that questions the existing processes in the company culture as well as making tangible gains.

For the purpose of improving the availability of machines in the production process and identify the actions that should be taken to optimize the maintenance process, the paper's primary objective was to identify the life-time factors of machines that influence the frequency and duration of failures. The Six Sigma approach was used to this objective. The initial phases of the study involved defining the Six Sigma project's scope and collecting process data. Then, analyses were carried out to find probable elements that could affect the process. Based on the findings, the following variables were identified as having an impact on the frequency and duration of failures: machine age, spare part management, employee performance. A detailed analysis of variables enabled the discovery of the most frequent reasons for failures and the recommendation of action plans. The case study company has seen some benefits after all the improvements were carried out.

The results of the changes were monitored for four months. As a result of the changes, availability ratio % of CNC machines is improved.

As a result of the study carried out by following the DMAIC project steps, availability losses were reduced to 2.21% as of the end of the 4th month. A 33% improvement has been achieved. This improvement refers to the improvement in the duration of downtime and breakdowns, which have non-value added within the working time of the machine. It is also described as an OEE percentage effect. OEE is a performance indicator that shows the condition of the equipment. It is a composite measurement reported as a percentage that is derived from factors such as equipment performance, availability, and output quality. OEE is a very crucial metric in company because it serves as the key performance indicator (KPI). It is calculated by considering all types of failures within a 33% improvement rate. The effect of this improvement in the 4-month period is approximately € 20,000 of saving. The saving is calculated by considering the cost of improving the production unit for one minute (€/min).

Analyzes made for the prioritization of investment plans accelerated the processes and supported the decision-making process in maintenance activities.

As a future study, a component-based failure monitoring system to be needed for maintenance work was deployed. The goal of the study is to identify possible areas for improvement and to establish a substructure so that production is carried out in accordance with the plan and decision-making assistance for maintenance operations is provided in Figure 32.

Reasons for the need for the future project:

- There is no component-based monitoring system while performing fault analyses in the factory. In this case, it becomes difficult to make a maintenance plan for the components.
- If the component that needs to be changed is out of stock, there will be long-term machine stoppages.
- The importance of unexpected machine breakdowns in production systems cannot be underestimated. A line shouldn't fail, and machinery should run without any issues, especially in systems which are run in series without backup units.
- The outputs of the project can be used to support the decision-making process in maintenance activities.
- The aim is to deploy a component-based failure monitoring system, collect failure data from equipment, and make life-time estimations.
- Within the scope of the project, the equipment hierarchy, which was changed due to failure, was created under the MES, and the improvement phase of the project continues.

The main outputs of the study will be:

- How many spare parts should we keep in stock for maintenance and breakdowns?
- How many machine breakdowns do we expect?
- In which periods should be planned for the maintenance of the machines?

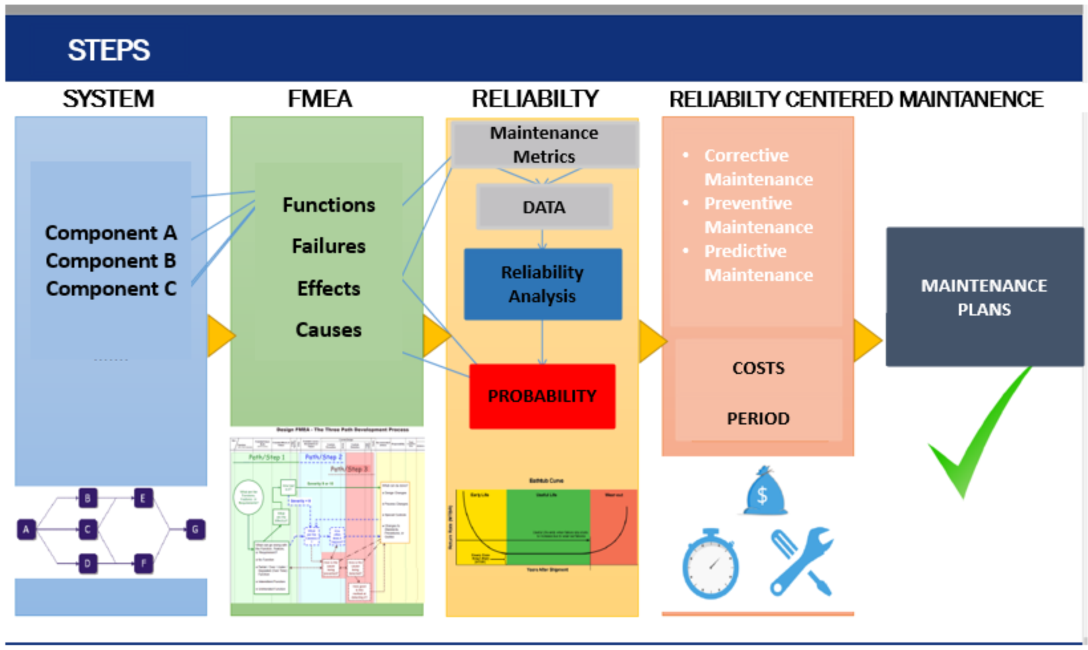

Figure 32. Steps of the Project

As the concepts of Digital Transformation and Industry 4.0 evolve and competition forces companies to innovate, Lean Six Sigma and similar applications will gain importance. Digital Transformation and Lean 6 Sigma activities are progressing in an integrated manner in the company.

It is clear that methods and tools of Lean Six Sigma cannot go beyond solving problems temporarily, unless the Lean Six Sigma method is embedded in a company and the change is primarily a cultural change. For this reason, top management should fully support Lean Six Sigma activities.

The knowledge infrastructure of the employees of the company about Lean Six Sigma is at a sufficient level. Since the company has been applying the Lean Six Sigma method since its establishment, it has the required number of employees with Six Sigma education, which are the most basic elements of Six Sigma. The knowledge and experience of the employees contribute greatly to the implementation of Lean Six Sigma in the company, and the need for educating future belts is continuous in order for this approach to be sustainable in the company.

REFERENCES

Alukal, G. (2003) *Create a Lean, Mean Machine*, Quality Progress, Vol. 4, pp. 29-35.

Atmaca, E. and Girenes, S. Ş. (2013) Literatür Araştırması: Yalın Altı Sigma Metodolojisi, Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi, Vol. 24(4), Available at: https://dergipark.org.tr/tr/pub/gazimmfd/issue/6682/88317 (Accessed: 1 January 2023)

Bañuelas, R., Antony, J., and Brace, M. (2005) *An Application of Six Sigma to Reduce Waste*, In Quality and Reliability Engineering International, Vol. 21, Issue 6, pp. 553–570.

Davies, C. and Greenough, R.M. (2010) *Measuring the effectiveness of lean thinking activities within maintenance,* Available at: http://www.plantmaintenance. com/articles/Lean_Maintenance.pdf. (Accessed: 1 January 2023)

Dumitrescu, C.D., (2010) *Lean Six Sigma Principles*, DAAAM International, Vol 21(1), pp.433-435.

Engin, G. (2006) Hizmet sektöründe altı sigma yaklaşımı ile süreç iyileştirme / Process improvement in service industries by using six sigma approach, Master Thesis, Maltepe Üniversitesi, Sosyal Bilimler Enstitüsü, İstanbul

Guarraia, P., Carey, G., Corbett, A., and Neuhaus, K. (2009*) Six Sigma-at your service,* In Business Strategy Review (Vol. 20, Issue 2, pp. 56–61.

Gupta, P. (2004). Six Sigma business scorecard. *Perspectives on Performance*, Vol. 3, pp. 10-11.

Gürsakal N., (2006) *Altı Sigma: Müsteri Odaklı Yönetim*, 1st edition. Ankara: Nobel Akademik Yayıncılık, pp. 107-143.

Hami, N., Shafie, S. M., Omar, S., Ibrahim, Y. M., Sabah, A. S. and Mohd, R. M. (2020) *A review of sustainable maintenance in the manufacturing companies,* International Journal of Supply Chain Management, Vol. 9(3), pp. 935-944.

Hostetler, D. (2010) Get Results: Improve Your Accounting Firm Processes Using Lean Six Sigma: Renewed Focus on Efficiency and Quality Can Beef Up Profitability, Journal of accountancy, Journal of Accountacy, pp. 38-42,

Işılgan, E., (2006) *Borusan Lojistik 6 Sigma Uzman Yesil Kusak Egitim Notları,* Kozyatagı, İstanbul.

Jasiulewicz-Kaczmarek, M., Antosz, K., Żywica, P., Mazurkiewicz, D., Sun, B., and

Ren, Y. (2021) *Framework of machine criticality assessment with criteria interactions,* In Eksploatacja i Niezawodnosc - Maintenance and Reliability, Vol. 23, Issue 2, pp. 207–220.

Karuppiah, K., Sankaranarayanan, B. and Ali, S. M. (2021) *On sustainable predictive maintenance: Exploration of key barriers using an integrated approach*., Sustainable Production and Consumption, Vol. 27, pp. 1537-1553.

Mahantı, R., Antony, J. (2005) *"Confluence Of Six Sigma, Simulation And Software Development,"* Managerial Auditing Journal Technical Paper, Vol. 20, Issue.7. pp. 741.

Milosavljević, P., and Rall, K. (2005) *Six Sigma Concept in The Maintenance Process Of Technical Systems,* Facta Unıversıtatıs Mechanical Engineering, pp. 93-108.

Mostafa, S., Dumrak, J., and Soltan, H. (2015), *Lean Maintenance Roadmap*, Procedia Manufacturing, Vol. 2, pp. 434–444.

Öztürk, A. (2009) *Kalite Yönetimi ve Planlaması*, 2nd edition. Bursa: Ekin Basım Yayın Dağıtım.

Pande, P. S., Neuman, R. P. and Cavanagh, R. N., (2003) *Six Sigma Yolu,* İstanbul.

P. Pande, and L.Holpp, (2001). *What is six sigma?*. 1st edition. New York (N.Y.): McGraw-Hill.

Polat, A., Cömert, B. and Arıtürk, T. (2005) *Altı Sigma Vizyonu,* 1st edition.
Ankara: Pelin Ofset Matbaacılık.

Polk, J.D. (2011) *Lean Six Sigma, Innovation, and The Change Acceleration Process Can Work Together*, American College of Physician Executives. Vol. 37(1), pp. 38-42.

Pophaley, M., and Vyas, R. K. (2015) *Fortification of Plant Maintenance Management Practices: Role of Six Sigma Approach,* Brazilian Journal of Operations and Production Management, Vol. 12(1), pp.56–64.

Pyzdek, T., (2001) *Six Sigma Handbook; A complete guide for greenbelts,*
blackbelts and managers at all levels, 5th edition. New York: McGraw Hill.

Saihi, A., Ben-Daya, M. and As' ad, R. A. (2022) Maintenance and sustainability: a systematic review of modeling-based literature, Journal of Quality in Maintenance Engineering.

Seow, C. and Liu, J. (2006) *Innovation in maintenance strategy through Six Sigma*, SME IEEE International Conference on Management of Innovation and Technology Vol. 2, pp. 793-797.

Sharma, M. S., and Sharma, M. V. (2014) *Employee Engagement to Enhance Productivity in Current Scenario*, International Journal of Commerce, Business and Management, Vol. 3(4), pp. 595-604.

Sreedharan V., R., Sunder M., V., and R., R. (2018) *Critical success factors of TQM, Six Sigma, Lean and Lean Six Sigma. In Benchmarking*, An International Journal, Vol. 25, Issue 9, pp. 3479–3504.

Thomas, A., Barton, R., and Byard, P. (2008) *Developing a Six Sigma maintenance model*, In Journal of Quality in Maintenance Engineering, Vol. 14, Issue 3, pp. 262–271.

Toomanian, A., and Mansourian, A. (2009) *An integrated framework for the implementation and continuous improvement of spatial data infrastructures*, In B. van Loenen, J. W. J. Besemer, and J. A. Zevenbergen (Eds.), SDI convergence : research, emerging trends, and critical assessment, pp. 161-174.

Topaz, K. and Sümen, H., (2003) *Kestirimci bakım yöntemini uygulamak,* Makine Tek Dergisi, Sayı:63, Bileşim Yayınevi.

Sharma, M. S., and Sharma, M. V. (2014) *Employee Engagement to Enhance Productivity in Current Scenario*. International Journal of Commerce, Business and Management, Vol. 3(4), pp. 595-604.

Ghayebloo, S., and Shahanaghi, K. (2010*) Determining maintenance system requirements by viewpoint of reliability and lean thinking: a MODM approach*, *Journal of Quality in Maintenance Engineering*, *Vol. 16*, pp. 89-106.

T.G. Tendayi C.J. Fourie (2013) *The Combined AHP-QFD Approach and its use in Lean Maintenance*, in 25th Annual Southern African Institute of Industrial Engineering Conference, SAIIE Stellenbosch.

Tsarouhas, P. (2021) *Maintenance scheduling of a cheddar cheese manufacturing plant based on RAM analysis*, In International Journal of Productivity and Performance Management, Vol. 71, Issue 2, pp. 666–690.

Türkan, Y. S., Manisalı, E. anf Çelikkol, M. F., (2009) *Evaluation of Critical Success Factors Effect on Six Sigma Project Success in Turkey's Manufacturing Sector*, Journal of Engineering and Natural Sciences, pp.105-117.

Wilson, P. M., (1999) *Six Sigma – Understanding the Concept, Implications and Challenges*, Advanced System Consultants, New York.

Womack, J. and Jones, D. (1998) *Yalın Düsünce*. 1st edition. İstanbul: Optimist Yayın Grubu., İstanbul.

Zonta, T., Costa, C.A., Righi, R.D., Lima, M.J., Trindade, E.S., and Li, G. (2020). Predictive maintenance in the Industry 4.0: A systematic literature review. Comput. Ind. Eng., 150, 106889.

APPENDICES

Appendix A. Phyton software dataset merge function

```
bakım_df.index = range(len(bakım_df))
```

```
# Applying merge_asof on data and store it
# in a variable
merged_dataframe = pd.merge_asof(durus_df, bakım_df, on="Tarih",
                                 by="Makine",direction="backward",allow_exact_matches=False)

# print the variable
merged_dataframe
```

	RefNo	MID	Makine	Duruş Kodu	Duruş Adı_x	Duruş Grubu Adı	Süre_x	Dk_x	Tarih	Bitiş Zamanı_x	...	Başlangıç Zamanı	Bitiş Zamanı_y	Durum	İş Tamamlanma Zamanı	Talep Tarihi	
0	30126714	41	101MMC101	1	Bakımcı Bekleme	Bakım Arıza	00:00:28	0.5	2018-01-02 09:41:33	2018-01-02 09:42:01	...	-9999.0	-9999.0	Yeni	-9999	-9999.0	17
1	30126719	41	101MMC101	921	SWITCH ARZ.	Bakım Arıza	01:09:15	69.3	2018-01-02 09:42:01	2018-01-02 10:51:16	...	-9999.0	-9999.0	Yeni	-9999	-9999.0	17
2	30126768	31	105MBH501	1	Bakımcı Bekleme	Bakım Arıza	00:50:19	50.3	2018-01-02 10:02:45	2018-01-02 10:53:04	...	-9999.0	-9999.0	Yeni	-9999	-9999.0	15
3	30126784	417	212MMC1201	1	Bakımcı Bekleme	Bakım Arıza	00:06:11	6.2	2018-01-02 10:09:26	2018-01-02 10:15:37	...	NaN	NaN	NaN	NaN	NaN	
4	30126788	422	211MMC1101	1	Bakımcı Bekleme	Bakım Arıza	00:04:35	4.6	2018-01-02 10:10:13	2018-01-02 10:14:48	...	NaN	NaN	NaN	NaN	NaN	
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
69713	51960608	298	209MBH901	1	Bakımcı Bekleme	Bakım Arıza	00:08:17	8.3	2022-01-18 21:13:44	2022-01-18 21:22:01	...	NaN	NaN	NaN	NaN	NaN	
69714	51960665	417	212MMC1201	1	Bakımcı Bekleme	Bakım Arıza	00:02:14	2.2	2022-01-18 21:16:45	2022-01-18 21:18:59	...	NaN	NaN	NaN	NaN	NaN	
69715	51960689	417	212MMC1201	957	KONV. ARZ.	Bakım Arıza	00:27:05	27.1	2022-01-18 21:18:59	2022-01-18 21:46:04	...	NaN	NaN	NaN	NaN	NaN	
69716	51960758	579	215MMC1501	922	ŞALT MALZEME ARZ	Bakım Arıza	00:16:26	16.4	2022-01-18 21:23:56	2022-01-18 21:40:22	...	NaN	NaN	NaN	NaN	NaN	
69717	51961470	298	209MBH901	1	Bakımcı Bekleme	Bakım Arıza	00:05:12	5.2	2022-01-18 22:15:14	2022-01-18 22:20:26	...	NaN	NaN	NaN	NaN	NaN	

Appendix B. Phyton software dataset sort function

```
bakım_df.to_excel("TİM PB Tarihleri.xlsx",index=False)
```

```
bakım_df = bakım_df.sort_values("Tarih")
```

```
bakım_df["Tarih"]
```

```
0       2017-06-08 08:05:44
1       2017-06-08 08:06:05
2       2017-06-08 08:06:12
3       2017-06-14 19:40:39
4       2017-06-14 19:40:51
                ...
1585    2022-02-25 14:31:52
1586    2022-02-25 14:43:23
1587    2022-02-25 14:44:08
1588    2022-02-25 14:52:06
1589    2022-02-25 15:07:31
Name: Tarih, Length: 1590, dtype: datetime64[ns]
```

```
bakım_df.index = range(len(bakım_df))
```

```
# Applying merge_asof on data and store it
# in a variable
merged_dataframe = pd.merge_asof(durus_df, bakım_df, on="Tarih",
                                 by="Makine",direction="backward",allow_exact_matches=False)

# print the variable
merged_dataframe
```

	RefNo	MID	Makine	Duruş Kodu	Duruş Adı_x	Duruş Grubu Adı	Süre_x	Dk_x	Tarih	Bitiş Zamanı_x	...	Başlangıç Zamanı	Bitiş Zamanı_y	Durum	İş Tamamlanma Zamanı	Talep Tarihi	
0	30126714	41	101MMC101	1	Bakımcı Bekleme	Bakım Arıza	00:00:28	0.5	2018-01-02 09:41:33	2018-01-02 09:42:01	...	-9999.0	-9999.0	Yeni	-9999	-9999.0	17
1	30126719	41	101MMC101	921	SWITCH ARZ.	Bakım Arıza	01:09:15	69.3	2018-01-02 09:42:01	2018-01-02 10:51:16	...	-9999.0	-9999.0	Yeni	-9999	-9999.0	17
2	30126768	31	105MBH501	1	Bakımcı Bekleme	Bakım Arıza	00:50:19	50.3	2018-01-02 10:02:45	2018-01-02 10:53:04	...	-9999.0	-9999.0	Yeni	-9999	-9999.0	15
3	30126784	417	212MMC1201	1	Bakımcı Bekleme	Bakım Arıza	00:06:11	6.2	2018-01-02 10:09:26	2018-01-02 10:15:37	...	NaN	NaN	NaN	NaN	NaN	