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Optimizing CNC Frame Machining for Low Voltage Motors: A Production Efficiency, Cost, and Capacity Analysis

Case study: Company x

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ABSTRACT:

The global demand for high-efficiency low-voltage electric motors is continuously increasing and that puts pressure on manufacturers to optimize their production capacity while managing operating costs, energy consumption, and the production machines reliability. Despite wide literature on CNC machining optimization, no similar research exists specifically focusing on electric motor frame machining. This thesis addresses that gap through a quantitative case study done at a manufacturing company in Finland.

The study investigates CNC machining efficiency at two vertical machining centers, one 1992 model (120-1) and one 2007 model (120-4). The author applies Overall Equipment Effectiveness (OEE), Total Cost of Ownership (TCO), and Lean manufacturing frameworks to analyze costs, process efficiency, downtime, and production capacity over 2024–2026. Data collection combined internal database analysis, semi-structured interviews, process observation, and manual time observations and studies. The researcher's three years of working experience at the case company as a maintenance mechanic, maintenance supervisor, and production development engineer provided essential knowledge for collecting data from systems and adapting theoretical frameworks to this specific manufacturing context.

The analysis examines the main cost drivers in CNC frame machining, including operator labour, maintenance, tool wear, cutting liquid, and energy consumption. In study process efficiency analysis identifies the key sources of non-value-added time at both task level and the shift level, and compares theoretical versus actual production capacity for the CNC-machines. Maintenance performance is evaluated using key performance indicators including Mean Time to Failure, Mean Time to Repair, Mean Time Between Failures, and Mean Downtime.

Based on the findings, a capacity forecasting model is developed for the case company, enabling estimation of future production volumes by adjusting parameters related to machine reliability, process times, and operational schedules. Practical recommendations are provided for improving maintenance strategy, optimising tool change, reducing non-value-adding process time, and supporting investment decision-making for future capacity expansion. Suggestions for future research and the limitations of the study are also discussed.

KEYWORDS: Frame Machining, Production Efficiency, Cost Analysis, Lean Manufacturing, Low voltage motor, Total Cost of Ownership

UNIVERSITY OF VAASA**School of Technology and Innovations****Skribent:** Max Nyholm**Avhandlingens titel:** Optimerar ramfräsning för lågspänningsmotorer: En Produktions Effektivitets, Kostnads och Kapacitetsanalys: Case study: Company x**Examen:** Master of Science in Economics and Business Administration**Program:** Industrial Management**Handledare:** Petri Helo**År:** 2026 **Sidantal:** 95

ABSTRAKT:

Den globala efterfrågan på effektiva lågspänningselektromotorer ökar kontinuerligt, vilket sätter press på tillverkare att optimera deras produktionskapaciter samtidigt som de ska hantera driftskostnader, energiförbrukningar och utrustningens driftpålitlighet. Trots omfattande litteratur om optimering av CNC-bearbetning finns inte liknande forskningar som specifikt behandlar CNC-bearbetning av elmotorers rammar.

Detta examensarbete fyller den luckan genom en kvantitativ studie genomförd vid ett produktionsföretag i Finland.

Studien undersöker CNC-bearbetningseffektiviteten vid två vertikala bearbetningsmaskiner, en modell från 1992 (120-1) och en modell från 2007 (120-4). Författaren tillämpar ramverken Overall Equipment Effectiveness (OEE), Total Cost of Ownership (TCO) och Lean-tillverkning för att analysera kostnader, processeffektivitet, driftstopp och produktionskapacitet under åren 2024–2026. Datainsamlingen kombinerade analys av interna databaser, semistrukturerade intervjuer, processobservationer och manuella tidsstudier. Skribentens treåriga arbetserfarenhet vid företaget som underhållsmekaniker, underhållschef och produktionsutvecklingsingenjör gav nödvändig kunskap för att samla in data från systemen och anpassa de teoretiska ramverken till detta specifika tillverkningsområde.

Analysen granskar de viktigaste kostnadsdrivarna vid CNC-bearbetning av rammar, inklusive operatörslöner, underhåll, verktygsslitage, skärvätskor och energiförbrukning.

Processeffektivitetsanalysen identifierar de viktigaste orsakerna till icke-värdeskapande tid på både uppgifts- och skiftnivå, samt jämförde den teoretiska produktionskapaciteten med den verkliga för CNC-maskinerna. Underhållsprestandan utvärderas med hjälp av nyckelindikatorer, inklusive medelfel till fel tid, medeltid för reparation, medeltid mellan fel och medel nedtid.

Baserat på resultaten utvecklas en kapacitetsprognosmodell för fallföretaget, som möjliggör uppskattning av framtida produktionsvolymerna genom justering av parametrar relaterade till maskinernas tillförlitlighet, processtider och driftsscheman. Praktiska rekommendationer ges för att förbättra underhållsstrategin, optimera verktygsbyten, minska icke-värdeskapande processtid och stödja investeringsbeslut för framtida kapacitetsutbyggnad. Förslag till framtida forskning och studiens begränsningar diskuteras också.

KEYWORDS: Ramfräsning, Produktionseffektivitet, Kostnadsanalyser, Lean produktion, Lågspänningsmotor, Total kostnad för ägandet

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Abbreviations

ABC	Activity-Based Costing
AC	Alternating Current
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CBM	Condition-Base Maintenance
CCR	Capacity Cost Rate
CNC	Computer Numerical Control
ERP	Enterprise Resource Planning
EU	European Union
IEC	International Electrotechnical Commission
IoT	Internet of Things
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Life Cyclew Analysis
LCC	Life Cycle Costing
LV	Low Voltage
MDT	Mean Down Time
MQL	Minimum Quantity Lubrication
MTBF	Mean Time Between Failures
MTTF	Mean Time to Failure
MTTR	Mean Time To Repair
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
PDM	Predictive Maintenance
PLC	Programmable Logic Controller
QR	Quick Response
RCM	Reliability Centred Maintenance
TCO	Total Cost of Ownership
TDABC	Time-Driven Activity-Based Costing
TES	Technical Equipment Specification
TPM	Total Productive Maintenance

1 Introduction

The manufacturing sector changes continuously, creating both opportunities and challenges for industrial manufacturing. A wide range of manufacturing organisations rely on machining operations to manufacture their products (Huda, 2018). Furthermore, the machining is one of the eight basic manufacturing processes used. The challenges for companies in this era are energy costs, machine efficiency, carbon emissions and production efficiency. To stay competitive in the industry, improvements and investments must be deeply analysed before actions (de Almeida et al., 2014). The low voltage motors are used in a wide sector and are ideal for water industries, agriculture, HVAC, general machinery and marine. They can also be used in OEM applications like pumps, compressors, and fans (ABB, 2025). In 2024, the electric motor market is estimated to be around 130 billion euros, and it is projected to be at 190 billion euros. Electric motors in industrial use consume 35-40% of the electricity generated worldwide. By far, electric motors are the most important load in industry, and account for 70% of industrial electricity consumption (Data Bridge Market Research, 2024). In 2023, several European manufacturers reported significant energy cost reductions when replacing old conventional motors with new, highly efficient, low-voltage motors that are designed to meet EU energy standards.

Due to demand increases, manufacturing systems and processes are getting more and more complex. The demand causes the users to fail to analyse and monitor the current system's status since the data is spread over different hierarchies and different computer subsystems (Windmann et al., 2015). Also, the increasing complexity of manufacturing processes and the increasingly growing amount of data can lead to an overload for the user with respect to process monitoring, data analysis and fault detection.

The CNC machining process is a widely used manufacturing process that automates the production of precision components, often used in industries such as automotive, aerospace, and medical devices. Reaching sustainable operations in CNC machining involves the use of efficient processes in the manufacturing of precision components. Sustainable CNC machining operations enable benefits for the environment but can also reduce costs and improve competitiveness in a world that focuses on sustainability (Soori et al., 2024).

As electric motors are made from heavy and dense metallic commodities such as iron and aluminium, this causes significant energy consumption and shipping costs across overseas supply chains. Companies must aim for improvements in electric motor design and production because it has a big impact on global manufacturing and supply chains (Ferreira et al., 2020). More than 70% of manufacturing businesses in the US and the UK rely on CNC machines as a part of their production capacity (Newman & Nassehi, 2007). Furthermore, because of globalisation, the manufacturing industry is under hard pressure to increase competitiveness. To be able to maintain the demand and compete with the design of flexible and robust production systems, it is important to provide operational success. The challenges cause manufacturers to improve the performance of their production systems to reduce production costs. This is the increasing cost competition as the products grow into the phase of the product life cycle.

Despite the growing literature on CNC-machining, energy efficiency, and optimizations in manufacturing, there is limited research on the specific context of machining analyzes on electric motor frame production. The already existing contexts focus on other high-volume industries, such as automotive, where the CNC-machining processes differ from the electric motor frame manufacturing processes. This thesis aims to fill this gap by providing a comprehensive analysis of CNC-machining for Company x.

1.1 Background

The background of the project comes from the production development team at Company x. As the demand for electric motors increases continuously according to (Data Bridge Market Research, 2024), the demand for motor frames increases, which causes challenges for the company in the frame machining efficiency, capacity and costs at the factory with the current CNC machines and processes. How can they manage to handle larger volumes in the future with the current setup? Currently, the two CNC machines' theoretical production volumes are not known, and predictions estimate that the demand exceeds current capacity. This thesis was then initiated to analyse the operation costs, machining capacities, and manufacturing processes of the two CNC machines.

This thesis was then created to explain the current capacities, costs and manufacturing process and where improvements could be made.

1.2 Problem statement and limitations

Company x faces current inefficiencies within the CNC machining process.

The main problem for the thesis is the lack of CNC frame machining performance. Currently, data on machine costs, energy consumption, downtime, and efficiency exists but is stored in separate systems, and has not been collected for analysis. This makes it difficult for the engineering team to identify inefficiencies, compare machine performance, or make investment decisions to increase capacity.

The research is constrained to two machines in the manufacturing process: one machine from the year 1992, called 120-1, one in the research and one machine from 2007, called 120-4, in the work. The analysis covers data from the years 2024–2026, and is limited to the specific frame types machined during those years. The findings are specific to the case company context and may not be directly generalizable to other manufacturing environments. Quality-related data, such as broken frames and rework, were not available for each machine and are therefore excluded from the OEE calculations.

1.3 Research purpose

By analysing the machining efficiency of the frames at two machines, such as costs, time and energy consumption, the research aims to map the weaknesses in the process to see where improvements can be made. While machine efficiency has been studied before, limited research exists on CNC-machining in production and specifically on electric motor frame machining in a manufacturing environment. This thesis addresses that gap by applying established manufacturing efficiency frameworks into this study. The purpose of the thesis is to show for the case company what the current efficiency of the machines is, what they should expect from them in the future and also to support them

with cost models in decision-making for new machines and for the increasing demand of electric motors, which will limit the current factory CNC-machining capacity.

To complete the work, the following research questions have been formed with 1 main question and then 3 supporting questions:

- How can frame machining for Company x be optimized in terms of cost and production capacity?

The supporting questions are:

- RQ1: *What are the main costs in CNC-machining of frames? How do maintenance, energy consumption, cutting liquid, and tool wear contribute to the cost per machined frame?*
- RQ2: *How do machine availability, downtime, and maintenance operations impact the production capacity of CNC-machining of frames?*
- RQ3: *What are the key factors affecting theoretical versus actual production capacity, and how can frame machining be optimised for future demand?*

The research questions above are presented in Chapter 5, and conclusions are made in Chapter 6.

1.4 Thesis structure

The thesis is divided into 6 main chapters: Introduction, Literature Review, Methodology, Current CNC-machining process, Results, Discussion, and Conclusion. The introduction leads the reader into the case study topic and presents the purpose of this study. The second chapter describes the literature used to complete the research and to reach the best possible results and conclusions. The third chapter describes the research methodology used for the study, which is a case study with a quantitative approach. Fourth chapter describes the current process of CNC-machining at the case company to let the reader get a better understanding of CNC-machining. The fifth chapter analysis the results and answers the research questions for the thesis, and then sixth chapter discuss the results and gives a conclusion, and suggest future analysis on the topic and case company actions after findings.

1.5 Company description

This section was hidden due to confidential information about the company. In this public version the company is referred as Company X. Also, images are hidden that show information about the company.

2 Literature Review

The purpose of this chapter is to provide information about industry, technologies, and cost analysis methods. Starting with the low voltage motor industry, electric motor manufacturing, continuing with a description of CNC machines and machining process, and maintenance of them. Furthermore, an overview of different cost analysis methods that are relevant for manufacturing cost analysis in the environment is provided.

2.1 Low Voltage Motor Industry

The low-voltage motor market witnesses a fast growth due to the need for energy-efficient, cost-effective, and reliable motor solutions that are reliable in commercial, industrial, and residential sectors. As an example, in 2023, several European manufacturers reported significant energy cost reductions when replacing old conventional motors with new, highly efficient, low-voltage motors that are designed to meet EU energy standards (Data Bridge Market Research, 2024). The rapid electrification of ground vehicles, aerospace, marine and other transportation systems has made a significant increase in the demand for electric motors. Especially, there has been a significant increase in demand for electric motors in specialised applications such as robotics and biomedical systems. In the last decade, product development in the manufacturing environment has had a central role in meeting the challenges of global competition. To survive in the international market, manufacturing companies must strategically examine customer needs and values in all their served market segments. The increase in complexity and costs of new products cause an increased importance on different cost analysis, (Chen & Keys, 2009). LV motors have become common products, where many companies are able to offer similar products, which reduce prices and profits. At the same time, governments are creating strict energy efficiency rules. For example, the European Union's Ecodesign laws require motors to meet high efficiency levels, which are IE3 and IE4 (European Commission, 2019). Building better motors causes the costs to increase as they need more exact manufacturing or finer materials. This sets companies in an uncomfortable position where they must invest in upgrades to meet the new laws, but the prices must also stay

low to compete. Therefore, a deep analysis of each production stage, like machining an electric motor's metal frame, is critical. Finding ways to cut waste and improve efficiency at this stage is one of the few ways to protect a company's small profits (Ferreira et al., 2020).

2.1.1 Electric Motors

An electric motor converts electrical energy into mechanical motion. They operate on the principles of electromagnetism. As the electricity flows through the motor's windings, it creates a magnetic field in the motor, which creates a mechanical force that is applied to the rotor shaft inside the motor. The motor rotates the output shaft, which is connected to a load. The motors can be powered by an alternating current (AC) power source or by a direct current (DC) power source (IBT Industrial Solutions, 2026). The AC motors are divided into two categories: asynchronous AC motors and Synchronous AC motors. The DC motors are classified into Brushed DC motors and brushless motors. The basic components of an electric motor are the rotor, stator, stator armature windings, carbon brushes, commutator, and frame. In Images 1 and 2(hidden) below, a picture of Company x cast-iron frame can be seen.



Image 1. Cast-iron frame

2.1.2 Manufacturing

Manufacturing is an organised activity that transforms raw materials into marketable goods. In economic terminology, marketable goods are known as economic goods. Manufacturing processes convert unfinished materials into finished products, often using machine tools. Examples are injection, moulding, die casting, progressive stamping, milling, painting, assembling, and testing (DeGarmo et al., 1997, p. 10). The industry is also called the secondary industry as it is in the sector of the country's economy that needs processed raw materials from suppliers in primary industries like forestry, mining, and the extraction of minerals. Usually, the manufacturing process contains a series of steps that are value-adding manufacturing processes to convert raw materials into finished products. An example is a piece of metal that is machined into parts, iron is melted and converted into castings, and at the end of the process, they are assembled into a product.

2.2 CNC machining in the manufacturing industry

The first NC (numerical control) machine was developed back in 1950, and after that computer numerically controlled (CNC) technology has had a heavy effect on manufacturing growth all over the world (Newman et al., 2008). Word CNC stands for Computer Numerical Control, and refers to a computer or controller that drives machine tools. Usually, a CNC machine system consists of a number of parts, like a CNC machining centre, an automated material handling system, unloading and loading stations, tool storage, and other equipment needed for operation. The definition of CNC manufacturing is the combination of machining and supporting activities with multifunctional machine tools, that enables both subtracting and additive processes in converting raw materials into completed products. Furthermore, the machining centres can perform turning, boring, drilling, milling, broaching, shaping, and planning and their method can be highly automated to increase efficiency and productivity. They are commonly used in mass or high-volume productions, as example a workpiece, such as an engine block for a car, is moved

from one station to another where specific machining operations are performed at each station, and after that, it is transferred to the next machine. However, there are situations when the types of products change rapidly due to product demand or changes in style or shape. In those kinds of cases, transfer lines are not economical. In the Figure 1 below, a machining centre is seen. On the left side in the figure, the tool storage is located with the tools. If the machine has a horizontal spindle equipped with an automatic tool changer, then the tool magazine can store up to 100 different cutting tools, depending on the design.

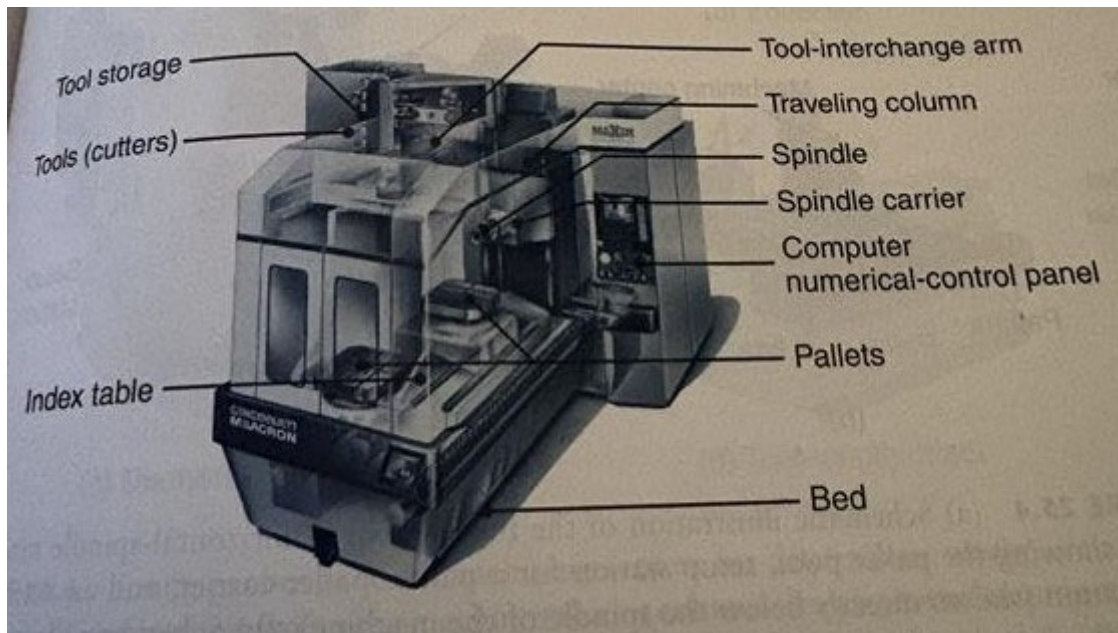


Figure 1. CNC-Machine, (Kalpakjian & Schmid, 2014, p. 705)

On the bottom left side, the index table can be seen, which moves around the pallet or trailer and keeps it in place. On the right side, from top, the tool-interchange arm brings the tools to a tool change arm under the machining process, the spindle keeps the tools in place and rotates with different speeds according to the programming. The travelling column moves the spindle forward, backwards, and up or down, and the spindle carrier keeps the spindle in place. The control panel is always located outside of the machine, as no one can be inside a machine under operation. The bed is where the cooling and the cutting liquid are recycled or collected to go into the machine again to be used under the continuous machining process.

In the machining center figure (see Figure 2), the detailed view of the tool-exchange arm was not visible. The arm swings around to pick up a particular tool and place it in the spindle. All of the tools in the machine have their own toolholder, which makes it highly efficient to attach them to the spindle under process or keep the new tool in one arm end while removing the other tool. The tools are identified by bar codes, QR codes, or tags connected to the tool holders.

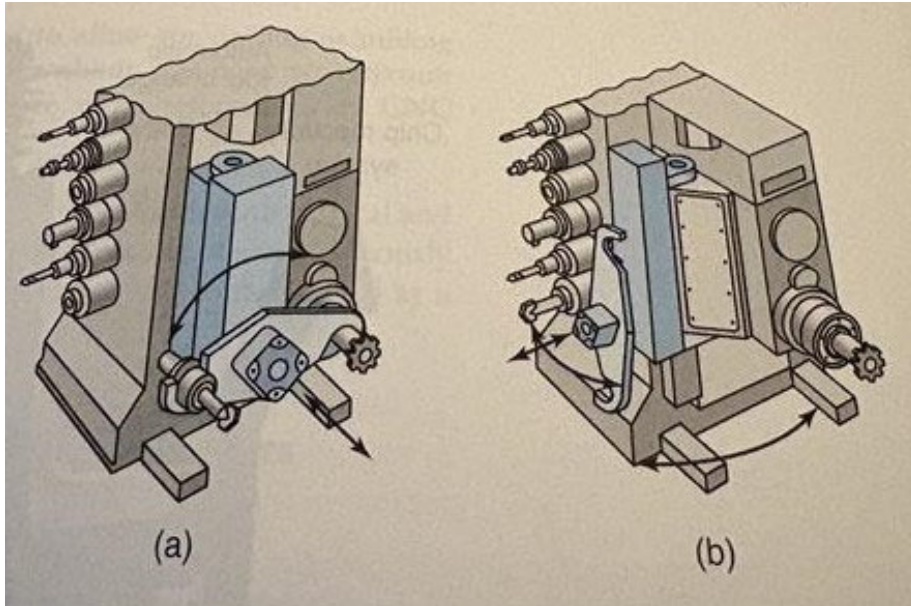


Figure 2. Automatic tool storage,(Kalpakjian & Schmid, 2014, p. 707)

More than 70% of manufacturing businesses in the US and the UK rely on CNC machines as a part of their production capacity (Newman & Nassehi, 2007).

The rotating head motion at the tool and a linear feeding motion on the object. The method is one of the most universal methods in the chip-removing machining sector, which enables the production of surfaces with varying surfaces. Furthermore, milling enables high precision manufacturing of surface smoothness, care, and flexibility. The milling process is known for the tool blades that touch the machined piece to remove material from it. Depending on the materials, the rotation speed is different, as the case focuses on cast iron, the specifications of milling cast iron are 0.1 – 0.2 mm/rotation and a cutting speed of 120 – 760 m/min, for another tool it can have 0.08 – 0.38mm/rotation and a cutting speed of 365 - 855. The feed speed mm/min is the tool's feeding speed against the piece (Jarfors et al., 2000, p. 370).

In automated productions, robots carry workpieces or cutting tools to the CNC workstations. At the loading and unloading station, all parts are clamped on a fixture which is mounted on a trailer or a vice. The part is then processed into the machine on the trailer. The machine moves in X, Z, and Y directions, so the zero point must be marked in relation to the three directions. In CNC machines, there are more opportunities for the zero point; it can be placed in the middle of the object or at the edges. The zero point also depends on how the piece is attached to the trailer or vice versa. Under the machining, many tools can be used, so during the process, tools have to be changed. Depending on the model, the change is done in different ways; in some machines, the operator changes the tool manually and attaches it with pneumatic pressure. In other machines, the process is automated, which means the machine stores the tools in the tool storage and changes them during the process.

As the CNC operation is completed, the part is removed at the unloading and loading station. The capability in the processes depends on the elements functioning correctly (Vichare, 2009). The CNC resources in the manufacturing companies are vital for making economic and efficient decisions in manufacturing. The decisions depend on the information about the manufacturing resources that CNC machines can provide. It is a fundamental basis for the production activities, including resource allocation and process planning.

Usually, the designer uses a Computer Aided Design or Computer Aided Manufacturing (CAD/CAM) program to generate the G-codes for the CNC machine, and then transfers the G-code from the CAM system into the Machine Controller for further use (Khanna, 2013). While CNC machining is widely acknowledged as a key part of modern manufacturing, the implementation efficiency varies depending on machine age and organizational context. Newman and Nassehi (2007) highlight that, despite the wide adoption of CNC technology, with over 70% of UK and US manufacturers rely on it, utilization rates in practice frequently fall well below theoretical capacity. This gap between theoretical and actual performance is more usual in older machine populations, where mechanical limitations, outdated control systems, and reactive maintenance cultures cause reduced

effective output. The study directly addresses this gap in the context of electric motor frame machining, where machines dating from 1992 and 2007 operate within the same layout and production system, which enables a controlled comparison of how machine age affects real-world CNC performance.

Furthermore, it is important noting that the existing CNC machining literature is heavily focused toward high-volume industries such as automotive and aerospace component manufacturing (Soori et al., 2024). These contexts differ fundamentally from electric motor frame machining in several aspects as frame geometries are larger and more variation, batch sizes are smaller relative to setup times, and the surrounding material handling infrastructure used like cranes, elevators, turning machines causes a proportionally larger share of the total cycle time. This mismatch limits the direct transferability of existing CNC optimization studies to the present case and reinforces the need for context-specific analysis.

2.2.1 Tool change in CNC machining

In CNC machining, productivity is calculated with the following equation: total cycle time equals the sum of machining time and non-productive time. In the machining process, cutting parameters are optimised, but the non-productive time consumed by the Automatic Tool Change (ATC) cycle remains the same and depends on the manufacturer's speed. Because the activities must be done to create the specific needs for the customer, it is important to optimise the changes and tool changes, and also the time it takes. Tool change effectiveness has an impact on machining speed in total, (Groover, 2020). A study that analysed CNC machining efficiency concluded that non-cutting activities, tool changes and workpiece handling can consume 15 - 30% of the total available time. Which underscores that reducing tool change time T_{ch} improves the overall equipment effectiveness (OEE) (Kumar et al., 2021). Tool changes and other changes in a machine can sometimes lead to losses.

2.2.2 Energy consumption in CNC machining

CNC machining in manufacturing and the processes involved use large amounts of energy, and the results of the impact on the environment can be measured. By reducing the consumption of energy in machine tools will make a significant improvement in the environmental performance of manufacturing systems and processes. Environmental studies for machined tools used in part manufacturing with milling shows that more than 99% of the impacts on the environment are due to the consumption of electrical energy, (Camposeco-Negrete, 2013). Many companies do not consider that machining machines save money and achieve better performance if the energy consumption is reduced, as 2/3 of the electrical energy that is used in the machining industry is for running drives and motors for cutting tools.

To do a comprehensive analysis of the consumption in machining, and especially, the energy used by machine tools during machining is higher than what the chip formation requires in theoretical energy. The specific cutting energy is less than 15% of the total energy consumed by a modern automatic machine tool during operation. Other machining processes may differ from this value; machine “tare” consumption, which is the energy consumed by the machine outside of chip formation, is significant. By studying the energy consumption of machine tools, organisations will get more valuable data that can be applied in the life cycle analysis (LCA) of the manufacturing stage. When the manufacturing supply chains analyse the impact on the environment, the carbon accounting becomes increasingly important, to have an accurate manufacturing energy data, (Vijayaraghavan & Dornfeld, 2010).

Energy consumption in CNC machining can be classified into three primary categories: ready energy, steady energy, and cutting energy (Balogun & Mativenga, 2013). The ready energy refers to auxiliary loads consuming power at specific rates independent of the other processing operations, such as computer panels, lighting systems, and cooling systems. Second, steady energy represents the tool components consumed in the machine during operation, such as motors, drives, pumps, and hydraulic systems. Cutting energy directly relates to material removal processes like drilling and milling.

Pušavec et al. (2009) identify several sustainable manufacturing practices relevant to CNC machining operations. According to ISO 14955-1:2014, energy efficiency is defined as the correlation between resources used and results obtained, representing a measure of manufacturing with reduced energy demand while maintaining high product quality. The trend toward reduced machine mass and increased operational speeds directly influences kinetic energy requirements for motion, with lower mass correlating to decreased energy consumption during operation.

2.3 Manufacturing Cost Analysis in CNC Machining

2.3.1 Machining Economics

When analyzing the economics of machining, many factors must be considered. The factors include the costs for (1) the machine tools, fixtures, work-holding devices, and cutting tools, (2) labor and overhead costs connected to indirect costs, (3) movement and material handling, the loading of the blank and the unloading the machined part (4) the time required to set up the machine for the particular operation, (5) the aim for surface finish and dimensional accuracy, (6) the cutting times and the non-cutting times, (Kalpajian & Schmid, 2014, p. 722). To consider the actual machining time is important, regarding the non-cutting time in high-speed machining. The economic analysis is based on the ability to achieve a predicted outcome, like surface finish and tolerance, which requires that the machining process is of good quality and under control. An example of it is if the cutter on the miller is mounted so the spindle length varies randomly with every tool change, this would cause high tolerances.

2.3.2 Total Cost of Ownership

The Total Cost of Ownership model (TCO) is a cost modelling tool in the supply chain. Ellram (1995) define TCO as a philosophy for understanding relevant costs associated with the purchase and use of a given item or service. In recent years, TCO has been recognised as an important tool for strategic life cycle management of products. The role for model is increasing along the whole lifecycle of the products, by supporting different decisions, both for investments and operational ones. The easiest way to describe it is that the total cost of ownership is typically the total expense involved in acquiring and using a good, service, or material. The method monitors all the additional costs beyond the purchase price that are connected with the life cycle of the purchased service or goods. The several key factors beyond the purchase price factors includes, operational costs, maintenance, tooling, training, and energy consumption (Gowico, 2024).

The TCO helps organisations to understand the long-term financial investment and helps to compare different CNC machine options efficiently. It is essential to consider all the costs associated with the CNC machines to decide on investments. There are 7 important factors to consider: the purchase price of the machine, which depends on the machine size, technology, and capabilities. Second is the installation and setup, which includes transportation, installations, and modifications to fit it into existing facilities. Third factor is the operational costs, which consists of day – to -day expenses like energy consumption, cooling, tooling, and other materials needed for the machine to operate. The fourth cost associated with the TCO is maintenance and repairs, maintenance that keeps the machine running, and unexpected repairs, especially when the warranty is no longer valid. The fifth expense is the training and labour costs for the CNC operations. The second last factor is the software updates for the machines, as they rely on software that requires updates to run and are one of the substantial expenses for the machine's life. Last TCO in CNC machines is the downtime costs, which include unplanned downtime for the machine that causes production losses and order delays.

According to Castellani et al. (2005) a key metric in modern TCO calculations is a given piece of equipment, such as a CNC machine that is in active use, how much time it is idling, and how much of its operational capacity is actually used. Analyzing these factors

can reveal under or over utilization of machines, which is a critical input when determining the optimal number of machines and their placement within a manufacturing organization. The level to the CNC machine is utilized will directly impact the frequency of expected downtime, given that mechanical and electronic components are made to wear and have operational lifespans. Furthermore, high utilization rates also affect the consumption of consumable parts, and the long-term reliability of the machine.

A broad range of activities can be expressed in time. Any activity involving labor can be represented as a share of the relevant employees' salaries. Similarly, machine downtime can be counted in terms of lost productivity and missed output. This dimension is particularly significant in the context of maintenance and repair, as many such calculations explicitly incorporate the cost of downtime as a main parameter.

In a machining equipment life cycle costing model (Bengtsson & Kurdve, 2016), a model was created that focuses on Life Cycle Costing (LCC) and Total Cost of Ownership (TCO) for manufacturing equipment. In the model, they have formed the research question "What are the crucial parameters to include in the model?" The Life Cycle Cost (LCC) model applied to manufacturing equipment can be used in different settings and defined in different ways. It can be used from the viewpoint of equipment users or from the supplier's viewpoint. From the user's viewpoint, LCC and TCO have usually been defined similarly, and both can include not only cost aspects but also LCP, performance and profit aspects. LCC can be separated into two different applications.

The model has identified parameters that focus on the running costs, such as operator and maintenance man time, tools and materials, including spare parts, cost of stopped line and lost production, energy and media use, and waste management, which includes cutting fluids.

2.3.3 Activity-based cost analysis (ABC)

In the 1980s, activity-based cost analyses were developed to fix problems in the traditional costing systems to keep up with rapidly changing technologies and the automated manufacturing, (Saeed et al., 2023). The method serves as an accurate way to determine

the actual expenses. ABC measures the performance and cost of activities, cost objects, and resources. It is another alternative to the traditional cost accounting system.

ABC is figuring out what the outcomes are for a product to be manufactured, or all the things that are done to get a complete product. The costing method is one of the best to enhance operational efficiency and competitiveness within a company. Many researchers have mentioned that the ABC method is a reliable way to determine the cost of products and services (Al Rababah, 2012).

The activity-based costing model uses a systematic approach which involves two steps to find indirect costs to cost objectives. The method is based on how much each activity affects the costs. First, manufacturing costs are divided into the different activities or departments using cost drivers that reflect how much each activity uses of the resources. Next are the costs of the activities allocated to specific products based on how much each activity is used by each service or product. The method can also be used to identify and remove operations that do not add value to the process, which makes the production system more efficient (Al-Halabi & Shaqqour,2018). The Activity Based Costing method uses these types of costs: production costs, fixed costs, variable costs, total cost, direct costs, and indirect costs.

Production costs represent the total amount of the outlays during the manufacturing process of the products, or the execution of a work. The production costs are complex, so it is necessary to use classifications for categories to divide the different expenses into different categories (Belciu & Căpuşneanu, 2010).

Each company must understand the named expenses and decide how to include them in costs. As differences in accounting can impact the overall financial results, and the analytical results overall for an organization. Production costs can be categorised into two types: raw materials expenditures and salaries expenditures. Raw materials expenditures refer to the costs of materials used in production, while salaries expenditures refer to the cost of labour, which includes wages and benefits. When calculating costs, we separate direct expenditures and indirect expenditures. Direct expenditures are directly related to a specific product or service, while indirect expenditures are not directly related but are allocated using specific methods.

Expenses can also be categorised based on the purpose of them, business expenses and activity expenses. Business expenses include costs that are related to company functions such as purchasing, production, and sales. The activity expenses include costs connected to specific business processes. Expenses can also be classified as fixed costs or variable costs, depending on how they behave when allocating costs to business processes. Both categories of expenditure are identified at the process level, considering the destination of the expenditure. The variability of costs depends on factors such as requirements for customers, development period, and complexity.

2.3.4 Time-Driven Activity-Based Costing (TDABC)

Developing the ABC models was often expensive solution, consumed time to maintain, and was hard to update when business processes changed. To solve these problems, Robert S. Kaplan & Steven R. Anderson (2004) introduced the Time-Driven Activity-Based Costing (TDABC) in the early 2000s. The method simplifies the original cost model by using time as a primary cost driver. Furthermore, the framework is built on two fundamental poles, which are described in the literature (Kaplan & Anderson, 2004).

The Capacity Cost Rate (CCR), first pole is calculated by dividing the total costs of a supplying resource (machine, department) by its time available for work (the practical capacity of it). The practical capacity is usually estimated to be 80 – 85% of the theoretical capacity, including unplanned downtime, breaks, and training (Kaplan & Anderson, 2007).

The Time Equation is the head improvement for modelling process complexity. Instead of having separate activities for every variation in the production process, like in the ABC model, TDABC uses a linear time equation. Kaplan & Anderson's (2004) equation explains the estimated time required to perform a specific activity.

2.4 Production efficiency

2.4.1 Lean manufacturing

Lean manufacturing can refer to a continuous improvement philosophy that is like the Toyota Production System or Kaizen. The concept was developed to increase resource utilisation by minimising waste in the process. It was spread after Japan's defeat in World War II, as it was first introduced in the Japanese car industry after World War II, since their resources, technical human power, and money were poor. At the Toyota Automotive company, Eiji Toyota and Taiichi Ohno came up with the Toyota Production System, which today is Lean Manufacturing (Kumar et al., 2022). The Lean Management process aims to achieve high quality, safety, and shorten lead times. It is a methodology that is employed by organisations to reduce waste in the manufacturing processes. To decrease waste in industries, they must first identify all hidden wastes to minimize them. To compete in the industry, one of the main tools is to integrate lean manufacturing to reduce costs, while maintaining quality, eliminating waste generations, and satisfying customers. (Ohno, 1988, p. 19) classified the wastes into seven categories, which are:

1. Overproduction

Overproduction is known as one of the main forms of waste in lean manufacturing. It occurs when the volume of production exceeds the actual demand from customers, which results in goods that consume companies' resources without generating any value. Manufacturing products in advance of or in excess of demand leads to significant wastage of financial resources, time, and storage space. Furthermore, overproduction is considered particularly problematic as it has the tendency to trigger other forms of waste within the production system, which makes it a primary target for elimination in lean manufacturing processes.

2. Waiting

Waiting in the method represents a form of waste that underlines production efficiency. Empirical studies suggest that approximately 99% of a product's total time in the manufacturing process is consumed by waiting, encompassing delays associated with orders,

plans, jobs, machine accessories, and communications. This type of waste shows when one process remains idle while awaiting the completion of another, which disrupts the smooth and continuous flow of operations. The effect of waiting wastes production processes and causes significant inefficiencies in the whole manufacturing system, highlighting the importance of synchronising production activities to maintain workflow without interrupting it.

3. Transportation

Transportation waste refers to all the unnecessary movement of materials, tools, machine parts, and accessories between different workplaces within the manufacturing facility. The type of movements is classified as non-value-added activities, as they consume both time and financial resources without contributing to the enhancement of the product's value. The usual transportation waste is frequently caused by poor facility layout and inefficient production planning, both of which cause extra material handling. Addressing transportation waste is essential not only for reducing operational costs but also for improving overall production flow and efficiency within lean manufacturing environments.

4. Over-Processing

Over-processing waste is defined as performing more work, or applying higher precision than what is actually required by the customers. It is represented by a misalignment between production activities and the customer requirements. This form of waste generates additional inefficiencies in terms of labour, raw material consumption, asset utilisation, and processing time, all of which contribute to increased operational costs without delivering customer value again. Background for over-processing often comes from a lack of clear understanding of customer specifications or from the application of complicated and unnecessary processes, instead of seeing the importance of aligning production activities with customer needs in lean manufacturing.

5. Excessive inventory waste

Excessive inventory waste refers to the inventory that remains untouched while awaiting use within the production process. The presence of excessive storage or inventory ties up valuable capital, increasing the storage costs. Moreover, high inventory levels are

widely acknowledged in the lean manufacturing literature as a mechanism that causes production problems and inefficiencies, such as machine breakdowns and quality defects, thereby preventing companies from identifying and addressing root causes of waste within their systems.

6. Defects

The sixth category in lean management is defects, which represent a critical category of waste in lean manufacturing. It focuses on any aspect of production that results in products failing to meet established quality standards. The consequence of defects goes beyond immediate production costs, as they will contribute to poor product quality, customer dissatisfaction, and a decline in market value and brand reliability, which could also result in reduced sales and product pricing problems.

7. Unnecessary Motion

The Unnecessary Motion Waste category analyses any movement of individuals or equipment that does not contribute value to the product or operation being done. This form of waste is closely associated with ergonomic inefficiencies and workplace design. Key causes of the motion waste include poor workstation layout that necessitates excessive walking, bending, and reaching; inefficient method design that requires the unnecessary transfer of parts between hands; large batch sizes that demand excessive handling; and the reorientation of materials during the production process. Addressing unnecessary motion waste requires careful attention to workplace planning and ergonomic design, ensuring that workstations are organised in a manner that minimises non-value-added movements and promotes efficient, streamlined production activities.

As the seven different impacts have been identified in lean manufacturing, they can be further divided into value-added, non-value-added, and non-value-added but necessary activities. These required actions must be done, but they do not necessarily add value for the customer. Most common activities are those required by the government or law. However, the non-value adding tasks can be optimised and eliminated to reduce the time and cost for each activity.

2.4.2 Overall Equipment Efficiency (OEE)

To succeed in the global manufacturing competition today, companies need to operate at a high level of efficiency. In manufacturing industries globally, a common tool to measure performance is Overall Equipment Efficiency (OEE). Many challenges are associated with OEE implementation to monitor and manage manufacturing performance, (Anderson & Bellgran, 2015). One of the most crucial applied tools of performance measurement in manufacturing is the OEE. The OEE detects the hidden costs that are associated with the equipment and efficiency. The definition of the OEE is a measure of total equipment performance. Comparing the current and expected OEE measurements can provide important information for the manufacturing organisations to improve the maintenance, which contributes to continuous improvements in the manufacturing system. Typically, manufacturing companies operate in the OEE around 60-65%, but a world-class OEE is at 85% or better. In Figure 3 below, the different levels of OEE can be seen.

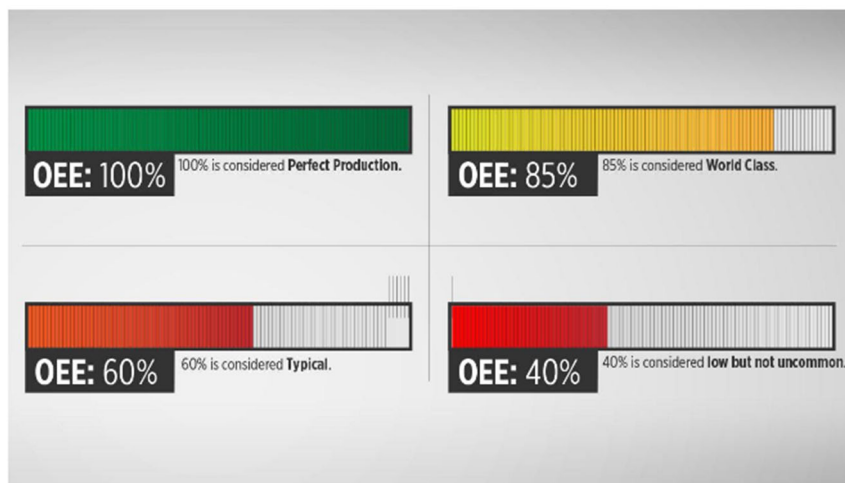


Figure 3. OEE (Reliableplant, 2026)

There are variations in calculations of OEE, but most identify three main elements, which are availability, performance efficiency, and quality rate. In recent publications, arguments are saying that OEE figures are commonly 15 – 25% below the target level, which makes it one of the most significant challenges faced by industries today.

An analysis with OEE provides details of the production system's improvement opportunities. Furthermore, it detects how well the production system's performance is relative to the designed capacity during the operating time (Tsarouhas, 2019).

A central parameter in the process is the availability of machines. The higher the degree of availability, the more available resources machines have, which provides a more sustainable production. The availability can be calculated in many ways, but the availability of equipment tells us how often it is ready to be used and is affected by the time it cannot operate or work (Ståhl et al., 2012).

2.4.3 SMED Single Minute Exchange of Die

In the competitive market, to survive, the industrial units must reduce costs and produce quality products. The best way to achieve it is to improve production processes by minimising downtime and achieving objectives. To reach this goal, one of the best models is Lean manufacturing (Godina et al., 2018). The idea is to increase competitiveness by reducing costs. The optimal value is to only spend the amount that adds value to the final product. By using these targets, Lean manufacturing removes all the possible waste in the process. One of the building stones in lean manufacturing focuses on rapid setup, which means the faster the setup time, the less downtime arises. To reach waste reduction, lean manufacturing uses the tool SMED, which stands for "Single Minute Exchange of Die", which means quick tool change with other words. The tool helps companies to improve the continuous interruptions in processes, which have been proved to be an obstacle in efficient manufacturing. A quick tool changeover is when the machine is switched from making one product to making another. The changeover time is how long it takes to make the switch, from the last product of the first batch to the first product of the next batch. The fastest process is the one that achieves the five goals in every phase of rapid tool change: fixing the tool, positioning, and transporting. The method SMED helps make tool changes faster and more efficiently. SMED the goal is to do the tool changes under 10 minutes. This is achieved by making tasks simple and making the process more efficient. SMED offers a calculation solution, which shows which of the quick tool change processes has the highest return on investment. In this thesis, the SMED method is applied in Section 5.2.4, where automatic tool change times at both

machines are measured and compared to identify the primary source of non-cutting time during the machining cycle of frame.

2.4.4 Production Capacity Planning

Planning manufacturing capacity is one of the most complicated tasks that organisations have to do in manufacturing industries, as it plays a critical role in their performance, and has an impact on the strategic planning on operational levels. Usually, the capacity in manufacturing depends on the employees' skills and the number of workers, but in machining, the capacity depends on the machines. It is easier to do capacity planning for machines than for humans, as it is more unpredictable and fluctuates more (Teerasoponpong & Sopadang, 2021).

2.5 Maintenance in manufacturing

Maintenance has an impact on business performance in terms of productivity and profitability to increase. One day's unplanned stoppage will not be recovered without additional costs like overtime work. A failure in the manufacturing equipment results in losses of productivity, but also a loss in timely service to company customers. Furthermore, it can also lead to safety and environmental problems that can destroy the company's image for new customers or existing ones. Maintenance has traditionally been considered a necessary tool, but in fact, maintenance is a profit centre rather than an unavoidable and unpredictable expense (Alsyof, 2007). The right maintenance strategies in manufacturing industries play a key role in continuously being able to produce products, to compete with other manufacturers, on-time delivery of products, keeping down costs and maintaining a good reputation among customers. In the analysis of frame machining, the direct costs of tooling, labour, and material are often the focus, but when doing deeper research, maintenance is also a central strategic cost driver. Efficient maintenance management, preventive, and Total Productive Maintenance, makes

an impact on machine availability, product quality, and overall lifecycle cost (Runge et al., 2018). Normal types of maintenance strategies are Breakdown or Corrective or Run to failure maintenance, second one is Preventive maintenance, third Planned maintenance, fourth Proactive maintenance, fifth Condition-based maintenance, sixth Reliability Centred maintenance, and seventh Design-out maintenance (Vishnu & Regikumar, 2016). In Benhanifia et al.'s (2025) research paper, they identified four main maintenance strategies:

1. Corrective maintenance or reactive maintenance is an approach where equipment is only repaired or replaced when it has already broke down. This method needs little or no advance planning, and costs are low, but it frequently causes unpredictable downtime and higher costs over the long term.
2. Preventive maintenance (PM) is done on a fixed schedule, where equipment is maintained regularly regardless of the current condition. This approach helps lower the risk of unexpected failures through routine check-ups. But it can sometimes lead to unnecessary repairs and waste resources both in time and spare part costs when maintenance is carried out before it is needed. To handle the unpredictability failures of the machine equipment, Preventive Maintenance (PM) is used. PM is a time or usage strategy that involves scheduled inspections, servicing, replacing parts, and calibrations designed to prevent failures and downtime (Moblely, 2014). But according to (Vishnu & Regikumar, 2016), PM is old, and research has shown that less than 20% of all components fail before the actual described period, causing relatively high costs involved in implementing Preventive Maintenance.
3. Condition-Based Maintenance (CBM) use a more data-driven approach by utilising real-time information collected from sensors to see the current state of the machine. Instead of following a fixed schedule, maintenance is only performed when the data shows that it is necessary for machines. It reduces unnecessary

maintenance. Despite the advantages, the method requires expensive monitoring infrastructure and may cause disruptions in operations due to its reactive nature.

4. Predictive Maintenance (PDM) builds upon the principles of CBM but integrates advanced technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT) to predict potential equipment failures before they actually happen. But implementing this approach typically comes with higher investment costs and more complexity.

There are two basic strategies in doing plant maintenance: Corrective maintenance and Preventive maintenance. But, depending on how the basic strategies are applied, five more sub-strategies can be distinguished: Failure-Based maintenance, Design-Out Maintenance, Use-Based Maintenance, Condition-Based maintenance and Detection-Based Maintenance (Vishnu & Regikumar, 2016). The financial background of PM is that the planned cost of the operations is lower than the costs of an unexpected breakdown, including all other consequences for production, such as missing deadlines. Usually, it is worth doing, but it also involves specialist costs to perform the work. In an economic view, running to failure is preferred, but in those cases, the production can't rely on those machines or only one machine. But to have proper maintenance at plants, a combined method of Reliability Centred Maintenance (RCM) was introduced, but it remains unimplemented in many plants still because of well-handled methodologies and tools.

A well-known and widespread concept of improving production performance is TPM, one of the most widely used lean tools, founded by Nakajima. Nakajima wrote, "TPM is a production-driven improvement methodology that is designed to optimise equipment reliability and ensure efficient management of plant assets through the use of employee involvement, linking manufacturing, maintenance and engineering". The TPM has 6 main pillars that it prevents, which are breakdowns, setup/adjustments, idling/minor stops, reduced speed, process defects, and reduced yield (Nakajima, 1988).

Overall Equipment Effectiveness (OEE) is also an important measure within the concept of TPM. The OEE measure is traditionally used by organizations as an operational measure to monitor production performance, but it can also be used as an indicator for process improvement activities in different production context, (Andersson & Bellgran, 2015). Idling and system stops are moments when no products are produced, examples are when the operator waits, the repairer waits, small stops and a lack of precision in measuring devices. Direct system losses are divided into two groups: direct and indirect. Direct stops hit larger areas, like an area of a factory. Examples can be conveyor systems or other transportation methods, computer systems, storage failure, cutting liquids filters clogged, or greasing systems and metal chip conveyors, which are all involved in a CNC machining machine. Indirect stops are affecting the line before the specific process step.

2.5.1 Maintenance Key Performance Indicators

In evolving manufacturing maintenance, there are key performance indicators (KPI) such as Mean Time to Failure (MTTF), Mean Time to Repair (MTTR), and Mean Time Between Failure (MTBF) tools to evaluate maintenance performance and impact on machines (Vejjanugraha & Pawasarn, 2025). Mean Time to Failure (MTTF) measures system reliability (Mili & Sheldon, 2009), while MTTR represent the efficiency of taking actions and repairing a machine or system to restore its functions. Vejjanugraha & Pawasarn (2025) saw a pattern for organisations' MTBF, that they underestimate the reliability in the machines when doing Preventive Maintenance, especially for the systems with increasing faults. The study established higher and lower bounds for MTBF.

3 Methodology

The approach used for the research is a case study with a quantitative approach.

The methods used for data collection are presented in this chapter. For the case study, the LV motors frame sizes xxx (hidden) is measured and compared for machine A (120-1) and machine B (120-4). The method included semi-structured interviews with production workers, production supervisor and managers. Furthermore, meetings were held with supervisors from the company to reach the best possible results.

The project was executed in the following order:

- Kick off meeting with supervisors from work
- Literature review of the project
- Continuous update meetings with supervisors from work
- Research proposal presentation
- Follow the CNC-machining process at the factory
- Conduct research
- Presentation of the results for the company supervisors
- Final research presentation

3.1 Case study approach

A case study is a comprehensive research approach that examines a specific system, program, or project in a real-world setting and analyses it from multiple angles. By investigating the "why" and "how" behind a particular phenomenon in case studies, they develop new theories and ideas, (Flyvbjerg, 2006).

The thesis is completed based on a case study research strategy with a quantitative approach. The research questions were developed in collaboration with the Company x supervisors in the production development team, reflecting real operational challenges faced in production. This is essential with the action research and case study tradition, where case study supervisors co-define the research agenda (Yin, 2018). To execute the project and to be able to answer the objectives and research questions, data have been

gathered and analysed. Table 1 below shows the methods used to collect the data for the study.

Table 1. Data collection methods

Data collection	Title	Method	Purpose
Observations	Author		Observation of CNC-machining production processes to understand production process data
Interview	CNC-Machine operator	In person interview	Simple questions regarding production process steps observed
Collect data	Production Manager	Email	Collect time data for frames CNC-machining processes
Interview	Production Manager	In person interview	Understand the conducted data for frame machining
Collect data	Maintenance Manager	In person	Collect yearly maintenance costs for machines, done by a CNC machine manufacturer
Collect data	CNC-Coder 1	In person	Collect Excel files with data for machine production overhead costs (cutting liquid, machine tools) and operator work hours
Interview & collect data	CNC-machine supervisor	In person interview	Understand the operator's salary and frame production bonuses from The system collects Excel files. with bonus systems
Interview	Production Manager	In person interview	ERP-system functions and where to find production prices for frames in system
Collect data	Thesis supervisor from the CASE COMPANY	In person	Collect energy consumption data for machines in Excel files
Meetings	Thesis supervisors from Productio Development Engineering team	In person	To give updates on the thesis, Reform the research questions. According to the case, the company needs

The data used for the research can be divided into 3 categories: supporting literature, semi-structured interviews, and all the data collected from the Company x systems. It focuses on the current manufacturing process's capacity, efficiency, and costs.

3.1.1 Quantitative research approach

The basic characteristics of quantitative research are the use of statistics and mathematics to analyse numerical data. Statistics are used when you need to analyse and process large volumes of quantitative data to test theories and verify hypotheses. It is also often used when there is uncertainty related to the theories under consideration. The research method can be effectively conducted with questionnaires that contain simple questions and short answers. In the end, the data obtained can be quantified and compared easily. The type of research is connected with experiments and involves the investigation of phenomena. It often uses questionnaires with questions that are closed questions, and they focus on the quantification of relations and features. The process includes the collection, processing, and presentation of quantitative data (Basias & Pollalis, 2018).

The quantitative research base is built on the use of statistical techniques to know certain details of interest in the sample or population under the research (Creswell & Creswell, 2018). The method tries to quantify, measure and grade certain phenomena and their intensity. The goal with quantitative research is to generalise universal results from a sample, within the margins of confidence and error. Both objective factors (like sales targets, profit margins, share prices, product defect rates, and costs) and subjective factors (such as manager and employee opinions) can be considered. To gather information on these factors, various methods are used, including surveys, interviews, measurements, and reports.

In the quantitative study, semi-structured interviews were performed. The semi-structured interviews approach is a data collection method on a framework that is thematic, which means the questions are chosen beforehand, but without an order. This approach enables flexibility and opportunities to ask additional questions. Furthermore, the guide is not a rigid script, but instead a flexible framework that allows natural conversation. Typically, it includes open-ended questions and follow-up probes to explore the topics deeper (Adeoye-Olatunde & Olenik, 2021).

3.1.2 Interviews and observations

In addition to the quantitative data collected from company systems, semi-structured interviews in person were conducted with key workers involved in the CNC machining operations. The interviews included CNC machine operators, CNC-machine supervisor, CNC-coder, and production manager. The interviews were used to gain a practical understanding of the machining process and to verify the data collected from the databases. Direct observations of the operations were also done during January 2026 to become familiar with the production environment and to collect manual measurements of tool change times.

So, becoming familiar with the CNC-machining process at the factory was based on observation and interviews with the machine operators. The author was already familiar with the machines and processes on a basic level, as three years had been spent at a case company in the positions: maintenance mechanic, maintenance manager, and production development engineer during the studies. But to achieve a deeper understanding of the process, observations and interviews were done. The phases were observed from when the motor frames arrive at the factory until they are a finished product from the CNC machines. The interview questions with the CNC-machine operator had a semi-structured framework, and the questions were created before, but not in any order. The operator explained the process that had been observed, which supported the production process times and data.

The other interviews were with white-collar employees, who were production managers and production supervisors for CNC-machining of frames. To understand the collected data correctly, which were large Excel files with times from different frame machining operations, an interview was conducted with the production manager, who could explain all the sheets and data. Furthermore, a short interview was conducted with the CNC-machine supervisor to confirm the manufacturing frame bonuses operators earn and their work hours.

3.1.3 Data collection

The data for the thesis were collected from multiple sources during December 2025 to January 2026. The primary quantitative data was collected from the company's internal Power BI system and maintenance software, which recorded frames machined at each machine, maintenance faults, and maintenance activities. Energy consumption data was obtained from factory energy sensors on the machine. Labor cost data was sourced from the company's ERP system. Tool wear and cutting liquid data were collected from Excel files that CNC coders had stored.

In addition to data stored in databases, manual time measurements were conducted at the machines to record tool change durations at both CNC machines. These manual measurements were necessary because tool change times were not automatically recorded in the machines. The manufacturer could not provide them because the machines were too old, so to collect tool changing times, the author observed the process and then timed 4 different frames and their machining processes at the two machines. The tool changes were analysed with a timer under machining operation and then noted into an Excel file to know what kind of tools were used during the process, the number of tools, and the times noted in seconds to be able to analyse what effect the tool changing time has on the machines and the total machining time of frames. The collection of them caused an ± 0.5 second accuracy as it was done by hand, and the machine was under operation. Table 1 provides an overview of the data collection methods used in this study and the corresponding data types obtained from each source.

3.2 Reliability of Research

A key importance for credible research findings is the proper reliability and validity of the research method. In the context of a master's thesis employing a case study approach with quantitative research methods, reliability determines whether the findings of a study can be trusted, replicated, and generalised beyond the immediate research

context. While validity addresses whether a study measures what it intends to measure, reliability concerns itself with the consistency and stability of measurements across time, instruments, and researchers (Yin, 2018). When data is collected from organisations or companies, reliability becomes even more critical because organisational data is dynamic, context-dependent, and numerous sources of error could appear. In academic research, reliability is closely intertwined with the concept of research quality. Golafshani (2003) writes that reliability and validity are the two most important criterias when evaluating the quality of quantitative research, a study's conclusions cannot be trusted without reliability. The sources of unreliability in quantitative studies, including , sampling errors, and data entry mistakes, require careful attention at every stage of the research process (Creswell & Creswell, 2018). The case study approach is traditionally associated with qualitative research and has increased recognition in quantitative contexts. Yin (2018) defines a case study as an empirical inquiry that investigates a phenomenon in its real-life context, making it particularly appropriate for studying organizational processes and business performance within companies. However, this combination introduces unique reliability challenges, as the data collected is inherently situated within a specific organizational context, raising questions about whether measurement procedures are appropriate for the company under study (Flyvbjerg, 2006).

4 Motor frame machining process

This chapter provides an overview of the current IEC low-voltage motor frame machining process at Company x. It covers the CNC machines used in Section 4.1, the machining process stages in Section 4.2 and the maintenance strategies on both machines in Section 4.3. This current process description forms the basis for the cost, efficiency and lean analysis presented in the results chapter, where the theoretical frameworks introduced in Chapter 2 are applied to the data collected for the work.

The machining process of the motor frame is one of the key manufacturing process stages to a finalised electric motor. The machining process of the frames needs to be accurate, so all the other parts in the assembly stage will fit the frame and become a complete motor. In Figure 4 below, the machining of the frame is marked in red in the supply chain of the frame production at Company x.



Figure 4. CNC-machining location in the supply chain

4.1 CNC-machine description

To understand the data and to be able to do the research, the CNC machine layout and the work positions are marked and described in Figure 5 and Table 2. By drawing the equipment to the layout, an overview of the lean manufacturing is easier to develop as the positions are marked and the times for tasks have been recorded. The case study focuses on the factory's two CNC machines out of six. Machine 120-1 is an older model from 1992, and Machine 120-4 from 2007 is a newer version but with the same kind of setup and layout, whose technical specifications are important for the TCO and machine costs that are analysed with maintenance KPIs from literature. Furthermore, the machines are vertical machining centres, but the frames are put in two positions both vertical and horizontal position as the CNC-machine only moves in x,y, and z direction. In

Figure 5 below the main operation positions in the process have been marked with boxes in different colours. The two machines described are evaluated in Chapter 5.

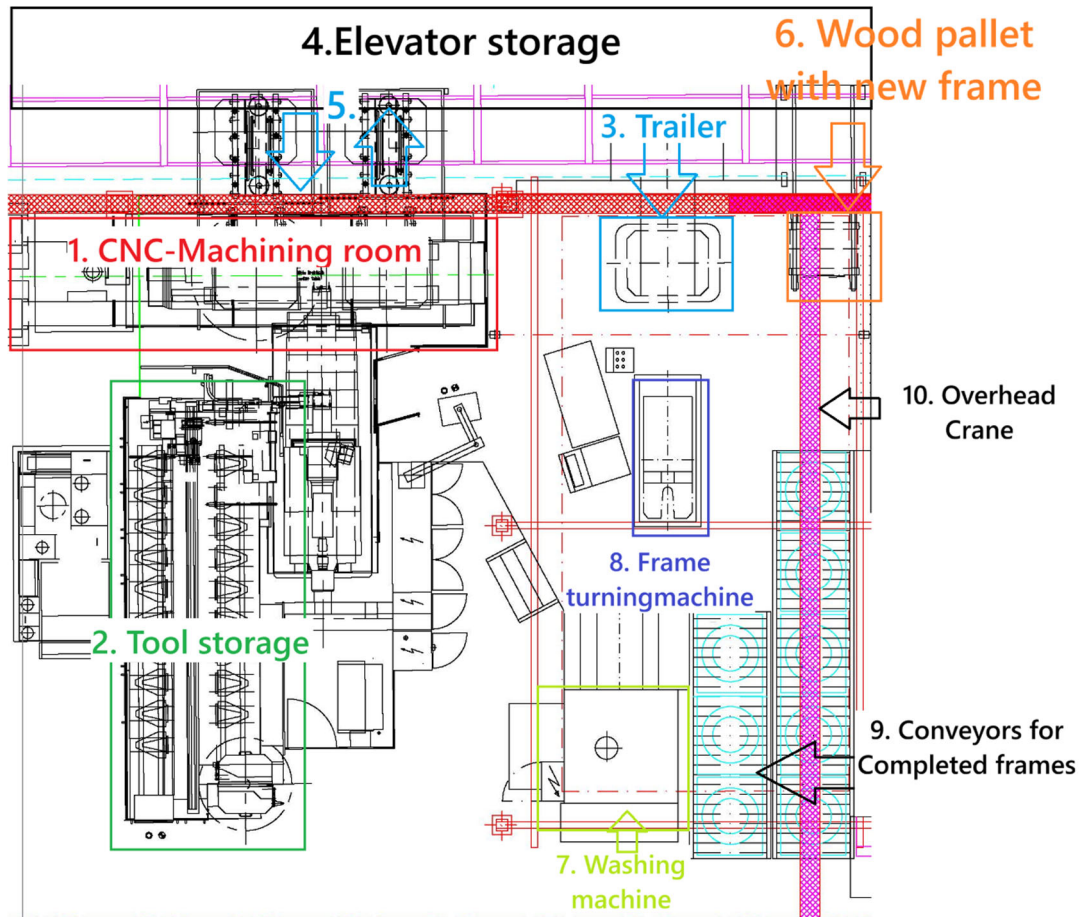


Figure 5. CNC-machine layout

Table 2. CNC-machine layout description table

Number	Position	Task
1	CNC machining room	Where frames are machined
2	Automatic tool storage	Where are the machine store tools
3	Trailer position	Where frames are mounted to trailers
4	Elevator storage	Where pallets and trailers are moved and stored
5	Chain conveyor	The machine moves trailers in and out of the room
6	Wood pallet with a new frame	Where new frames are brought on a pallet with an elevator
7	Washing machine	Wash machines after the operation
8	Frame turning machine	Where frames turned between vertical and horizontal positions
9	Conveyor for completed frames	Where frames are moved to a pallet for the next production operation
10	Overhead crane	Move around frames between the different positions

As seen in Figure 5, the tool storage is an automatic storage system. As discussed in the literature, the tool changing speed and physical limitations of the storage depend on the machine manufacturer and model. In analyzing the process for tool changes, it was observed that storage movement speed depends on the tools used and their weight, which is further analyzed in Chapter 5.2.5.

The distances between key work positions like the trailer station, the wood pallet area, the frame turning machine, and the washing machine. Which will be demonstrated in Chapter 5.2.2, that these distances directly contribute to long transportation and motion times, which are among the sources of non-value-added activity in the production process. This relationship between the layout and operational efficiency is a central topic of the lean manufacturing analysis presented in the results.

4.2 CNC-machining process

The frame machining process at case company contains many different work stages, each of which consumes time, energy, labour, and tools. For cost analysis of the CNC process, every stage can be marked as a cost activity, which is described in the ABC, TCO, and machining economics cost literature. In Figure 6 below, an overview of the CNC operation is described in a process flow chart, which is a normal machining process, a two-stage frame machining process at the case company. In total, there are 34 different work stages that have been timed for the results and are analysed in the results chapter 5.2 to find Waste in process. Furthermore, a comparison can be done for Theoretical and Actual Productive time.

From a lean manufacturing perspective, the setup and frame machining post activities during this stage represent a potential source of non-value-added time to the frame machining operation, which is invested in the results. Based on the process observations of the timing data collected for the study, the machining sequence for all three frame types was mapped in detail. The machining steps for Frame 1 and Frame 2 are presented in Figures 17 and 18, respectively, in the results. Each machining step was categorised as either value-adding or non-value-adding in accordance with lean manufacturing

principles (Womack & Jones, 1996). Value-adding activities are defined as those that directly contribute to the transformation of the cast-iron frame into a finished machined component meeting dimensional specification. Non-value-adding activities include waiting, repositioning, tool changes, and setup operations.

Value-adding activities are those that directly contribute to the transformation of the cast-iron frame into a finished machined component. Non-value-adding activities include waiting, lifting, tool changes, and setup operations that consume time and resources without directly contributing to the product's specification. Non-value-adding but necessary activities are those required by operational or safety constraints, such as torque checking and level measurements of frames that cannot be deleted but may enable time reductions.

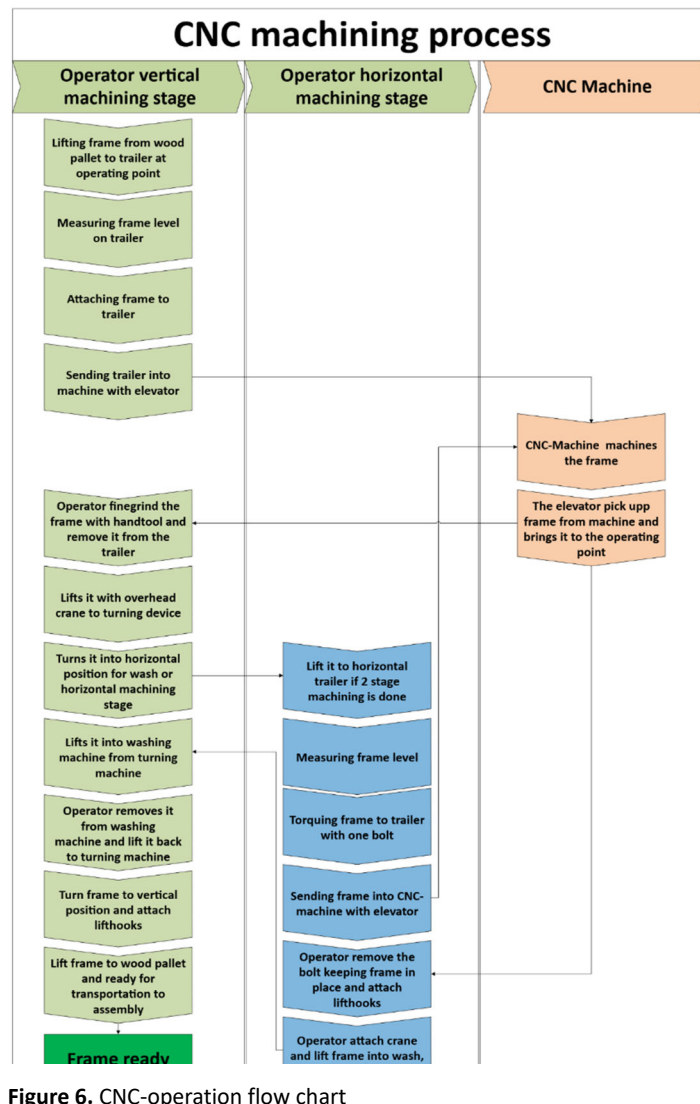


Figure 6. CNC-operation flow chart

4.2.1 Vertical Machining stage

The vertical frame machining stage is the first machining stage for all the frames. The preparation for the vertical machining process is also similar for all the frames. To execute the work task, the frame is ordered on a wood pallet through the automated storage system. The right trailer for the frame and position is also ordered through the same storage. As they arrive at the machine, the machine operator attaches the overhead crane chain hooks to the frame's lift hooks and lifts it onto the trailer. The moving of the frames refers to Motion and Transportation waste defined by Ohno. The hooks are then removed from the frame, and the operator puts one spirit level inside the frame and one on the side to measure the vertical and horizontal position of the frame. If they are not in level, the operator adjusts one screw for the vertical and one for the horizontal position. As the frame is level, the operator uses an electric socket wrench to torque 12 bolts, which secure 5 mounts in place at the trailer. As they are torqued into position, the operator checks the levels of the frame and checks the bolts with a torque wrench. As everything is set, the operator sends the frame into the machine with the automated storage elevator. After that, the machine machines the frame, which includes different machining tools, energy and time consumption to reach a machined frame. As described in Chapter 2.2.2, one of the key consumers in CNC machining is energy consumption. Another time consumer in the process, according to literature, is the non-cutting time in the process, which is caused by the spindle and tool change speed.

4.2.2 Horizontal Machining stage

The horizontal frame machining stage is the second machining stage. For horizontal frames, the preparation is the same for all the frame sizes, and the same trailers can be used for all sizes. The process starts with the order of a trailer for horizontal frame position, and this stage is done after the vertical machining stage. The operator lifts the vertical frame into the frame turning machine and turns it into a horizontal position. As the right trailer has arrived, the next step is to attach the overhead crane hooks to the frame's top mountings and move it to the trailer from the turning machine. The trailer has steering pins where the frame's holes go in. This makes the process a lot faster than

for vertical position. The hooks are then removed, and the frame is torqued into place with a threaded rod that goes through the frame and is screwed into the bottom of the trailer. On the frame top, one mount is placed vertically over the frame and then torqued into place with a wrench by hand. No spirit levels are needed for the horizontal or standing machining stage, as it is level and straight, so the frame can then be sent into the CNC machine with an elevator.

4.3 Machine Maintenance

The maintenance strategy applied to both CNC machines is primarily reactive in nature, consistent with what the literature describes as a Run-to-Failure or Corrective Maintenance approach (Benhanifia et al., 2025). This means that maintenance actions are done for unexpected faults on machine faults rather than by scheduled condition assessments or predictive monitoring.

However, both machines have planned preventive maintenance. Each machine has an annual service performed by the machine manufacturer, which takes 48 hours per machine per year. Also, the cutting liquid is cleaned and refreshed four times per year, with each cleaning taking approximately four hours, adding a further 16 hours of planned downtime annually per machine. Beyond this planned maintenance, the records extracted from the company's maintenance system for the years 2024 to 2026 reveal a substantial volume of unplanned reactive maintenance events, as analyzed in detail in sector 5.1.2 and 5.2.1 .

The two machines differ in their failure patterns; neither of the machines is currently equipped with real-time condition monitoring or IoT-based sensor systems that enable a transition toward condition-based or predictive maintenance strategies, as discussed in Chapter 2.5. All fault detection relies on operator observations during production, which causes delays between the time a fault occurs and its reporting in the maintenance system. As noted in Chapter 3.1.3, this reporting delay can cause an uncertainty of up to ± 30 hours in the recorded downtime figures collected and calculated from the maintenance system. The quantitative impact of this maintenance strategy on machine

availability, production capacity, and cost per frame is analyzed through maintenance KPIs, including MTBF, MTFE, MTTR, and MDT in sector 5.2.1..

5 Results

The result section is the core of the thesis, and in this chapter, the results of the research are presented based on the research methodology. The goal of the project was to provide accurate results to the case company concerning the research objective and questions.

In Chapter Section 5.1, RQ1 is addressed by analysing the cost structure of frame machining. Section 5.2 addresses RQ2 by examining machine availability, downtime, and production efficiency. Section 5.3 further addresses RQ3 through a direct comparison of the two CNC machines and finally integrates all findings into a capacity forecasting model, heading toward an answer to the main research question.

The supporting questions are:

RQ1: What are the main costs in CNC-machining of frames? How do maintenance, energy consumption, cutting liquid, and tool wear contribute to the cost per machined frame?

RQ2: How do machine availability, downtime, and maintenance operations impact the production capacity of CNC-machining of frames?

RQ3: What are the key factors affecting theoretical versus actual production capacity, and how can frame machining be optimised for future demand?

5.1 Cost effects on CNC-machining

This section of the results addresses RQ1 by analysing the cost drivers that contribute to the per-frame machining costs at the two machines.

In section 3.2.3 Gowico (2024) said that the TCO factors include operational costs, maintenance, tooling, training, and energy consumption, which helps organisations to understand the long-term financial investment and helps to compare different CNC

machine options efficiently. So, after the scope was defined and limited, identifying what kind of expenses are involved in the CNC-machining process at case company was the next step, so the data could be collected. The results are mostly focusing on the costs for the year 2025, as for 2024, many of the tracking systems had problems before that, so data had not been saved and stored. Furthermore, operators' working hours were not saved for every machine, so there is no follow-up on the actual working hours. In the CNC-machining process of the frames, the main costs are:

- Maintenance costs
- Tool wear costs
- Operator's labor costs
- Energy consumption costs
- Cutting liquid costs

In the figures below (see Figure 7 and Figure 8), the costs are divided into categories which contribute to all the yearly machining costs for 2025. The costs are affected by the volumes of production and the hours machines have been operating.

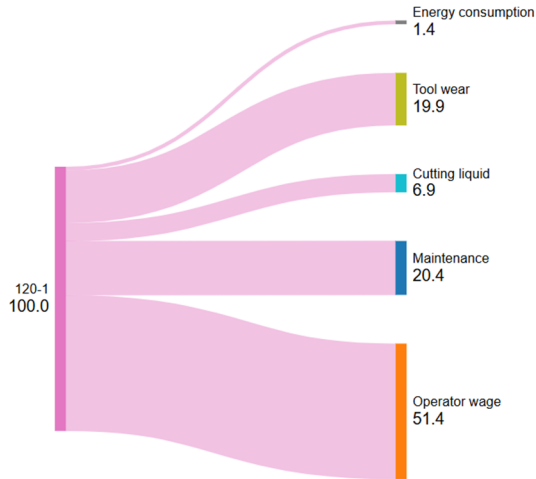


Figure 7. Sankey diagram for machine 120-1

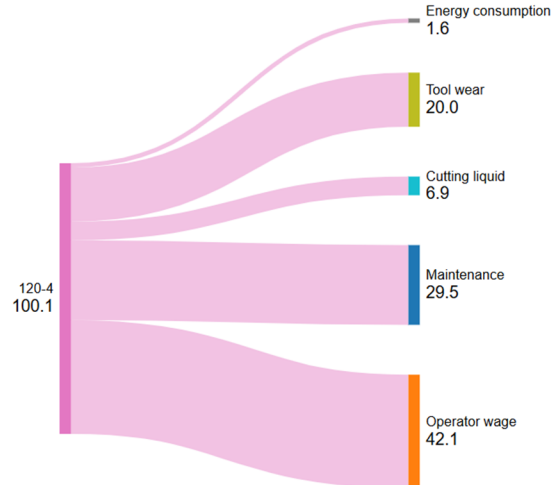


Figure 8. Sankey diagram for machine 120-4

The results are based on the year 2025, as machine 120-1 had 1706 operating hours related to CNC-machining of frames, excluding the washing step, the machine 120-4 had only 1185 operating hours of CNC-machining related tasks.

5.1.1 CNC-Operator labour cost

The key consumer of the total costs at the CNC-machines is the operator wages. These are 51.4% at the older machine and 42.1% at the newer machine of the total costs. The operator costs are calculated according to the best frame bonus, which depends on how many frames the operator machines during a shift. The time is taken from how many hours the machines had been operated in 2025. The operator hours can be more than the estimated ones, as their work times are based on the produced volumes and all the attaching and removing stages. As the working times are only analysed for 13 shifts for two days, the operators could have been faster or slower than normal, as they were aware of the monitoring.

5.1.2 Maintenance

As mentioned in the literature, the right maintenance strategies in manufacturing industries play a key role in continuously being able to produce products, to compete with other manufacturers, to ensure on-time delivery of products, and to keep costs down. The second largest consumer of CNC machines has been the maintenance for 2024-2026. In the older machine, 120-1 lower at 20.4%, and in the newer machine, 120-4 29.4%. The maintenance costs were calculated from maintenance system where the spare part expenses could be found for each machine, and then the maintenance hours could be calculated with the amount of hours spent on each machine and their average hour salary for company, as company uses both subcontractors for maintenance and own mechanics which costs more or less the average wage costs were used in the results.

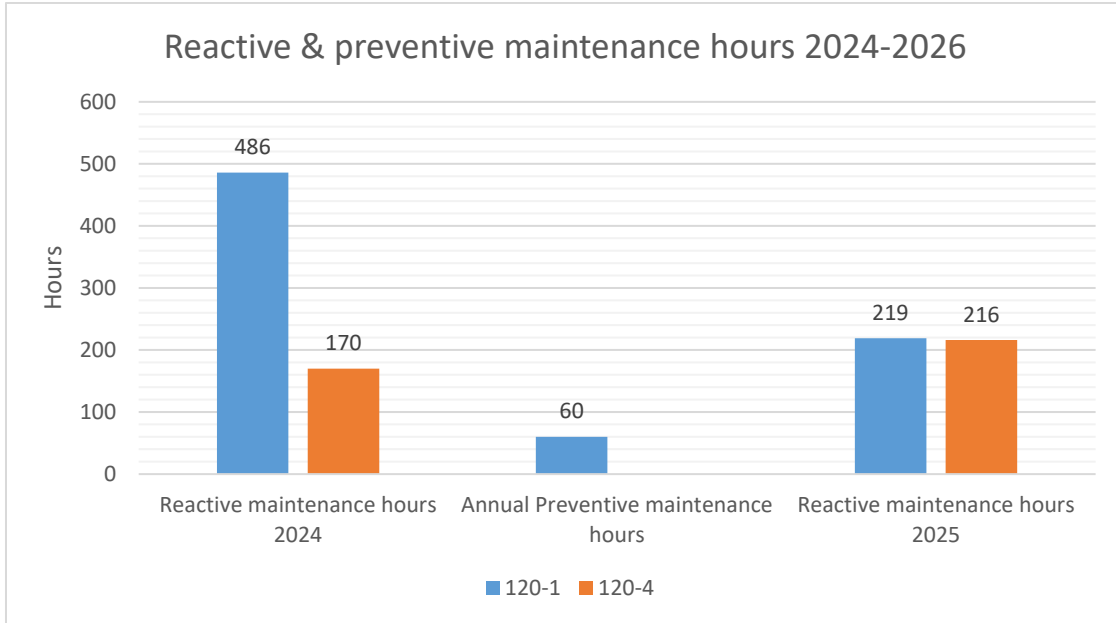


Figure 9. Reactive & Preventive maintenance 2024-2026

Analysing the result of reactive and preventive maintenance, the reactive hours are a lot higher than preventive on both machines, except 2024 for 120-4 with 170 hours, which is still a high number. As reactive maintenance is an approach where equipment is only repaired or replaced when it has already broken, it needs little or no advance planning, and costs are low, but it frequently causes unpredictable downtime and higher costs over the long term, according to Chapter 2.5, where reactive and planned maintenance are discussed.

However, seeing reactive and planned maintenance hours is one viewpoint, but seeing the actual faults for machines enables getting a deeper understanding of the causes. As illustrated in Figure 11, the 120-1 machine has different failures across multiple subsystems, most notably within the Control System and Tool Change mechanisms. Critical hardware faults, such as broken CPUs (COM, NC, and PLC) and tool-change stuck, which were reported 15 times in 2025, suggest that the electronic and mechanical components have surpassed their reliable service life. Furthermore, leaks in the hydraulic and pneumatic systems, which all contribute to an unpredictable MTTF and MTTR, are analysed later.

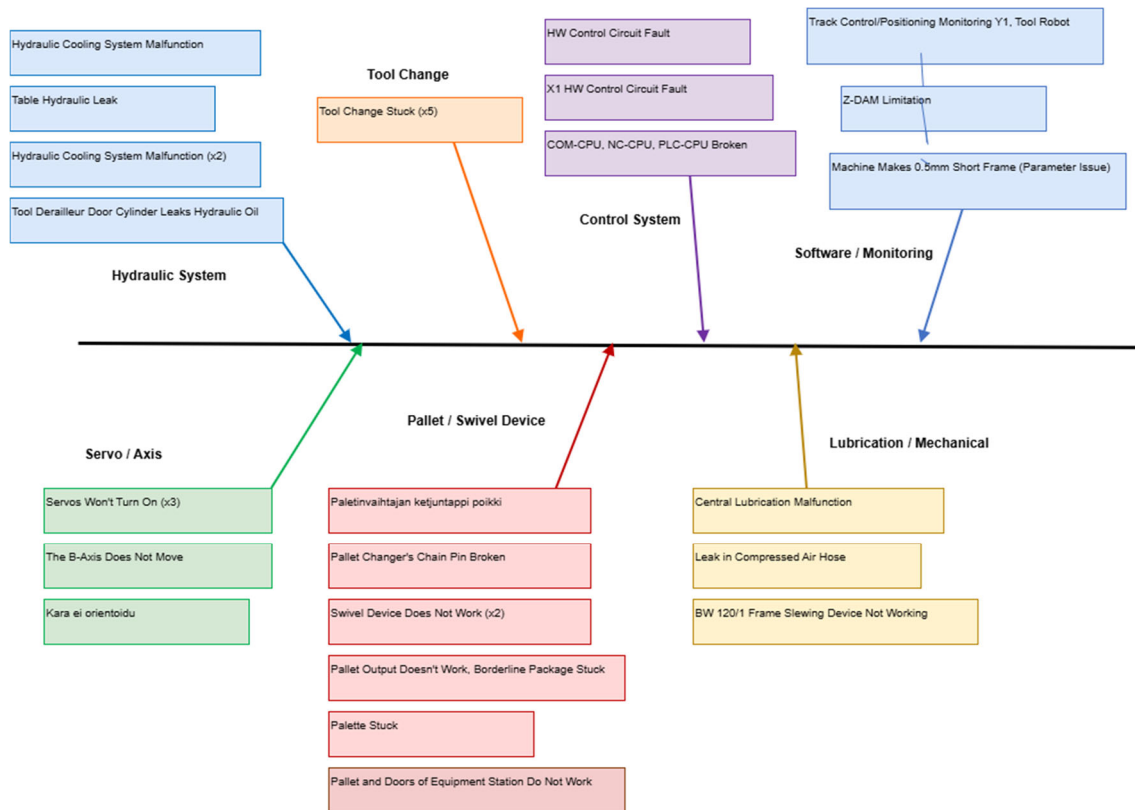


Figure 10. Critical faults Ishikawa Diagram 120-1 2025

In contrast, Figure 11 reveals that the 120-4 unit's failures are more concentrated in Electronic Sensors and Pallet/Trailer System. A single hardware error in an active sensor accounted for 59 hours of downtime, which highlights that a minor electronic failure can stop the entire production for several hours. The tool-change mechanism also represents a bottleneck, with 17 hours of downtime recorded for a single failure.

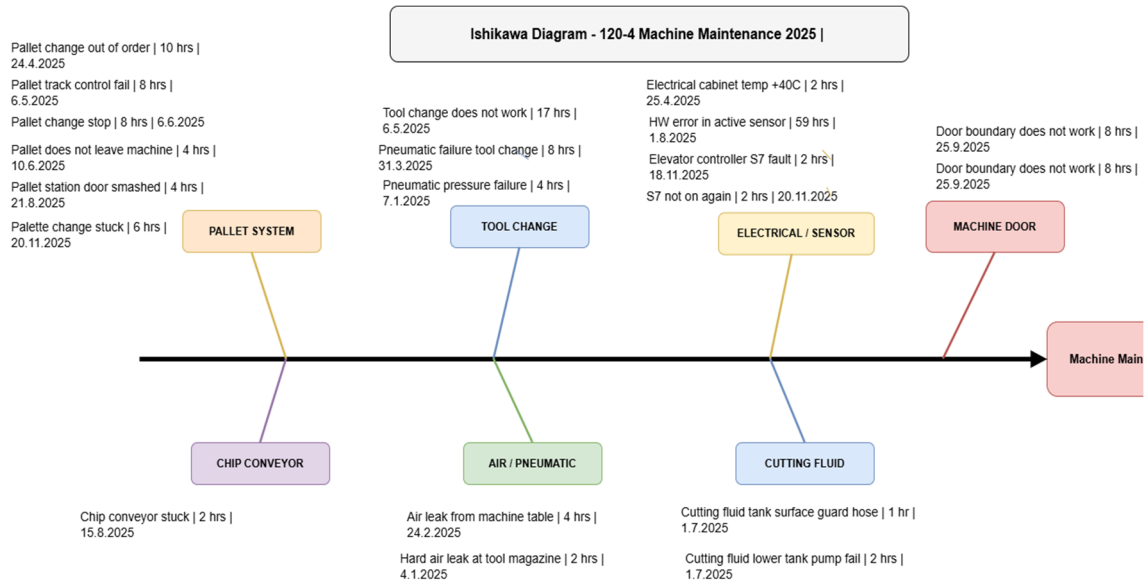


Figure 11. Critical faults Ishikawa Diagram 120-4 2025

The maintenance faults seen in the diagrams for the machines illustrate a heavy reliance on a Reactive (Run-to-Failure) strategy, which, according to Benhanifia et al. (2025), is characterised by low planning requirements but high unpredictable downtime

5.1.3 Tool wear

According to the analyses of the expenses in a Sankey diagram, the tool wear on the machines consists of 19.9% and 20% set to the current machining volumes. These are on the same level as maintenance costs, and tool wear is a critical cost driver in CNC machining, as the worn tools reduce the quality and increase cycle times in machining, and in the worst case, it can result in part rejection or machine damage (Kalpakjian & Schmid, 2014). The tool wear cost was only stored for the department, so the exact tool costs could not be analysed, as all the machine tools were ordered on the same ordering number and collected together. The total value was then divided among all machines to get the expense value for each of the analysed machines. These ranges could easily be $\pm 20\%$ as they have not been tracked; just know that all machines with the same speed have produced the same number of frames. While the 120-4 machine operates with a faster cycle time, the increased spindle load correlates to a higher rate of tool degradation per

frame compared to the 120-1, despite the 120-4 having fewer total operating hours in 2025.

5.1.4 Energy consumption

Energy consumption in CNC-machining consists of multiple phases, as described in the literature (Diaz et al., 2011; Gutowski et al., 2006). Analysing these is important for the machine comparison.

One of the smaller consumers in the process is the machine's energy consumption. The energy consumption during operation is a minor part of the whole consumption, with 1.4% and 1.6% of the total expenses. The company has a permanent electricity contract, so the energy consumption is tied to the operations and machines. In the chart below, the energy consumption in the newer machine 120-4 is slightly higher during one 8-hour shift than that of the older machine 120-1. The energy consumption could not be analysed for the whole year for the machines. So the average consumption is taken from one month of shifts in 2025 during operation. As they were collected, the non-machining time was not considered, as the consumption was close to 0. In a normal shift, the consumption ranged from 14-26 kWh, as seen in Figure 12 below. The average energy consumption during operation for the old machine, 120-1, was 16 kWh, and for the newer machine, 23.6 kWh.

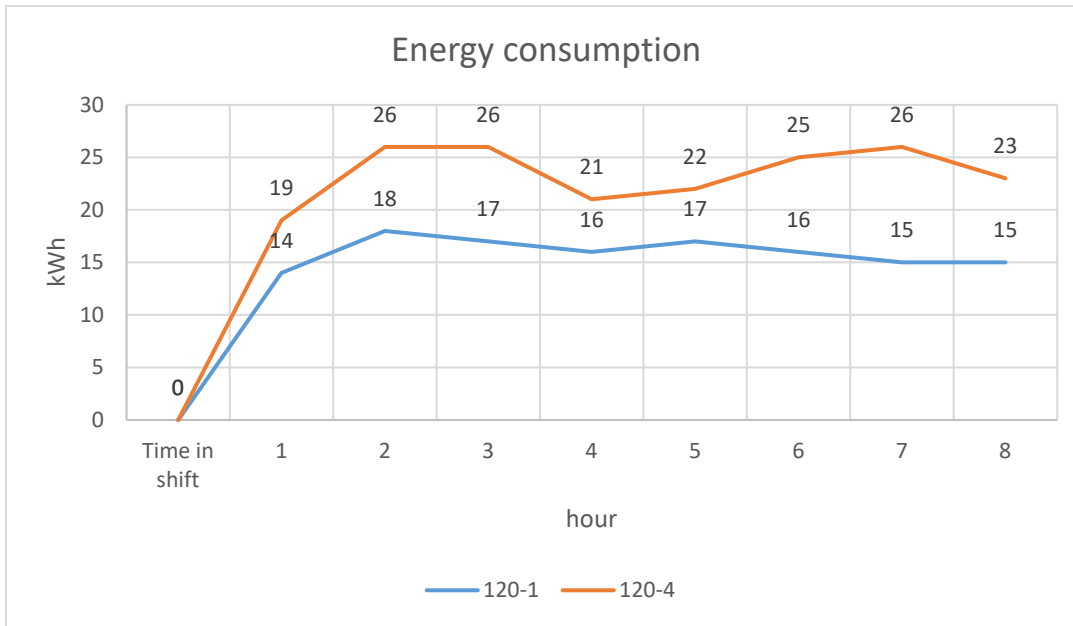


Figure 12. CNC machines' energy consumption

Considering that the machining time at the older machine is slower than that of the newer one.

5.1.5 Cost impact for frame

Continuing from the Sankey diagram, where the different machining expenses were divided, the actual effect on the frame machining costs is shown. To answer the research question, Machining economics, TCO, ABC and TDABC cost analysis methods were applied and used as described in chapters 2.3.1, 2.3.2, 2.3.3, and 2.3.4. For the research question, the costs that were considered on the frames were maintenance, cutting liquid costs, tool wear costs, and energy consumption. As the operator wages are not included in the Figure 13 below with the expenses, maintenance leads to the expense for each frame because of the annual maintenance, but then all the unplanned downtime, maintenance hours, and new spare parts. The maintenance costs per frame for 120-1 are high at 26.45€ and even higher for 120-4 at 37.28€. The second-highest cost is also here, the tool wear costs for the machine being at 19.42 and 30.62€. As the tool wear cost is divided among all of the machines, it can be higher or lower, but as the frame sizes are different, which means the machined areas are larger and smaller depending on the machine. Then, there is also one other aspect when collecting them, which is the

machine speed, as the newer machines are faster but have fewer frames, it is not possible to know the exact price. The cutting liquid, as the third biggest expense, reaches 6.71€ and 10.58€ for each frame in 2025

The last expense is energy consumption, which is tiny at only 1.32€ and 2.41€ for each frame. For the results, the average energy consumption was used with the calculated machining hours. In total, the expenses are 53.90€ and 80.79€ for every frame made in 2025. The results per-frame costs reveal that at both machines, the tool and maintenance are the most expensive costs for the machines without considering labour costs.

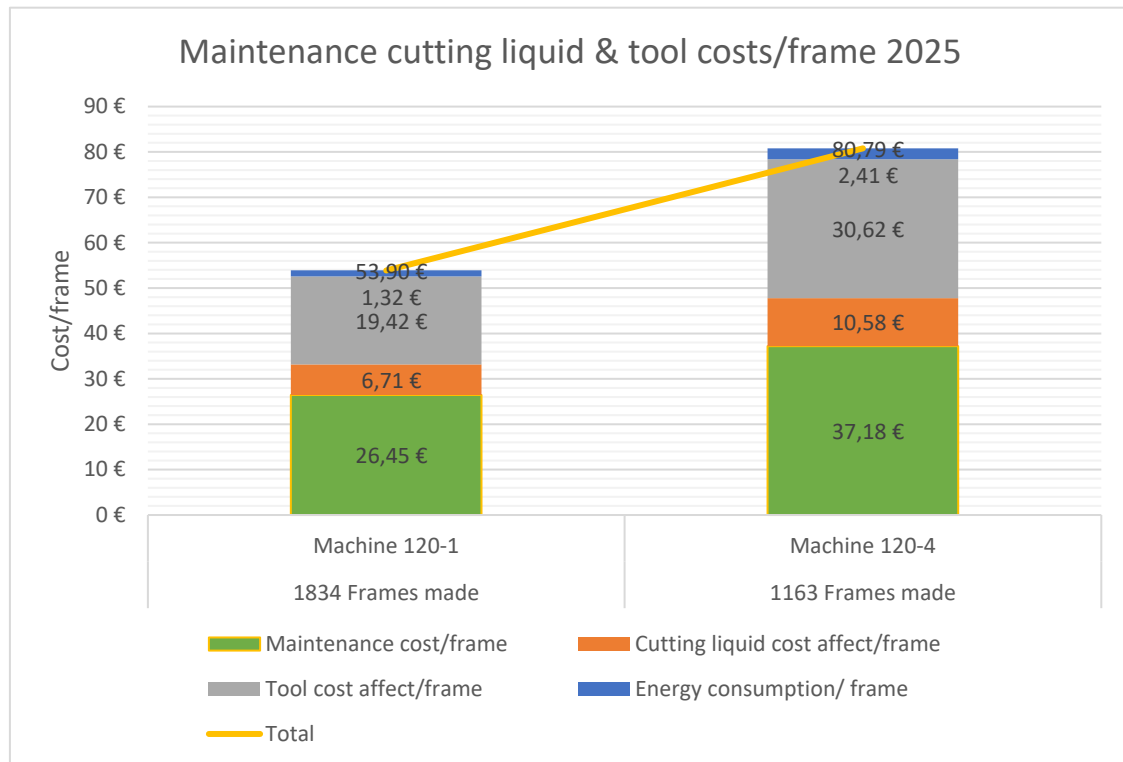


Figure 13. Expenses/frame 2025

5.2 Process efficiency

This sector addresses the second research question 2: How do machine availability, downtime, and maintenance operations impact the production capacity of CNC-machining of frames?

5.2.1 Downtime and Maintenance Analyses

Downtime is a primary driver of the Availability component in OEE. Following the classification system used in Lean manufacturing and TPM literature (Nakajima, 1988).

The effect of downtime and maintenance impacts the availability of the machines, as it shows how well the production system's performance is relative to the designed capacity during the operating time (Tsarouhas, 2019). In chapter 2.5, four types of maintenance strategies were introduced, of which two were identified in the results for maintenance impact. At company, preventive maintenance and reactive maintenance are used as strategies for the CNC machines. Furthermore, in chapter 2.5.1, important KPI for maintenance were analysed to implement, such as MTTF, MTTR, MTBF, and MDT, for the study to see the maintenance and downtime results of the faults.

By first limiting the scope to the two machines, one of the main interests in a production process is the inefficiency that the downtime causes in the production of frames. For the research, the data had to be limited to the years 2024-2026, as some of the data before that were missing, so the other analysis and calculations could not be completed. The downtime for machines was collected from the maintenance system. To conduct it from the machines, the maintenance systems database had to be limited to the years 01.01.2024-01.01.2026. The next step was to limit the system to one of the machines; after that, an Excel file could be generated with the data in work card form. The file with work reports does not have the downtime, as the system does not have that feature. The files for 120-1 included 75 reports, and 120-4 reports. So, to find the downtime, all the work reports were first noted when they had been created by the CNC machine operator, as they had been registered into the maintenance system as a critical problem for the machine. As there are also problems that don't cause the machine to stop, and can be repaired without stopping production, they could be deleted from the files. The reports also include the ending time and date of the work, so that when the maintenance team has fixed the problem, they can check the report as done. The completed check time could then be noted, and the downtime could be calculated from the report time and date to the completed time and date. This was done twice, once for each machine. As the report is done by the machine operator and maintenance mechanics/electricians,

the machine downtime can be ± 30 hours in the system, since the reports by maintenance are usually fixed at a computer in their office, not directly at the machine when it has been fixed. Furthermore, a machine operator may not report the problem directly to the maintenance system. The reactive maintenance and preventive maintenance hours are also noted by mechanics for every operation, so they can be analysed. In Table 3 below, unplanned and planned breakdowns are shown. The Preventive Maintenance and planned breakdowns consist of 48 hours of annual maintenance, and the rest is for cleaning, cutting liquid 4 times a year and 3 hours each time. The unplanned breakdowns are the critical ones that have caused the CNC machine to not be able to operate. To calculate the maintenance KPIs, the following formulas were used:

$$MTTF = \frac{\text{Run time}}{\text{Number of failures}} \quad (1)$$

$$MTTR = \frac{\text{Total Time to repair}}{\text{Number of failures}} \quad (2)$$

$$MTBF = \frac{(\text{Start of downtime} - \text{Start of uptime})}{\text{Number of failures}} \quad (3)$$

$$MDT = \frac{(\text{Start of uptime} - \text{Start of downtime})}{\text{Number of failures}} \quad (4)$$

MTTF and MDT could only be calculated for 2025, as machine hours could not be obtained for 2024.

Table 3. Maintenance KPI results

	Machines	120-1	120-4
1	Machine operating 2025 (hours)	1706,7	1185,2
2	Annual Preventive maintenance (hours)	60,0	60,0
3	Planned breakdowns 2024 (amounts)	5	5
4	Reactive and Preventive maintenance 2024 (hours)	486,0	170,0
5	Reactive Preventive maintenance 2025 (hours)	219,0	216,0
6	Unplanned breakdowns 2024 (amounts)	30,0	9,0
7	Unplanned breakdowns 2025 (amounts)	25,0	20,0
8	Unplanned downtime 2024 (hours)	803	71,44
9	Unplanned downtime 2025 (hours)	467,05	622,36
10	MTTF 2025	68,2	59,3
11	MTTR 2024	11,1	8,6
12	MTTR 2025	7,6	7,7
13	MDT 2024	26,8	7,9
14	MDT 2025	18,7	31,1

In the table above, we can see a huge difference in planned downtime, unplanned downtime and the number of faults set to preventive maintenance. In 2024, the newer machine 120-4 managed to reach only 71.44 hours of downtime with 9 critical faults, but the older machine had 803 hours of downtime and 30 faults. In 2025, both machines had high hours of downtime with 467 hours and 622 hours, respectively, 25 and 20 critical faults. On rows 4 and 5 in the table, reactive maintenance hours are presented. These are part of the downtime in the table that have been work hours for maintenance. The rest of the downtime is caused by no work time for maintenance during evenings and nights, and also a lot of spare parts not being available directly. On rows 10-16, maintenance KPI are calculated with the formulas. MTTF have been 68 hours and 59 hours, which are approximately 11 shifts and 10 shifts of machining time and can be executed in 3-4 working days. Mean time to repair in 2024 and 2025 has also been high, with an average of 1 working shift for each critical repair, and even higher for 120-4 in 2024, reaching 11hours. Mean downtime for the 120-1 machine has 26 hours and 18 hours,

which is around one day every time for the machine to be fixed and run again. The second machine has a low value at 7,9 in 2024 but 31 hours in 2025, which is the highest for them in this research. It shows that 30% of the machine downtime is filled by repair work, while the rest is for waiting for parts and night hours when maintenance doesn't repair them.

To get a better understanding of how large the differences are between planned and unplanned downtimes for the machines, they are shown in Figure 14 below.

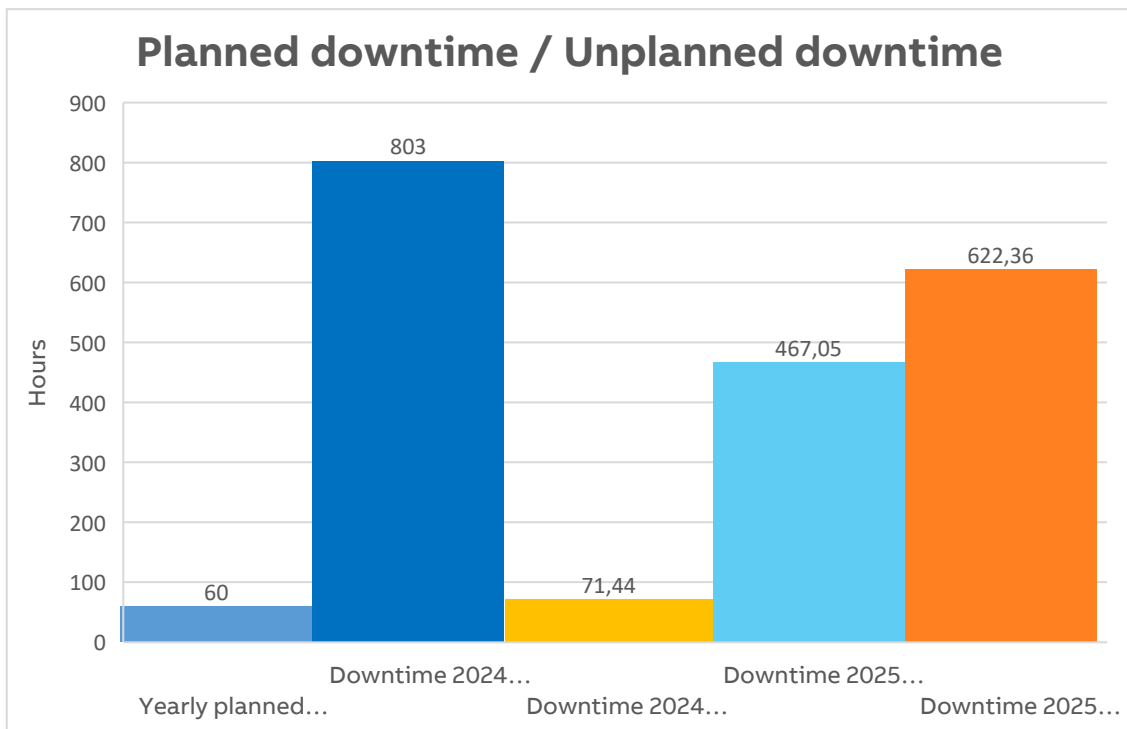


Figure 14. Planned downtime/Unplanned downtime

By analysing unplanned and planned downtimes, the amounts of them can be seen and the actual downtime set to planned, but not how the production has been affected by the breakdowns during operation. In the charts below, the 24 respective 20 breakdowns have been added to the charts with their caused downtime before being fixed. In the charts, the production volumes for each month are presented as bars. The produced volumes are collected from February 2025 to January 2026, as the software had problems and had not saved machined frames in January 2025 and before that.

For the newer machine, 120-1 results for faults and machining volumes are seen in Figure 15 below. The 24 faults are marked with yellow dots on the x-axis, and the orange line crossing the chart shows how much downtime the faults have caused before repair. The blue bars are for the production volumes of frames every month.

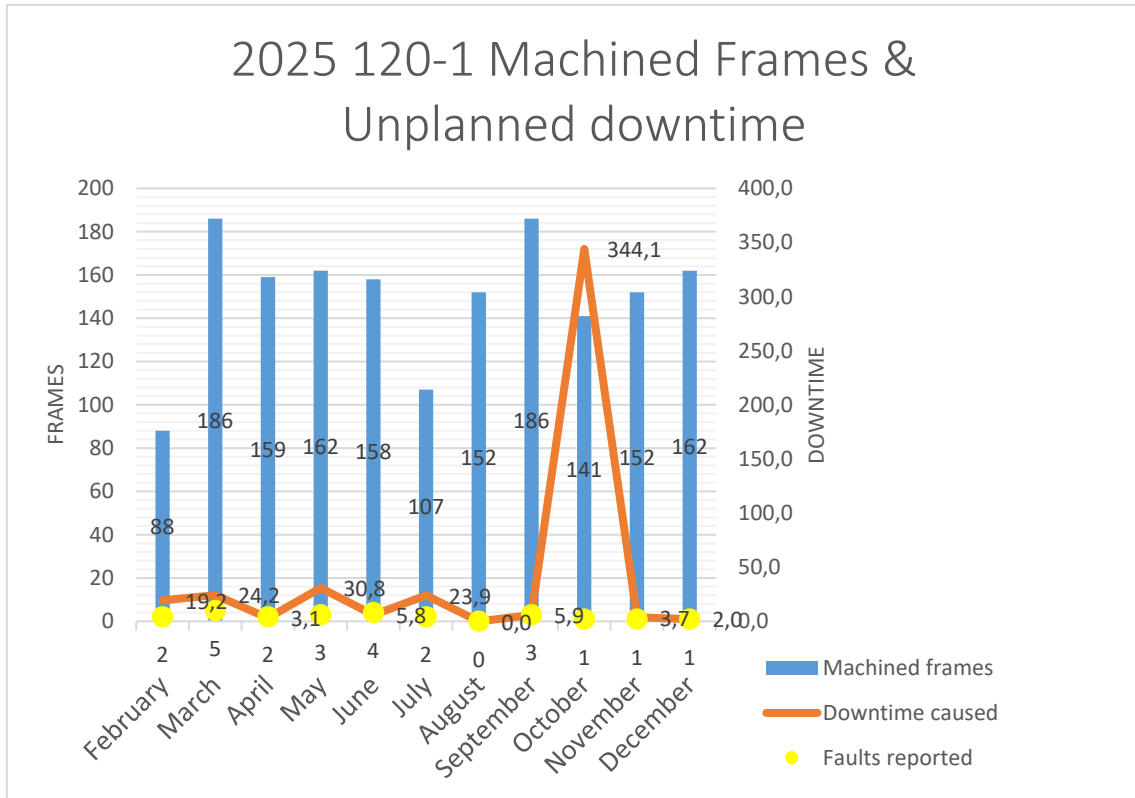


Figure 15. 120-1 Machined Frames & Unplanned downtime

In Figure 15 above, the February frame amounts have been recorded from the middle of February, so the volumes are lower because of that. For the rest of the months, the average production volume has been 156 frames each month. Taking that into account, only the months not delivering 156 frames are July and October. In October, the downtime has been high with 1 critical failure, but in July, there is no correlation between volumes and downtime as there are 2 critical failures causing approximately 24 hours of downtime.

For the 120-4 machine that had 20 breakdowns in 2025, the chart (see Figure 16) is done in the same way, with critical faults marked in yellow, an orange crossing line representing downtime caused by critical faults, and the blue bars are the frame production volumes for each month during the year. Also, here the volumes are lower in February because the recording starts from the middle of February.

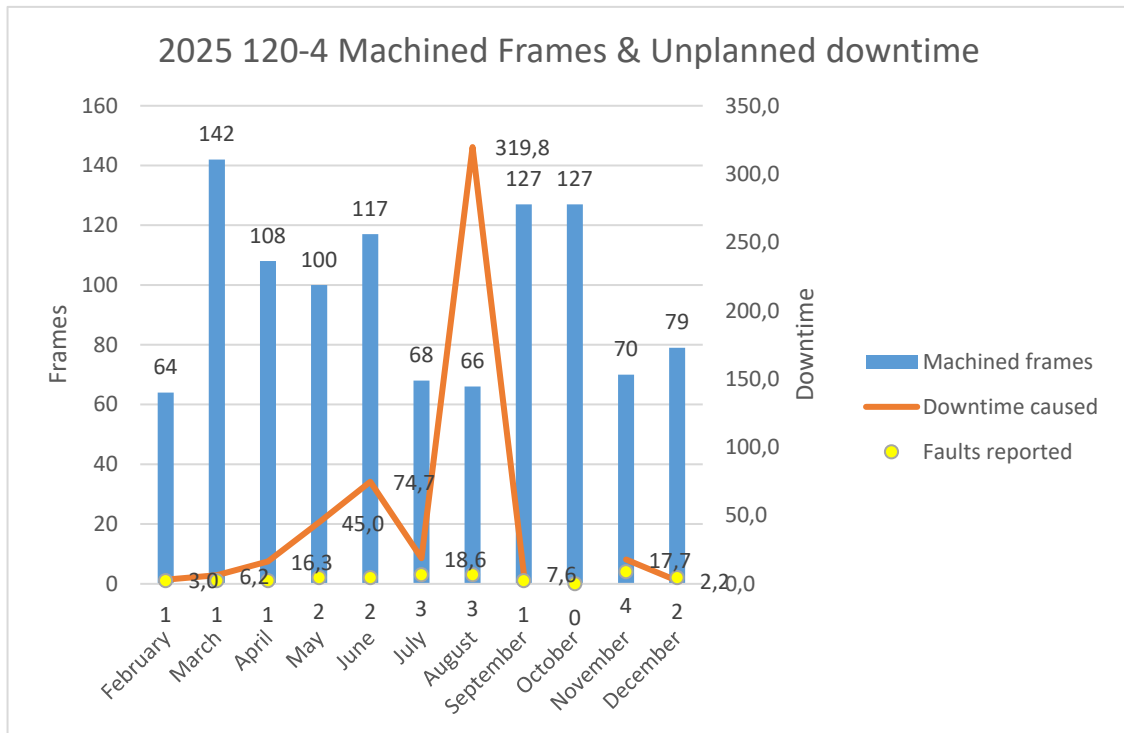


Figure 16. Machined frames & Unplanned downtime

Calculating the average production volume between March and December is 100 frames each month. Analysing the chart above and considering 100 frames for each month, July, August, November, and December are lower than 100. In August, there are 3 critical faults and almost 320 hours of downtime, causing the production volumes to be low, but during the other months, there is no correlation between downtime and low production volumes. Low volumes in July can also be caused by vacations and by new workers who are not as experienced as full-time workers, who may solve most of the problems by themselves.

5.2.2 Process Time Analysis and Theoretical vs Actual Productive Capacity

This section addresses RQ3:

What are the key factors affecting theoretical versus actual production capacity, and how can frame machining be optimised for future demand?

To answer this question, the analysis is built in four different layers, starting from individual task-level waste identification, through the non-productive time during shifts, to the full annual capacity gap. Together, these layers establish the analytical foundation for the capacity forecasting model presented in Section 5.3.

To see the full efficiency of the CNC-machining, the machining process was analysed from a lean manufacturing perspective to improve the process and find the inefficiencies. In chapter 2.4.1, Taichi Ohno classified the wastes into seven categories: Overproduction, Waiting, Excessive inventory waste, Defects, and Unnecessary Motion. Also, in chapter 2.3.1, Kalpakjian and Schmid (2014, p 722) say that considering the actual machining time is important, regarding the non-cutting time in a high-speed machining environment. In the lean manufacturing method, identifying non-value adding time and reducing waste of time is a similar target by analysing the times for the 34 different tasks during production of the motor frames. The unnecessary Motions can be detected. By comparing the times in Gantt charts, it is easier to understand how the times of the tasks affect the total efficiency in the process. At the end of the chapter, the table with all the tasks will be presented. For this work, the times at the newer machine were analysed, because the only difference between them was the machining time; other times are the same as the layouts, lifting equipment and washing machines.

In Figure 17 below, the different tasks are visualized in a Gantt chart showing how they affect the total machining time.

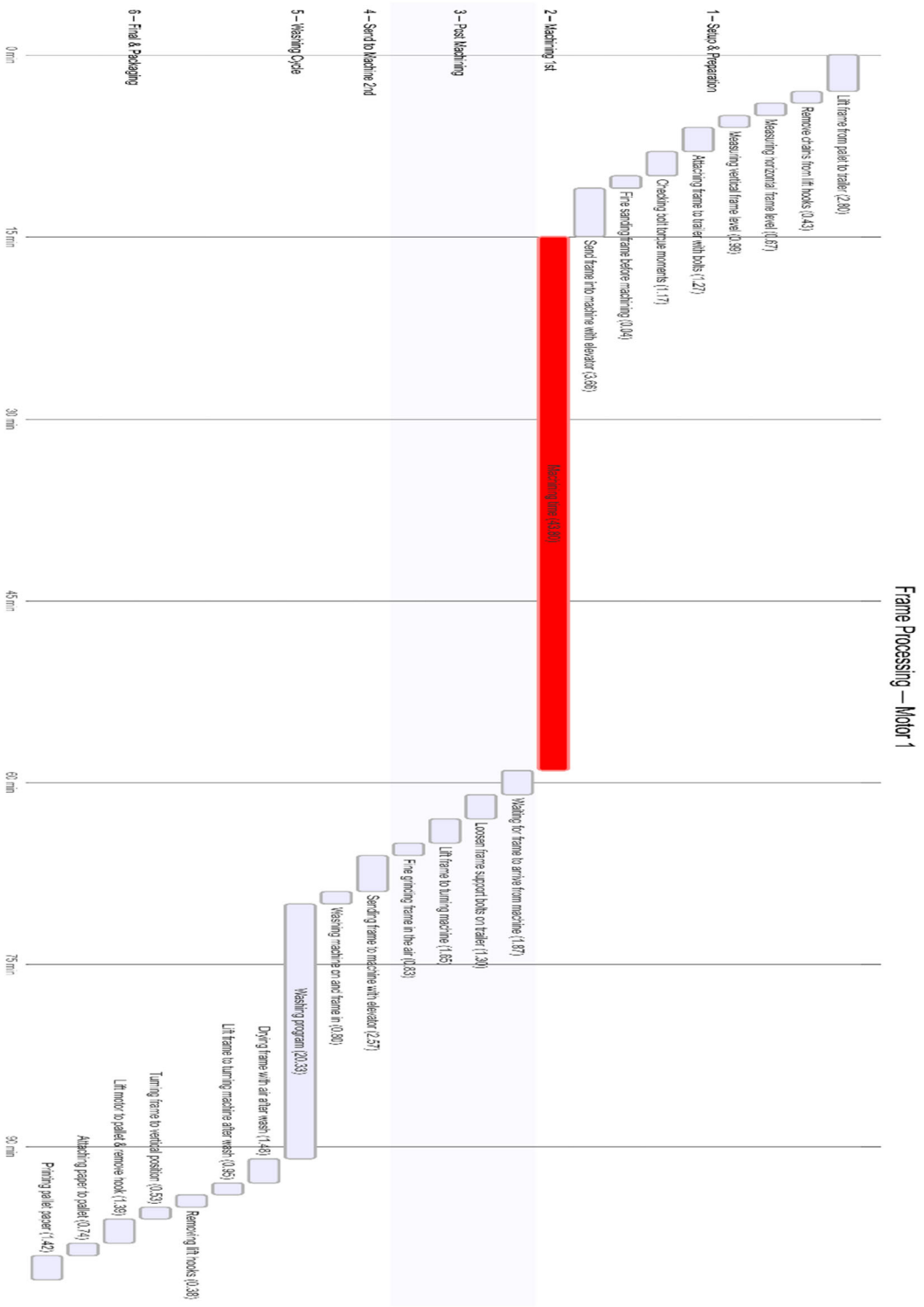


Figure 17. Frame 1 Machining steps

For Frame 1, which undergoes a single-stage machining process, the Gantt chart reveals that the two largest time consumers in the process are the CNC machining program itself and the washing cycle that follows it. However, when all subtasks are considered together, including lifting the frame onto and off the trailer, sending it into and out of the machine with the elevator, turning it between vertical and horizontal positions, and completing post-machining finishing. The total time spent on these non-machining activities exceeds the machining time alone.

The second frame model that is machined in 2 steps is seen in Figure 18. For them, it is a similar pattern where the machining in both vertical and horizontal is the longest time spent. This also points out that the elevator uses and lifting the frames on and off pallets are the longest operations. The 2-stage machining requires 2 more movements with the elevator, in and out, to machine. This stage also requires more unnecessary lifting as the frame is transported between the frame turning machine twice.

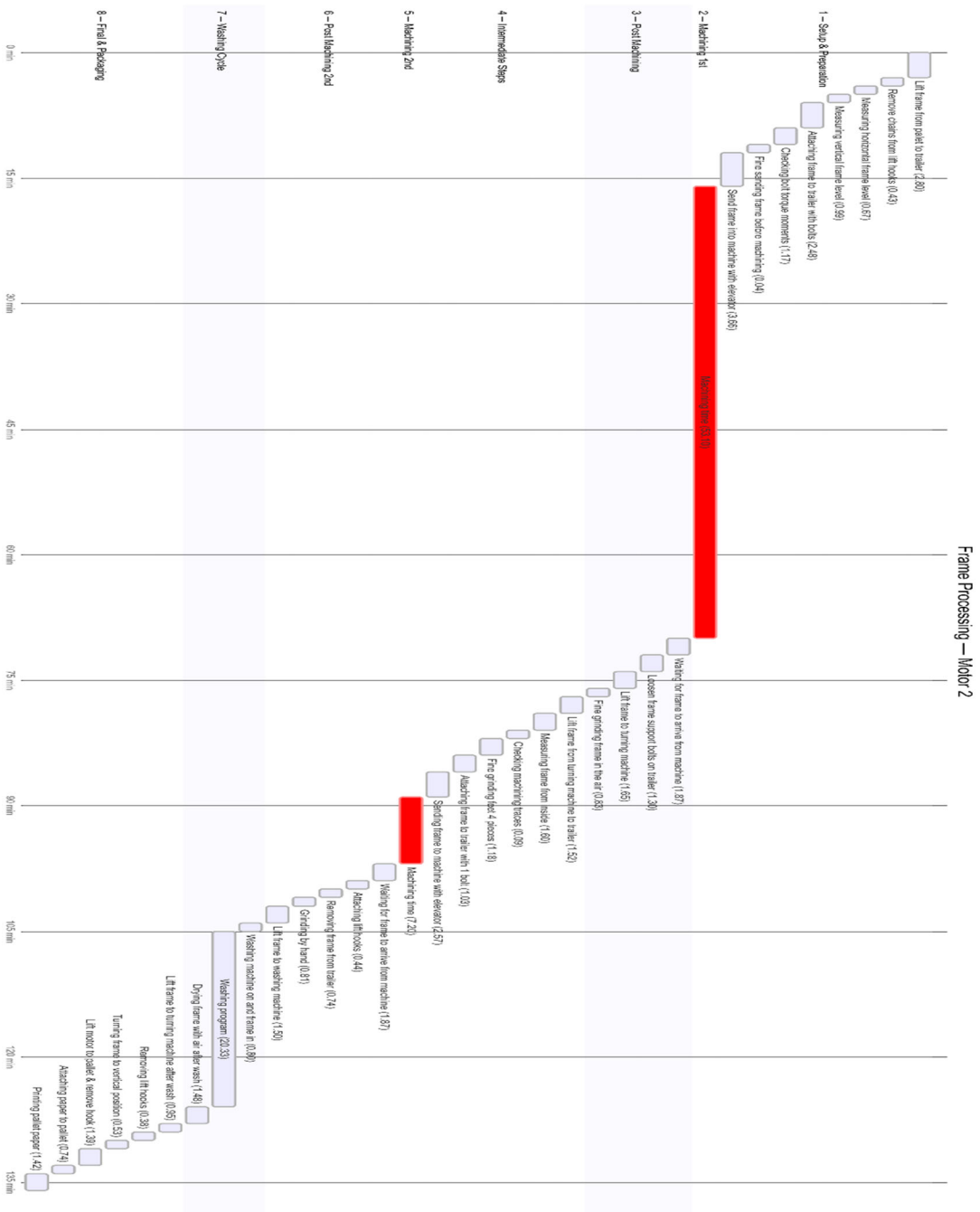


Figure 18. Frame 2 Machining steps

For Frame 2, which requires two-stage machining in both vertical and horizontal positions, the pattern is similar. The two machining stages account for a smaller amount of the total cycle time as the two-stage process requires two more elevator movements, and also requires two extra lifts to and from the frame turning machine. As a result, the

proportion of total cycle time consumed by transportation, lifting, and waiting activities is higher for Frame 2 than for Frame 1.

The detailed task times for both frames, together with their lean categorisation, are presented in Table 4 below.

Table 4. Production Timing Table

Step	Task	Motor 1	Motor 2	Lean analyzes
1	Lift the frame from the pallet to the trailer	2,80	2,80	NVAN
2	Remove chains from frame lift hooks	0,43	0,43	NVAN
3	Measuring horizontal frame level	0,67	0,67	NVAN
4	Measuring vertical frame level	0,99	0,99	VA
5	Attaching the frame to the trailer with bolts	1,27	2,48	NVAN
6	Checking bolt torque moments	1,17	1,17	VA
7	Fine sanding frame before machining	0,04	0,04	NVAN
8	Send the frame into the machine with the elevator	3,66	3,66	NVAN
9	Machining time	43,80	63,10	VA
10	Wait for the frame to arrive from the machine	1,87	1,87	NVA
11	Loosen frame support bolts on the trailer	1,30	1,30	NVAN
12	Lift the frame to turning machine	1,65	1,65	NVAN
13	Fine grinding frame in the air	0,83	0,83	VA
14	Lift the frame from the turning machine to the trailer.		1,52	NVAN
15	Measuring frame from inside		1,60	NVAN
16	Checking machining traces		0,09	VA
17	Fine grinding feet (4 pieces)		1,18	VA
18	Attaching the frame to the trailer with 1 bolt		1,03	NVAN
19	Sending the frame to the machine with the elevator	2,57	2,57	NVAN
20	Machining time		7,20	VA
21	Waiting for the frame to arrive from the machine		1,87	NVAN
22	Attaching lift hooks		0,44	NVA
23	Removing the frame from trailer		0,74	NVAN
24	Grinding frame by hand		0,81	NVAN
25	Lift the frame of the washing machine.		1,50	NVAN
26	Washing machine on and frame in	0,80	0,80	NVAN
27	Washing program	20,33	20,33	NVAN
28	Drying frame with air after wash	1,48	1,48	NVA
29	Lift the frame to the turning machine after washing	0,95	0,95	NVAN
30	Removing lift hooks	0,38	0,38	NVA
31	Turning the frame to a vertical position	0,53	0,53	NVAN
32	Lift motor to pallet & remove lift hook	1,39	1,39	NVAN
33	Attaching paper to a pallet	0,74	0,74	NVA
34	Printing pallet paper	1,42	1,42	NVA

Applying the lean model to all 34 tasks reveals important patterns. For Frame 1, there are 6 NVA tasks, 13 NVAN tasks, and 4 VA tasks. For Frame 2, there are 6 NVA tasks, 21 NVAN tasks, and 7 VA tasks. The higher NVAN count for Frame 2 reflects the additional handling tasks required by the two-stage frame processes, which are all operationally necessary but contribute no direct value to the finished product. The largest sources of non-value-added time identified in the analysis were lifting the frame between positions, waiting for the elevator to move the trailer in and out of the machining room, the washing cycle and its pre- and post-steps to it, and lastly attaching and removing the frame to and from the trailer at each stage. These time consumers are summarised by category in Table 5 below.

Table 5. VA, NVA, NVAN Summary Table

Frame	Frame 1	Frame 2
NVA task	6	6
NVAN Tasks	13	21,00
VA task	4	7
Attaching and removing vertical (minutes)	3,74	4,95
Attaching and removing horizontal (minutes)		1,77
Lifting frame around (minutes)	7,60	11,06
Waiting for trailer in and out of the machine (minutes)	5,53	9,97
Measuring frame level (minutes)	1,66	3,27
Washing machine and post steps (minutes)	23,97	23,97
Other NVAN tasks (minutes)	1,40	2,21

The total process time from the first task to the last is 91.07 minutes for Frame 1 and 129.57 minutes for Frame 2. Of the total time, the actual CNC machining program accounts for 43.8 minutes for Frame 1 and approximately 51 minutes combined across both stages for Frame 2. This means that for both frame types, the subtasks around the machining cycle consume approximately twice the duration of the machining cycle itself. From a lean manufacturing perspective, this represents a significant efficiency gap, as most of the operator time and elapsed clock time in the process is spent on

transportation, motion, waiting, and necessary but non-value-adding activities rather than on the machining operation that directly adds value to the product.

These findings are directly consistent with the transportation and motion waste categories identified by Ohno (1988) and reviewed in Chapter 2.4.1. The layout analysis presented in Chapter 4.1 provides the explanation for these time losses. The distances between the trailer station, the wood pallet station, the frame turning machine, and the washing machine mean that every transfer between positions involves significant crane travel time and operator walking distance, neither of which contributes to the product specification.

As the sources of waste have been found at the individual task level, the analysis now continues to examine how much of a full eight-hour work shift for the operator is theoretically available for productive machining in Table 6. Even considering unplanned downtime and process waste, a working shift contains mandatory non-productive tasks which come from the working time agreement in the metal manufacturing industry (TES 2025–2027), as well as from operational requirements that cannot be eliminated from the process.

Table 6. Theoretical Productive Timer Per Shift

Theoretical productive time	
Type of task	Time (minutes)
One hour shift 8 hours	480.00
Lunch break and coffee breaks in total	59.00
Change of tools	10.74
Shift preparations	4.03
Washing the machining area after the shift	2.90
Changing the filter in the machine	1.81
Weekly service by the operator is divided into shifts	0.82
Filling water into the machine	0.26
Total non-productive time during the shift	80.56
Total theoretical time for one shift	399.44

Of all time, 480 minutes in an eight-hour shift, the total non-productive time amounts to approximately 80.56 minutes, leaving a theoretical maximum of 399.44 minutes

available for the machining process, including all surrounding tasks. The largest single contributor to the non-productive time for operators is the lunch and coffee break that takes 59 minutes, according to the TES agreement. The other non-productive time comes from tool changes for worn tools, averaging 10.74 minutes per shift, shift preparation activities of 4.03 minutes, post-shift cleaning of the machining area taking 2.9 minutes, filter changes of 1.81 minutes, weekly operator service divided across shifts at 0.82 minutes, and water level checks and refilling at 0.26 minutes.

An important note is that the tool change time recorded here refers to the exchange of worn tools between shifts or during shift operation, and is distinct from the automatic tool change cycles that occur within the CNC machining program itself. The latter are analysed separately in Section 5.2.5.

The practical results of the shift-level analysis are that the effective working time available per shift, including all value-adding and non-value-adding tasks, is approximately 399 minutes instead of 480 minutes. This represents approximately 17% of the stated shift length before considering unplanned downtime, machine breakdowns, or process inefficiencies. As the planning for production capacity or evaluating the increasing volumes, this reduction must be considered.

Combining the findings from the task level and shift level analyses with the unplanned downtime data presented in Section 5.2.1 enabled a frame to complete a picture of where the yearly machine capacity is lost and how far the actual output is from the theoretical maximum.

The theoretical annual production time available in Finland for CNC machining, after accounting for weekends, holidays, the annual preventive maintenance service, and cutting fluid cleaning, is 4,966 hours based on a 251-day working year with three shifts of 7.01 productive hours each. This theoretical model already includes the shift-level non-productive time identified in Table 7 and represents the maximum realistic productive

time that could be achieved under ideal conditions with no unplanned downtime and no waste in process beyond the mandatory non-productive periods discussed earlier.

The actual annual performance of both machines against this theoretical target is shown in Figures 19 and 20 below.

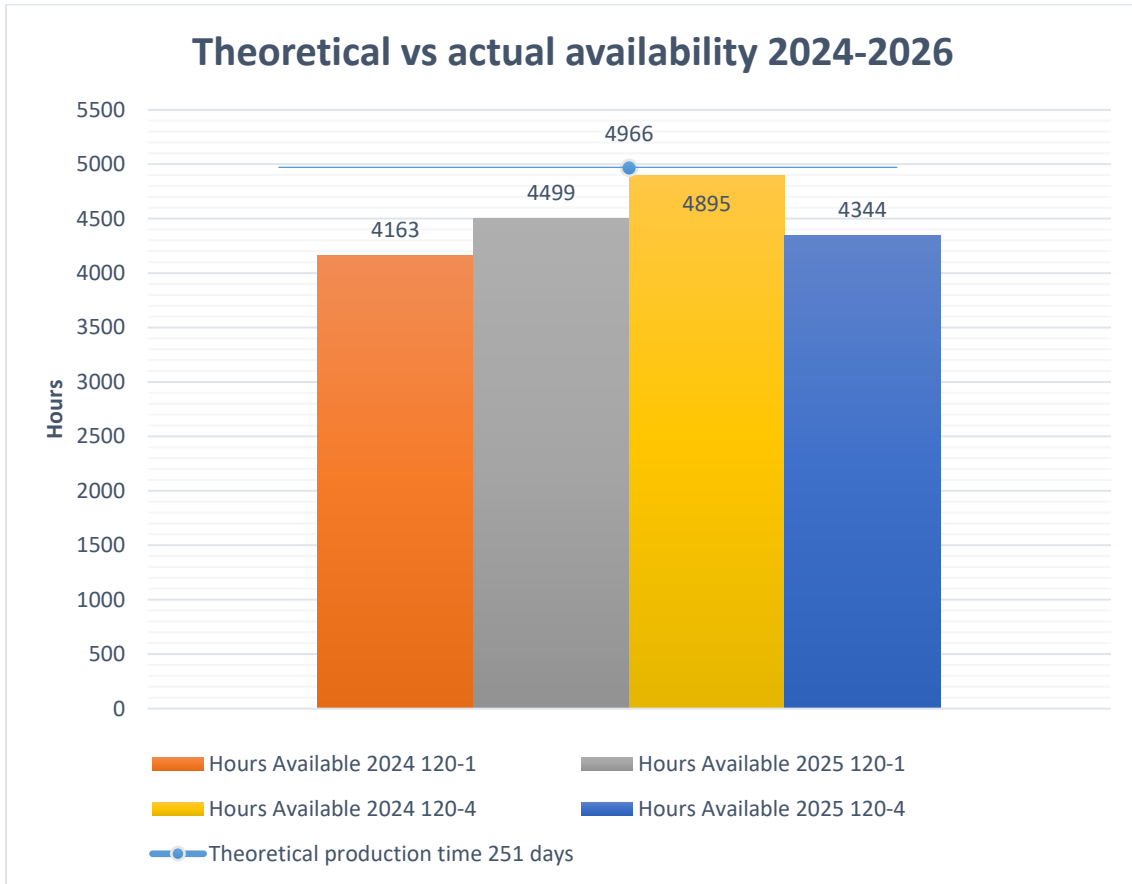


Figure 19. Theoretical vs Actual Availability

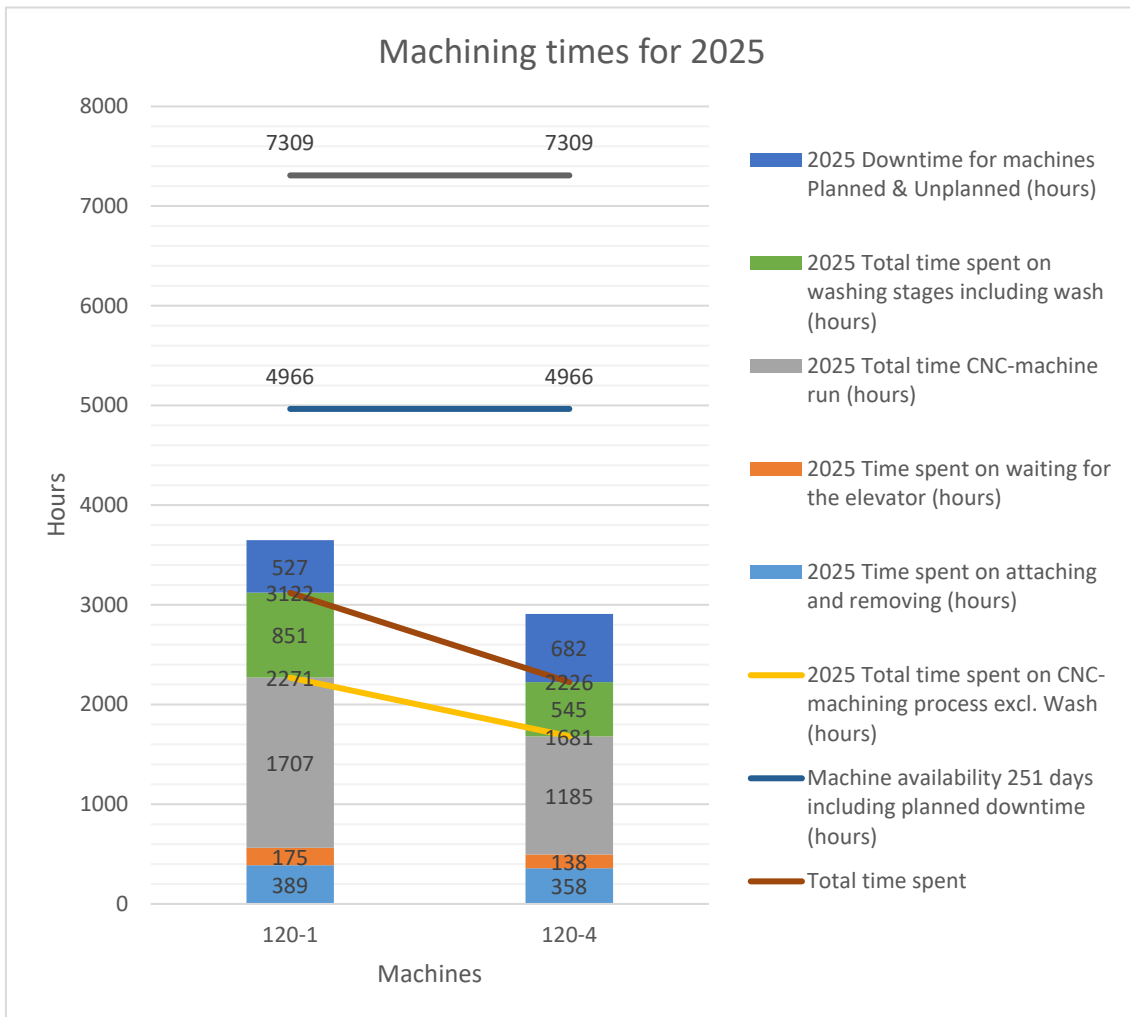


Figure 20. Machining times for 2025

As the bar charts show, neither machine approaches the theoretical availability of 4,966 hours in 2025. Machine 120-1 achieved 4,499 available hours, and machine 120-4 achieved 4,344 available hours after accounting for planned and unplanned downtime. The gap between the actual availability and the theoretical maximum is primarily connected to unplanned downtime, which for 2025 reached 467 hours for machine 120-1 and 622 hours for machine 120-4 as reported in Section 5.2.1. Of the available hours, the time actually spent on CNC machining programs was 1,707 hours for machine 120-1 and 1,185 hours for the newer machine 120-4. The other available hours were consumed by the other subtasks in process, which are: attaching and removing frames from trailers, lifting frames around, elevator transport, and washing cycles. For machine 120-1, the total time spent on all CNC-related process tasks excluding washing was approximately

2,271 hours, which means that the machining program itself accounted for approximately 75 per cent of the total process time when washing is excluded, but only around 56 per cent when washing is included in the process. The machine 120-4 had 1,681 hours of total process time excluding washing, with the machining program accounting for approximately 70 per cent of that time.

These results confirm that at the yearly level, as the Gantt analysis illustrated. A large amount of operational time is consumed by activities surrounding the machining process rather than by the machining cycle itself. The washing stage alone accounted for approximately 527 hours for machine 120-1 and 682 hours for machine 120-4 in 2025, which represents the second largest non-machining time consumer during the year. When elevator transport time and attaching and removing time are added, the total non-machining process time reaches 851 hours for machine 120-1 and 545 hours for machine 120-4. However, the lower non-machining process time for machine 120-4, despite its lower output volume, reflects the different mix of frame types processed at each machine. Machine 120-4 processed a larger frame size and more two-stage frames during 2025, which have longer individual machining times but have a similar process to 1-stage frames. Also, the higher unplanned downtime at machine 120-4 in 2025, at 622 hours compared to 467 hours for machine 120-1, caused a reduction in the number of frames that could be completed.

5.2.3 Machine availability and Utilisation

Digging deeper into the research question for the results shows that the CNC-machines downtime or availability set to theoretical production time is not even close to what it should be according to OEE levels in manufacturing. In the literature review in chapter 2.4.2, Tsarouhas (2019) says that the three main pillars in OEE are availability, performance efficiency, and quality rate. According to Ståhl et al. (2012) the availability can be calculated in many ways, but the availability of equipment tells us how often it is ready to be used and is affected by the time it cannot operate or work.

The availability is calculated with the following formulas:

$$Availability = \frac{Run\ time}{Planned\ Production\ Time} \quad (5)$$

Machine utilisation rate is also connected to OEE and can be calculated with the formula:

$$Machine\ utilization = \frac{Actual\ time\ worked}{Total\ available\ time} \quad (6)$$

To calculate the availability of CNC machines, the downtimes for the machines were analysed earlier.

For both machines, the total theoretical availability time yearly with 365 workdays should be 7324 hours with all the nonproductive tasks, work agreements, annual maintenance, cutting liquid cleaning and other mandatory stops considered. As the company aims to do the CNC-machining in 5-day weeks, the available days in one year without weekends and red days are on average 251 days in Finland, minus the mentioned mandatory operations, when the machine can't run, it is 5021 hours.

In the table below, both 365 and 251 operation day options are used, as the machines have been running on weekends in recent years, but as they aim to machine everything during normal days, it is also included.

The results for availability and machine utilisation are presented in Table 6 below.

The machine utilisation is calculated to be only 16 - 33% for the whole year. To calculate the availability for 2025, the downtime, annual maintenance, and tool cutting liquid

cleaning were added to the total machining time, as there were no other machining schedules. Then, the total machine time was divided by the total time, including stops and downtime.

The results for the availability at the machine are 79% and 66%, which is between typical and world-class, that is, 60-80%, according to Reliableplant (2026).

Table 7. Machine availability, utilisation 2025

2025 Machining time	365 operating days		251 Operation days	
Machine	120-1	120-4	120-1	120-4
Runtime (hours)	1706,7	1185,0	1706,7	1185,0
Planned production time (hours)	2173,8	1807,4	1985,1	1807,4
Total available time (hours)	6857,0	7252,6	4561,7	4406,4
Machine utilization	25 %	16 %	33 %	27 %
Availability	79 %	66 %	76 %	66 %

5.2.4 Tool Change Time Analysis

The tool change time analysis was formed with the case study supervisors, as seen on the CNC machines. From before, the old one has a slower machining time than the newer machines, but what is affecting the machining time at the machines? According to Kumar et al. (2021) a study that analysed CNC machining efficiency concluded that non-cutting activities, tool changes and workpiece handling can consume 15 - 30% of the total available time. The SMED literature in section 2.4.3 says that the tool helps companies to improve the frequent interruptions in processes, and that quick tool changeover is when the machine is switched from making one product to making another, which could be implemented in tool change when machine changes from one tool to another to do next task in program. The production for one frame was always 43.8 minutes on the 120-4 machine and 11.2 minutes longer on the old machine 120-1, so 55 minutes. The

manufacturers of the machines are the same, but they could not provide the times for the tool changes. So, to analyse the times at the two machines, as the operator put on the program for the frame, the times of the machine movements were timed with a timer with an accuracy of ± 0.5 seconds. But after monitoring the machining process at the two machines, the tool change time for the machines caused the main time difference. By comparing the two machines and their tool changing times in the chart below, there is a big difference in the changing times. By calculating the average tool change time and counting the number of tools used for the 120-1 machines, the average tool change took 55.5 seconds, and the longest change took 92.3 seconds. For the 120-4 machines, the average was 29.71 seconds, and the longest change took 80.0 seconds. The longest times for the tool changes were caused by heavy tools, as the automatic storage in the CNC-machines could not handle two heavy tools at one time, so the heavy tool that had been used had to be brought to storage by machine before the second heavy one was brought to the machining room. With lighter tools, the machines can keep two tools at one time in the storage arm to speed up the tool change process.

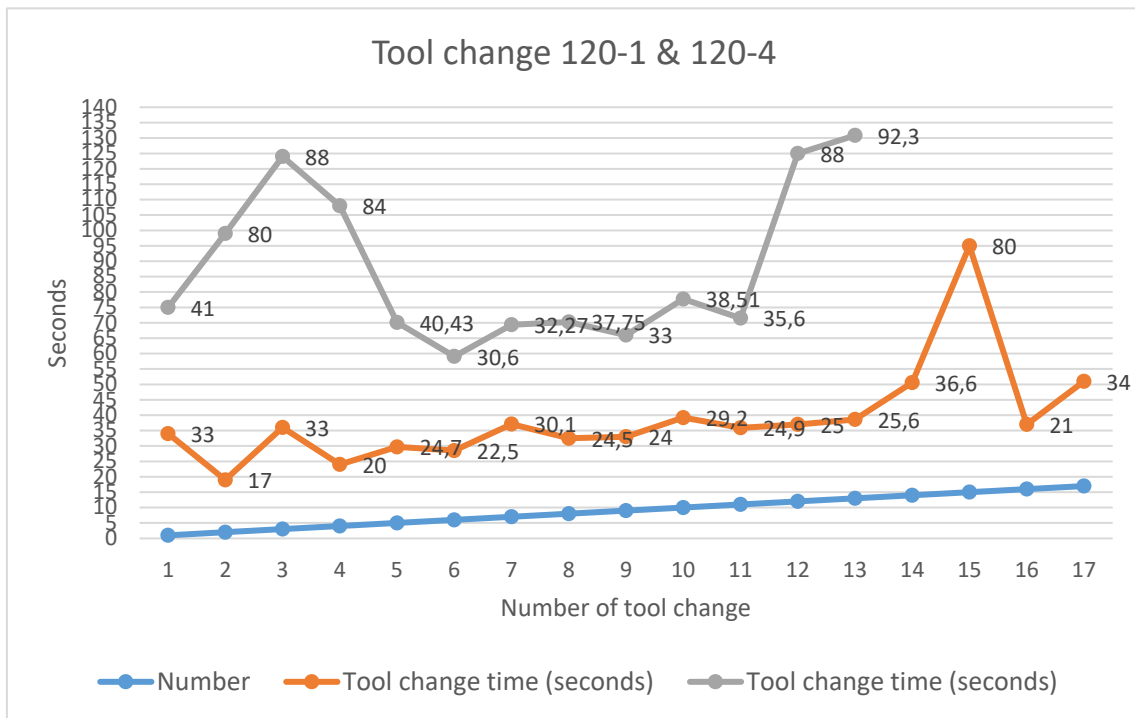


Figure 21. Tool change times at CNC-machines

As the study research results were 15 - 30% of the total available time, these tool changes correlate to 13.86 minutes of the machining time at 120-1 machine, and 6.95 minutes at the newer machine. These are 25.2% and 16% of the total machining time, so inside the literature study results.

5.2.5 Machine Comparison Overview

Summarising the results for Chapter 5 according to the TCO framework (Gowico,2024). with the total costs of operating the CNC machines. The following TCO analysis in Table 8 takes into account all of the cost components analysed in the results chapters for a comparison between the two machines. In the table below, all the yearly impacts on manufacturing have been listed, such as labour, maintenance, energy, and cutting liquid. In total, it makes an impact of 152,13€ and 233.09€ euros of the frames machined.

Table 8. Summary of machine comparison for Chapter 5

Machine comparison 2025		
Metric	120-1	120-4
Machining time equal frame (min)	55	43.8
Energy consumption (kWh)	16,0	23,6
Availability (251 days)	76 %	66 %
Machine utilization (251)	33 %	27 %
Tool change time of machining time	25.2%	16 %
Frames machined	1823	1167
Total Maintenance Costs	46 980,00 €	41 301,00 €
Labor costs	180 000,00 €	180 000,00 €
Tool costs	35 612,33 €	35 612,33 €
Cutting liquid costs	12 306,67 €	12 306,67 €
Total costs per frame 2025	152,13 €	233,09 €

The variation in the impacts is caused by the amount of frames machined. Depending on working stages, the machine 120-4 machined more 2-stage frames than 120-1, which requires more time in setup and the whole process. The most waking result in the table is that the machine 120-4 being 15 years newer than 120-1 but still the downtime and availability is worse.

5.3 Capacity forecasting model

The capacity forecasting model represents the output of this thesis, combining the cost analysis from Section 5.1, the process efficiency findings from Section 5.2, and the maintenance KPI results from Section 5.2.1 into a practical decision-support tool for the case company's Advanced Manufacturing Engineering team. The model addresses RQ3 by visualising the relationship between machine reliability, process efficiency, and production volume targets under varying operation conditions. The model was created and developed with the Gemini Canvas framework, which enables adjustments of input parameters and immediate recalculations of capacity outputs.

As one important detail for the case company is the potential capacity of the machines and the current operation process. With the current times explained in the earlier chapter, these would be the possible volumes weekly in the figure below (see Figure 23, 24). The process is done with the current production model, where they do preparation and post tasks during the machining stage of another frame. With this tool, estimations on volumes can be made for the current machine speeds and processes, which are using OEE at 80%, so world-class according to literature. Section 5.2.2. Analysed the operator time, so for the model, the shift is also set to 7 hours, considering the results for an eight-hour shift. However, the results in the figures below are done with 8 hours of work in 3 shifts for 5 days a week. The estimated value would be 60 frames a week with 2-stage machining. In the model breakdowns, the total value is also included, and the total value is 3000 frames with all tasks included and the current downtimes at the machines. If the MTTF were 1000 hours instead, the capacity should be 3750 frames in 50 weeks, 3 shifts and 8 hours, but 7 hours available time of the operator. But with the current MTTF of 60 hours and MTTR of 20 hours, it would be 3000 frames in 50 weeks, and 60 frames weekly. With the model above, the company can edit the parameters and estimate production volumes. But with the model created, the company should be able to produce 3000 frames annually in 50 weeks with the 120-4.

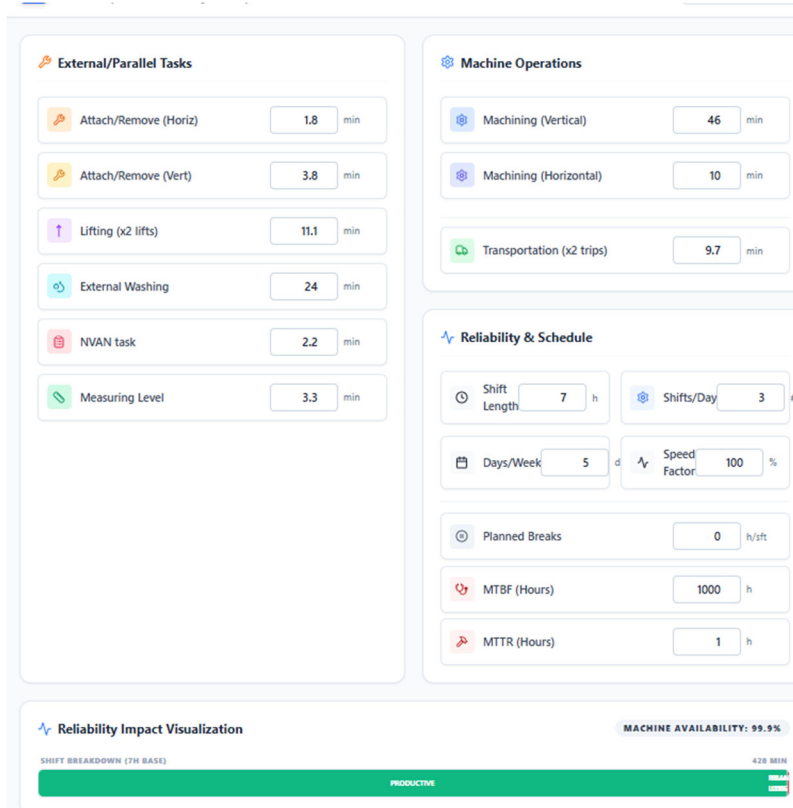


Figure 23. Gemini Canvas forecasting model, (Google, 2026)

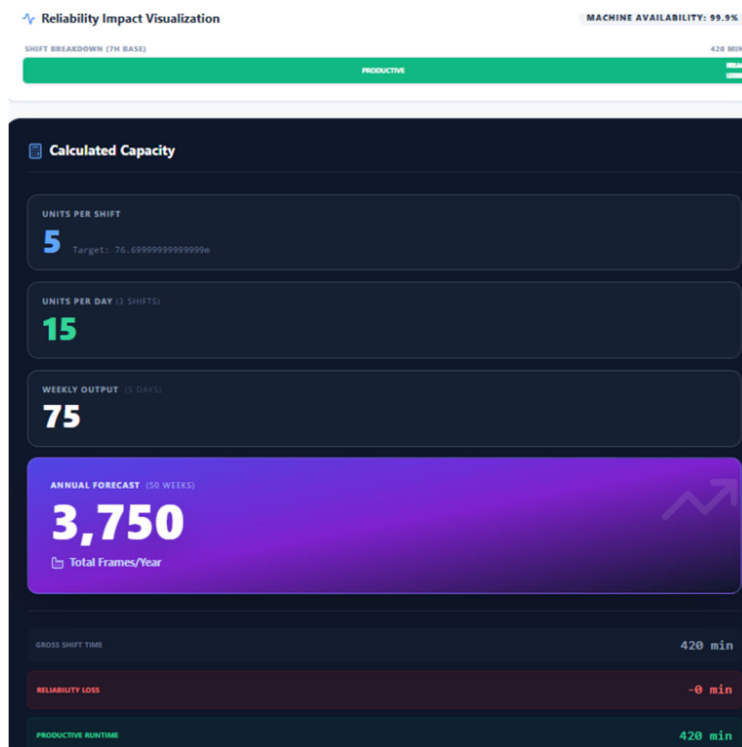


Figure 24. Gemini Canvas forecasting model 2, (Google, 2026)

6 Discussion & Summary

In this chapter the results are summarized, main findings are discussed, recommendations for company are suggested, suggestions for future research, and limitations impacting the study are listed.

6.1 Summary of the Study

The scope of this thesis was to analyse the current CNC-machining efficiency for electric motor frames at Company X. By investigating two specific machines, the 1992 model (120-1) and the 2007 model (120-4), the study aimed to map weaknesses in the manufacturing process and to provide data for improvements and decisions. The work combined direct observation in the factory, manual time studies from 13 eight hours shifts, and data extracted from the company's Power BI, ERP, and maintenance systems. It was necessary because no system contained all the information needed to build a complete picture of cost, availability, and capacity. In practice, the analysis required reconciling data from sources that were designed with different purposes in mind and had never previously been combined for this type of assessment.

The research successfully answered all three supporting research questions and the main question regarding how frame machining at Company x can be optimized in terms of cost and production capacity. The findings reveal a manufacturing process with inefficiencies in process flow, cost structure, maintenance strategy, and machine layout, which indicates a gap between current performance and what kind of performance could be achieved.

6.2 Main findings

This sector of the thesis answers the research questions.

6.2.1 Cost findings

What are the main costs in CNC-machining of frames? How do maintenance, energy consumption, cutting liquid, and tool wear contribute to the cost per machined frame?

From the results, we could see that labour costs for machines are the highest, followed by maintenance, tool wear, cutting fluid, and energy consumption.

The cost analysis reveals a clear structure of expenses for both machines. Operator labour is the main cost driver, representing 51.4% of total costs at machine 120-1 and 42.1% at machine 120-4 in year 2025. The finding correlates with the machining economics literature (Kalpakjian & Schmid, 2014), which identified labour cost as typically the highest variable cost in machining operations. Tool wear and maintenance represent approximately 20% of total costs at both machines, which together account for 40% of costs. That proportion underscores the significance of machine reliability and tooling management as cost levers. Cutting liquid accounts for approximately 6.9% at both machines, while energy consumption represents only 1.4% and 1.6%, respectively.

The per-frame cost analysis reveals a difference between the two machines, with 53.90€ per frame at machine 120-1 compared to 80.79€ at machine 120-4, and excluding labour costs. Newer and faster machines had higher per-frame costs, which can be explained by lower utilisation rates and substantially higher maintenance expenditure at machine 120-4 in 2025, where a single sensor failure accounted for 59 hours of downtime, but also the large frame sizes and 2-stage machining. Results for the low amount of energy costs during operation, despite the environmental significance of CNC energy consumption written in the literature (Camposeco-Negrete, 2013; Vijayaraghavan & Dornfeld, 2010), highlight an important point. Investment in energy efficiency alone is unlikely to

reduce costs. The dominant levers for cost reduction are maintenance strategy improvement and utilisation rate increases, which both address the gap between available machine time and productive machine time.

6.2.2 Efficiency Findings

RQ2: How do machine availability, downtime, and maintenance operations impact the production capacity of CNC-machining of frames?

Results for efficiency analysis showed findings in three categories: maintenance performance, process level waste, and the shift level capacity of an operator.

At the maintenance level, both machines are operated under a reactive strategy, faults are usually addressed after they occur rather than being repaired before. In 2025, this resulted in 467 hours of unplanned downtime at machine 120-1 and 622 hours at machine 120-4. The gap between Mean Time to Repair (MTTR) which was approximately 8 hours and Mean Downtime (MDT) of 18–31 hours is an important finding. It indicates that most of the downtime is not spent on active repair work but on waiting for spare parts, maintenance staff during night shifts, and failing reports to be registered into the system.

At the task level, the analysis of 34 individually timed work stages showed that non-machining activities consume almost twice the time of the actual CNC machining program for both frame types in the study. Lifting, elevator transportation, frame washing, and trailer attachment and removal together account for most of the operator's time during a frame machining cycle. This is consistent with the transportation and motion waste categories described by Ohno (1988) and is directly connected to the physical distances between workstations in the current layout. The tool change analysis provides a similar finding in waste, non-cutting time within the machining cycle itself accounts for 25.2% of total cycle time at machine 120-1 and 16% at machine 120-4, which is mostly caused by the tool storage arm's inability to handle two heavy tools simultaneously.

At the shift level, the observation of 13 shifts established that effective productive time per eight-hour shift is approximately 399 minutes, not 480 as on paper. The 81-minute difference consists of mandatory breaks under the TES working time agreement, operator tool changes between shifts, machine cleaning, filter changes, and weekly service tasks. The reduction finding of around 17% must be built into any capacity planning calculation before unplanned downtime is even considered.

Machine availability of 79% and 66% falls within the range that OEE benchmarks that can be acceptable. However, machine utilisation, with the proportion of total available time actually spent running the CNC machines in 251 days was only 33% and 27%. This gap between availability and utilisation is largely explained by the sub tasks in the process, as the machines are technically available for much of the working day, but the operator's time is consumed by transportation in and out of machines, washing, and setup activities that are necessary but do not run the machine.

6.2.3 Capacity Findings

RQ3: What are the key factors affecting theoretical versus actual production capacity, and how can frame machining be optimised for future demand?

The theoretical annual production time of 4,966 hours, which was calculated for a 251-day working year with three shifts and mandatory non-productive time taken into account, was not reached by any of the machines. Actual available hours were 4,499 for machine 120-1 and 4,344 for machine 120-4, with actual CNC machining program time of only 1,707 and 1,185 hours, respectively.

This gap between theoretical and actual productive time was caused by three factors, unplanned downtime removing available hours, tasks around the process consuming a large amount of the remaining available time, and lastly, the structural shift-level constraints that were identified in the time analysis.

The capacity forecasting model developed in Section 5.3 transform the thesis findings into volume estimations. With the current operating process, and downtime the model

forecasts approximately 3,000 frames annually per machine. Improving MTTF from 60 hours to 1,000 hours increases this estimate to 3,750 frames, which is a 25% capacity gain achievable without any other changes, such as machining speed or workers. However, with current machines it is not possible due to current reliability seen in analyzes, but with a new machine it would be possible. Additional improvements are possible through layout modification and process waste reduction, which the model enables by editing the values to see how it affects the volumes that could be procuded.

6.3 Practical recommendations for the Case company

The findings in this thesis suggest five recommendations for the case company:

The first recommendation is to improve maintenance data infrastructure and downtime recording. The ± 30 -hour uncertainty in downtime recording, a machine-specific tool cost tracking system, and the lack of operator hour monitoring per machine prevented accurate performance values and reliable capacity planning.

Implementing machine-specific data capture through the machine PLC, which would analyze the spindle movement to monitor only cutting time.

The second recommendation is to optimize the tool magazine. One bottleneck in machining cycles at both machines was the tool storage arm's inability to handle two heavy tools simultaneously, causing the heavy-tool changes to require an additional storage cycle, which increased the change time. Modifying the CNC program tool order to reduce times between changes,

The third recommendation is to design a new machine layout focused on reducing crane travel distances between the trailer station, frame turning machine, washing machine, and the completed frame conveyor. As The task analysis found that transportation and motion activities consume approximately twice the machining time, and that this value has a direct impact on physical distances in the current layout. The layout design would require calculations on time and how the stations could be moved closer to each other, but it is beyond the scope of this thesis, despite the strong support from

the time results. In this suggestion for improvement, another option could be to design a lifting tool, that could turn the frames directly in the air when lifting them up in the air. This would reduce all moving time for the frames but the large size difference in frames makes it difficult to develop a tool that fits all.

The fourth recommendation is to use the capacity forecasting model developed in Section 5.3 as a planning tool, updating the input parameters with improved data to evaluate the capacity increase of potential investments in new machinery, additional shifts, or process redesign to reduce subtask times.

The fifth recommendation is to investigate and consider investing in new machines. As the current downtimes were so high set to the machine time, this would reduce the unplanned downtime and increase reliability and capacity according to the capacity model.

6.4 Suggestions for future research

A suggestion for future research would first be digital monitoring integration. Future research could explore the integration of machine monitoring systems (IoT sensors, machine controller APIs) to automate OEE data collection, eliminating manual measurement limitations and enabling continuous performance improvement (Windmann et al., 2015).

Another research could investigate how the layout could be optimized to reduce subtask times, so the machines would have less waiting time and operators would have less waste and more Value-added time. This would be applied to the whole CNC-machining center, including elevators.

Third suggestion could be to analyze how the machines could be combined. As current process completes all machining stages at one machine, but as the second machining stage is so short. The optimization of 6 machines together could enable 4 machines to machine vertical position and 1-2 to machine horizontal.

Fourth future research can be to analyze if non-value-adding activities like crane lifting, elevator transport, frame turning, attaching and removing, that consumed roughly twice the machining time itself could be replaced with automation by a robot solution and if it would be technically and economically feasible.

6.5 Limitations of the study

While this thesis provides a comprehensive analysis of CNC frame machining at company, several limitations must be listed in the findings:

The study is limited to two machines out of 6 in production.

The analysis is based on data from 2024-2026. Variations in demand during the year, amount of workers, or maintenance scheduling may affect the findings for other periods. Cycle time and tool change time recordings performed with a stopwatch cause minor measurement uncertainty. Repeated measurements were taken to improve reliability, observer-induced variability cannot be entirely eliminated. The Quality Rate component of OEE relies on scrap and rework records from the maintenance system and with manually counting frame amounts machined into times.

Energy consumption data depends on the factory's monitoring system. The cutting vs idle separation was not available in the system as it only counted 1 hour, energy breakdown estimates also have an uncertainty.

Manual time measurements performed with a stopwatch introduce minor measurement uncertainty of ± 0.5 seconds per observation. While repeated measurements were taken to improve reliability, the 13-shift observation window is limited, and the operators may have worked at other speeds during monitoring which cannot be excluded.

Tool wear costs were tracked at the department level rather than per machine, introducing an estimated uncertainty of $\pm 20\%$ in the per-machine tool cost figures. This limits the per-frame cost analysis and the TCO comparison between machines.

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