DEPARTMENT OF
MECHANICAL AND INDUSTRIAL ENGINEERING

GUSTAVO MOTA LOPES MARQUES GUIDO
BSc in Mechanical Engineering Sciences

METHODOLOGY TO DEFINE TOOL USAGE TIME BASED ON MONITORED DATA IN HIGH-SPEED MILLING

INTEGRATED MASTER IN MECHANICAL ENGINEERING

NOVA University Lisbon
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To my father and family

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Abstract

This dissertation investigates the complex factors influencing tool life in machining processes, with a specific focus on operations at Aernnova, a leading aero structures manufacturing company. The primary objective was to develop a more accurate and reliable method for predicting tool life, thereby improving process efficiency and reducing operational costs in the manufacturing of aluminium thin-walled parts. The research began with a review of traditional theoretical models, such as Taylor's Tool Life Equation, which were found to have limited applicability due to high variability in tool life data across different machines. To address these challenges, an approach was proposed, incorporating corrected machine air time values and specific operational conditions to compute tool life more accurately with the help of a developed methodology that combined power usage, tool air time and tool usage time.

Key findings include the identification of significant discrepancies in tool life predictions when using traditional models, necessitating a more tailored approach that accounts for the specific conditions present at Aernnova.

The practical application of this research is expected to result in significant improve-ments in tool management, leading to better quality control, reduced downtime, and lower operational costs for Aernnova. This dissertation contributes to the broader field of manufacturing engineering by showing the importance of combining empirical data analysis with theoretical models to achieve more accurate tool life predictions in complex manufacturing environments.

Keywords: Machining monitoring, Aluminium, Thin-walled parts, Methodology, Tool life prediction

Resumo

Esta dissertação investiga os complexos fatores que influenciam a vida útil das ferramentas em processos de maquinação, com um foco específico nas operações na Aernnova, uma empresa líder na fabricação de estruturas aeroespaciais. O principal objetivo foi desenvolver um método mais preciso e fiável para prever a vida útil das ferramentas, melhorando assim a eficiência dos processos e reduzindo os custos operacionais no fabrico de peças de paredes finas. A pesquisa começou com uma revisão dos modelos teóricos tradicionais, como a Equação de Vida de Ferramentas de Taylor, que se revelou ter uma aplicabilidade limitada devido à alta variabilidade dos dados de vida útil das ferramentas entre diferentes máquinas. Para enfrentar estes desafios, foi proposta uma abordagem que, incorporando valores corrigidos de tempo em ar da ferramenta e condições operacionais específicas, calcula a vida útil das ferramentas de forma mais precisa com a ajuda de uma metodologia desenvolvida que combinou valores de potência utilizada, tempo da ferramenta no ar e tempo total de uso da ferramenta.

Os principais resultados incluem a identificação de discrepâncias significativas nas previsões de vida útil das ferramentas ao usar modelos tradicionais, exigindo uma abordagem mais personalizada que tenha em conta as condições específicas presentes na Aernnova.

Espera-se que a aplicação prática desta pesquisa resulte em melhorias significativas na gestão de ferramentas, levando a um melhor controlo de qualidade, redução do tempo de inatividade e menores custos operacionais para a Aernnova. Esta dissertação mostra a importância de combinar a análise de dados empíricos com modelos teóricos para alcançar previsões mais precisas da vida útil das ferramentas em ambientes de manufatura complexos.

Palavras-chave: Monitorização de maquinação, Alumínio, Peças de paredes finas, Metodologia, Previsão da vida útil da ferramenta

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ACRONYMS

ATC Automatic Tool Changer *(p. 7)*

CSV Comma-separated Values *(pp. 15, 17)*

FRF Frequency Response Function *(p. 14)*

MQL Minimum Quantity of Lubrication *(p. 7)*

PN Part Number *(pp. x, 17, 23, 30, 40, 41, 43, 45, 48, 49)*

SL Spindle Load *(pp. 43, 44)*

TL Tool Life *(pp. 5, 18, 23, 25–27)*

TWP Thin-Walled Parts *(pp. 3, 4, 18)*

Symbols

a_e radial depth of cut [mm] *(pp. viii, 15, 19)*
a_p axial depth of cut [mm] *(pp. viii, 15, 19)*

f feed rate [mm/rev] *(p. 14)*
f_z feed per tooth [mm/tooth] *(pp. 14, 19)*

v_c cutting speed [mm/min] *(pp. 18, 19)*

1 Introduction

1.1 Context

The aviation industry stands as a dynamic and indispensable sector, playing a pivotal role in global transportation by connecting people and goods worldwide. Encompassing diverse activities such as aircraft design, manufacturing, operation, and maintenance, it also includes essential infrastructure like airports and air traffic control systems.

Aircraft manufacturing is an intricate and highly sophisticated process, demanding a blend of engineering, design, technology, and unwavering adherence to safety and regulatory standards. The ability to design and produce airplanes is widely distributed across the globe today. When boarding a plane operated by any major airline, we find advanced parts and components sourced from American, European, and Asian countries [2].

This collaborative effort in aircraft manufacturing engages aerospace engineers, technicians, scientists, and an extensive network of suppliers. The entire process is governed by rigorous safety and quality standards to ensure the reliability and safety of the aircraft. Embracing technological advancements, the industry continually pushes boundaries in terms of efficiency, sustainability, and innovation.

The aeronautical industry is a crucial sector that generates a wide range of cutting-edge products with diverse applications. Consequently, it is a strategic activity from an industrial, commercial, and technological standpoint.

Aeronautical science and technology are multidisciplinary in nature.

Portugal, a country of modest size, seeking to enhance its scientific, technological, and industrial development, would benefit from participating in collaboration programs and projects with more developed nations. The economic development attained through scientific and technological initiatives stems from the benefits derived from scientific and technological knowledge being placed at the service of the productive apparatus. In practice, this implies leveraging new technologies to modernize traditional sectors and sectors with brighter growth prospects.

Aernnova Aerospace S.A. is a Spanish multinational aerospace company headquartered in Vitoria (Álava). The corporation commenced its operations in the aeronautical industry in 1986, with the creation of Fibertecnic and the attainment of the initial component manufacturing contract for CASA (now a part of the Airbus Group). In 2022, Aernnova closed the deal to acquire Embraer's two facilities in Évora.

1.2 Aernnova Évora

Aernnova Évora is a large, state-of-the-art aerospace factory situated in Évora, Portugal. It is one of the biggest manufacturing facilities of the Spanish company and currently stands as the largest production centre of Aernnova worldwide.

Aernnova Évora specializes in the fabrication and assembly of aerospace structures for a diverse range of aircraft, encompassing single-aisle and regional jets, as well as executive and defence planes. The factory places a strong emphasis on composite materials and employs a variety of advanced manufacturing procedures.

The acquisition of Aernnova Évora has been a major strategic move for Aernnova, solidifying its position as a leading supplier of aerospace structures in the global market. The factory is anticipated to play a pivotal role in Aernnova's continuous growth and expansion.

Aernnova Évora is composed of two plants, "Metallic Structures" and "Composite Materials". The challenge imposed by the company focuses on the first one. The "Metallic Structures" unit is responsible for the production of wings for different models of planes. Wings are commonly made from the assembly of a variety of parts, as shown in Figure 1.1. Aernnova Évora produces aluminium thin-walled aircraft structures, mainly Ribs, Spars,

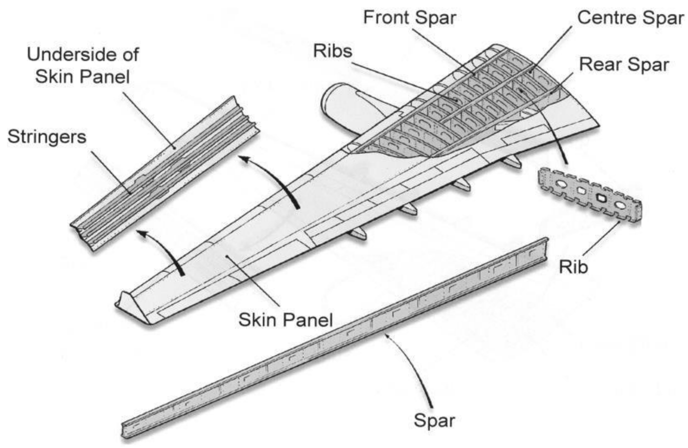

Figure 1.1: Integral elements of a common wing

and Skins. For example, ribs are complex structural elements shown in Figure 1.2.

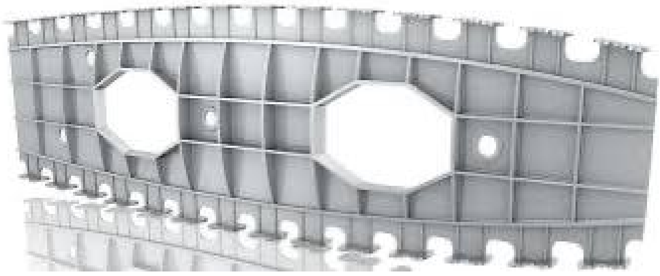

Figure 1.2: Example of a wing rib

1.3 Common problems of thin-walled elements machining

The term "integral (structural) thin-walled elements" is increasingly gaining traction. These elements possess a uniform design, relatively high rigidity, low weight in relation to their overall dimensions, and a remarkable strength-to-weight ratio [3–5].

They are commonly manufactured from monolithic plates made of lightweight metal alloys like aluminium [6]. During high-performance milling of these components, the amount of chips generated can account for up to 95% of the weight of the semifinished product [3, 5, 7–11].

Machining thin-walled elements poses several challenges due to the delicate nature of these structures. Thin-walled components are frequently employed in the aerospace, automotive, and other industries to reduce weight, but their machining can be intricate due to their susceptibility to distortion, vibration, and other issues.

The main manufacture problems are resumed below.

- Vibration:
  The machining of Thin-Walled Parts (TWP) presents a unique set of challenges due to their delicate nature and tendency to vibrate. These vibrations can cause chatter, which can lead to various issues, including poor surface quality, tool wear, and shortened tool life [12–15].
  The intricate design and thin cross-sections of TWPs make them susceptible to vibration during machining. This vibration arises from the inherent flexibility of these components, which are often constructed from lightweight materials like aluminium or titanium [16]. As the cutting tool removes material, the TWP experiences dynamic deformations, generating vibrations that can amplify and destabilize the machining process [12].
  These vibrations not only compromise the precision of machining, but also contribute to premature tool wear. As the tool engages with the vibrating workpiece, the alternating forces and stresses lead to accelerated wear and tear [14]. This can significantly shorten the tool's lifespan and increase machining costs [15].

- Deformation:

  Deformation in TWP can arise from various factors, broadly categorized into mechan-ical and thermal induced deformations. In most cases, TWP deformation is a result of the interplay between mechanical and thermal effects. Low structural stiffness and uneven stress distribution are significant contributors to TWP deformation [17].

  These factors, if not adequately addressed, can negatively impact the machining process and ultimately compromise the final machining quality.

  During machining, deformation can lead to various issues, including position error and cutter back-off. In the post-machining stage, deformation manifests in poor surface quality [15], low geometry accuracy [18], and the appearance of residual stresses [19].

- Damage:

  The high contact force between the fixture and the TWP often leads to various types of damage on the TWP's surface, including indentations, scratches, and clamping deformations [20]. This fixture-induced damage has a detrimental impact on the work holding effectiveness and quality of the TWP [21].

- Low adaptability:

  The limited adaptability of TWP fixtures primarily manifests in their inability to effectively adjust to the changing machining loads and complex geometric structures of TWPs. This shortcoming hinders the provision of sufficient support to counteract machining forces, ultimately leading to inaccurate machining outcomes [21–23].

  Moreover, TWP fixtures lack adaptability in terms of their layout. The limited number of adjustable elements or the restricted range of adjustment for these elements restricts the fixture's ability to conform to the specific machining process and the intricate geometry of TWPs [21].

  This lack of flexibility impedes the fixture's ability to effectively secure the workpiece and maintain stability during machining, compromising the overall machining quality.

In summary, machining thin-walled elements presents a multitude of technological challenges, primarily stemming from the susceptibility of these structures to deformation and elastic and plastic displacements. These displacements can lead to vibrations during machining, ultimately causing geometric errors in the workpiece's structure. [24].

Also, tool wear and the high variability of tool life values introduce another layer of complexity since it becomes hard to predict how tools will behave. This is a critical point that needs to be addressed in order to reduce downtime and part scraps.

1.4 Objectives

Driven by the current challenges and motivations in the factory, this project seeks to develop a methodology for defining practical tool life values based on real-time monitored machining data. **This work aims to utilize data measured by machining centres to gain insights into current processes and identify opportunities for improvement.**

The methodology will address identified issues on the shop floor and contribute to several key objectives:

- **Extend Tool Life (TL):**

  Enhance the lifespan of cutting tools, minimizing costs and downtime associated with frequent replacements

- **Optimize tool performance:**

  Achieve a balance between cutting speed, cutting depth, and feed rate to maximize process efficiency while maintaining desired part quality.

- **Minimize insert failures:**

  Reduce the frequency of insert breakage or premature wear, leading to more consistent production and less scrap.

- **Cutting Strategies (VeriCut):**

  Test different cutting strategies to reduce variability and increase production rates.

Figure 1.3 presents the process that aims to maximize work productivity through the analysis of the available machining database.

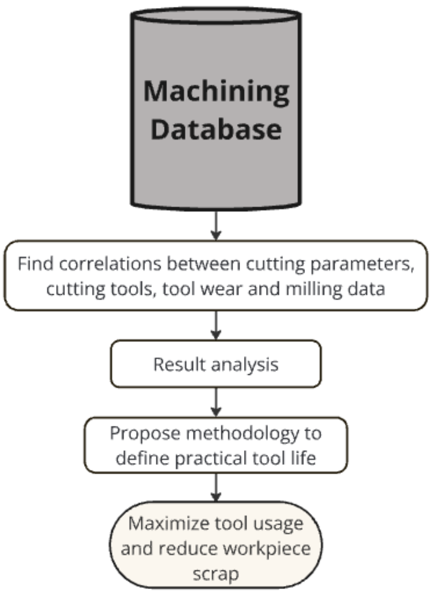

Figure 1.3: Flowchart describing main database objective and steps involved in the process

2

Current circumstances at the factory

2.1 Machining centers

The facility is outfitted with a diverse range of Makino MAG A12 Series machining centres, specifically engineered for high-throughput aerospace machining of large, intricate, aluminium monolithic components. These 5-axis horizontal machining centres, as shown in Figure 2.1, are equipped with cutting-edge technology that enables them to measure and record vibrations, heat, and calculate cutting forces in real time. Aernnova has machines that allow maximum workpieces of 20,000 mm X 2,300 mm x 500 mm.

Horizontal machining (with tool axis in horizontal direction) significantly reduces chip accumulation, a critical consideration due to the high material removal rates employed. This feature minimizes the need for frequent chip removal, enhancing machining efficiency and productivity.

Figure 2.1: Makino AG A12 - MAG 20.H

The Makino MAG A12-MAG Series technical specifications are given in table 2.1.

Table 2.1: Makino MAG A12 - MAG 20.H - Technical specifications

Technical Specifications	
A-Axis	220° (-110° ~+110°)
C-Axis	360°
Spindle RPM	33000 RPM
Rapid Transverse	65000 mm/min (X, Y & Z)
Cutting Feed rate	65000 mm/min (X, Y & Z)
Maximum Workpiece	Up to 20000 mm X 2300 mm x 500 mm
Maximum Payload	Up to 10500 kg
Automatic Tool Changer (ATC) Capacity	120 tools
Tool to Tool	13 sec
Maximum Tool Length HSK	305 mm
Maximum Tool Diameter	100 mm
Maximum Tool Weight	8 kg

2.2 Lubrication/cooling strategy

Cooling fluids play a crucial role in mitigating thermal or mechanical issues during machining [25]. Through lubrication, friction is reduced, and the resulting chips are efficiently removed from the cutting zone, contributing to prolonged tool life and enhanced machining quality [26]. However, the utilization of cooling fluids significantly impacts production costs and poses environmental and health hazards [26, 27].

Aernnova's chosen strategy is Minimum Quantity of Lubrication (MQL).

MQL offers several advantages, including reduced cutting fluid consumption, cost savings, diminished environmental impact, improved overall machining performance, and superior surface quality [28]. MQL machining has emerged as a practical approach for clean manufacturing within the context of sustainable production [29].

The cutting fluid can be classified into two categories based on the shape of the cutting zone: MQL technique, external distribution, and internal distribution [25]. The primary distinction between these two methods is depicted in Figure 2.2 [30].

In an external feed system, the aerosol generated in the atomizer is conveyed to the cutting zone via a nozzle that is externally attached to the machine tool, as illustrated in Figure 2.2(a) [30]. In contrast, the internal delivery system combines the cutting fluid and air within the nozzle before spraying the mixture into the cutting zone via a channel, as shown in Figure 2.2(b) [31].

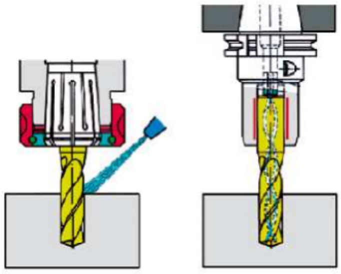

Figure 2.2: Two used methods of lubrication/cooling (a)- left & b)- right) [25, 30]

2.3 Common machining operations

As said in section 1.2, Aernnova mainly produces ribs, spars, and skins. These are elements with complex geometries that are difficult to machine. In figure 2.3 is shown a small section of a common part.

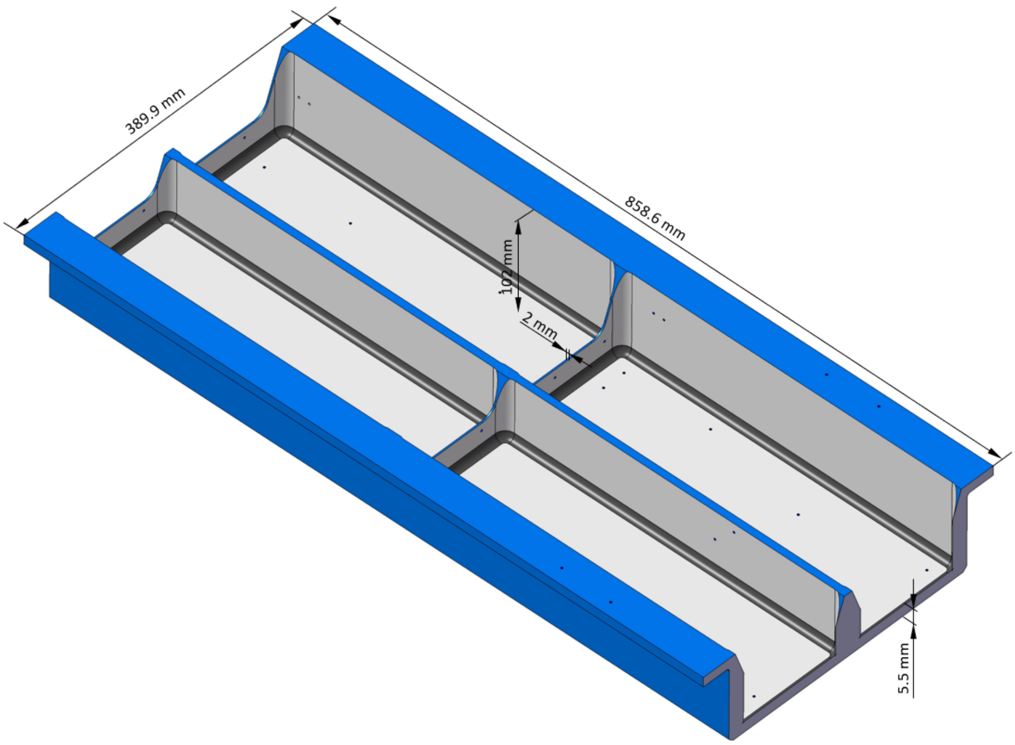

Figure 2.3: Common part section - General dimensions

The following list presents the operations needed to reach the final geometry and surface finish.

1. Rough Milling (Pocketing):

    - Purpose: Rough milling or pocketing is the initial stage of machining where most of the material is removed quickly to create the basic shape or cavity in a part, as shown in figure2.4.

- Process: In this operation, the tool removes large amounts of material in a series of passes, often using a larger tool with a more aggressive cut. The shape being cut can be a pocket (a depression) or another large feature of the part.
- Tool path: The tool path for rough milling is typically a zigzag or parallel pattern that gradually moves deeper into the material. The aim is to remove as much material as possible before switching to finer operations.

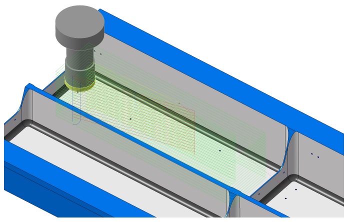

Figure 2.4: Rough milling - Tool path

2. Corner Reduction

- Purpose: Corner reduction refers to the technique of rounding or softening sharp internal or external corners in a part, as seen in figure 2.5.
- Process: This operation is usually done after rough milling, where the sharp corners are too sharp for either aesthetic or functional purposes. Corner rounding tools or end mills are used to ensure a smoother transition at the corner.
- Tool path: The tool typically follows the internal geometry of the corner, taking a shallow pass to reduce the sharpness without cutting too much material at once.

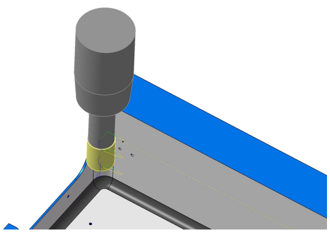

Figure 2.5: Corner reduction - Tool path

3. Bottom Surface Finishing

- Purpose: This refers to the final pass taken to smooth the bottom surface of a pocket or feature, as seen in figure 2.6.
- Process: After rough milling, the bottom of the pocket or feature may have a rough finish. A bottom surface finishing pass is made using a smaller, finer tool to smooth out the surface and achieve the desired finish.

- Tool path: A finer, more precise tool is used to make the final pass. The tool follows the bottom surface, often in a circular or spiral pattern, to ensure a smooth finish.

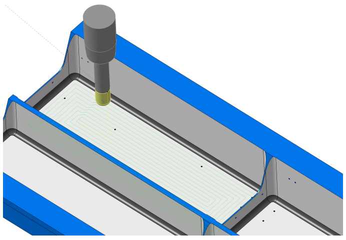

Figure 2.6: Bottom surface finishing - Tool path

4. Wall Surface Finishing

- Purpose: This operation focuses on finishing the vertical walls of a pocket or feature, as shown in figure 2.7.
- Process: After the rough milling phase, the walls may have tool marks or roughness that need to be cleaned up. Wall surface finishing is typically done using a smaller tool to ensure a smooth vertical finish.
- Tool path: The tool path follows the vertical walls of the feature, often with a step-over to reduce tool marks. A finer tool is used to achieve the desired surface quality.

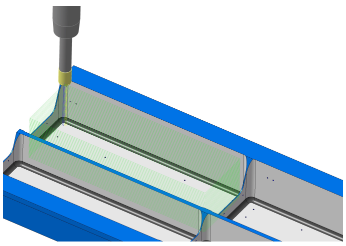

Figure 2.7: Wall surface finishing - Tool path

5. Radius Finishing

- Purpose: Radius finishing is a specific type of finishing operation where the goal is to smooth out a curved or rounded section of a part, as shown in figure 2.8.
- Process: This operation is performed on areas of the part with curved or radiused edges, where a fine tool is used to ensure that the radius is smooth and free of any tool marks.
- Tool path: The tool typically follows the radiused areas, often using a smaller diameter tool to get a precise radius finish. The tool path may be circular, following the contour of the radius.

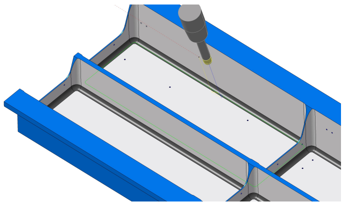

Figure 2.8: Radius finishing - Tool path

In order to optimize tools paths and machining strategies, Aernnova uses a software called Vericut. By simulating the tool path, it detects errors in programs as well as areas of inefficiency. A simulation illustration is shown in figure 2.9.

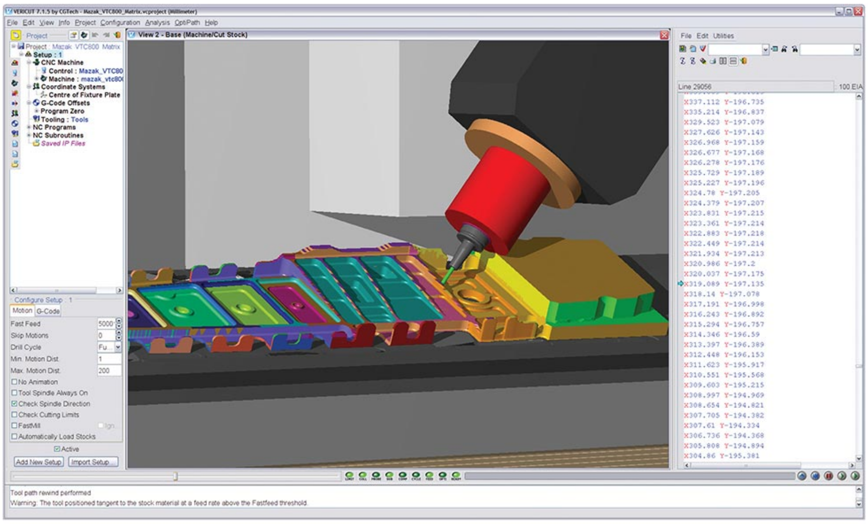

Figure 2.9: Illustration of a Vericut simulation

2.4 Tool selection

Machining of the parts utilizes carbide-coated tools: composed of a substrate and a thin (1-3 microns) hard, anti-frictional, chemically inert, and thermally isolating layer, these tools boast enhanced protection against mechanical stress, reduced friction and tool-chip interaction, and improved wear resistance across a spectrum of cutting temperatures [32].

Tool selection for each process and cut geometry is crucial: while prioritizing minimal tool diversity, the appropriate tool is chosen based on the specific machining process and desired cut geometry.

There is a wide variety of high-speed milling tools available:

- **Ball nose end mills:**

  Versatile tools that can be used for a variety of operations, including slotting, profiling, and helical interpolation. Ball-shaped end that can create smooth finishes and is less likely to chip than other end mills.

- **Bull nose end mills:**

  Similar to ball nose end mills, have a sharper nose that can be used for more aggressive cutting. Often used for roughing operations.

- **Flat nose end mills:**

  Flat end that is good for creating square shoulders and pockets. Not as versatile as ball nose end mills, but more efficient for certain operations.

- **Corner radius end mills:**

  Radius on the end that can be used to create rounded corners, good for creating smooth finishes.

- **Ball nose corner radius end mills:**

  Combine the features of ball nose and corner radius end mills, versatile tools that can be used for a variety of operations.

- **Roughing end mills:**

  Designed to remove large amounts of material quickly, have a large number of flutes and sharp cutting edges.

- **Finishing end mills:**

  Designed to create smooth finishes, more flutes than roughing end mills.

- **Milling Cutters:**

  Simultaneous radial and axial engagement with the workpiece. It creates an angled "ramping" motion as the cutter enters and exits the material. Particularly useful for machining features like pockets, cavities, and engravings with closed profiles.

2.5 Cutting parameters selection

2.5.1 Current approach for cutting parameters selection

Figure 2.10 presents a flowchart illustrating the current process for parameter selection. The steps for each parameter selection is explained in the upcoming section. Initially, the desired final part geometry dictates the selection of cutting geometry and machining process type. These two factors influence the choice of tool and the axial and radial cutting depths. Most of the parts are machined out of 7000 series aluminium, which needs high cutting speeds for the best results.

Subsequently, the Tap Test is performed on the chosen tool, reviling an optimal spindle speed. The process feed rate is also determined by the tool specifications. Finally, experimental tests are conducted, and the database is updated if the results meet the desired criteria.

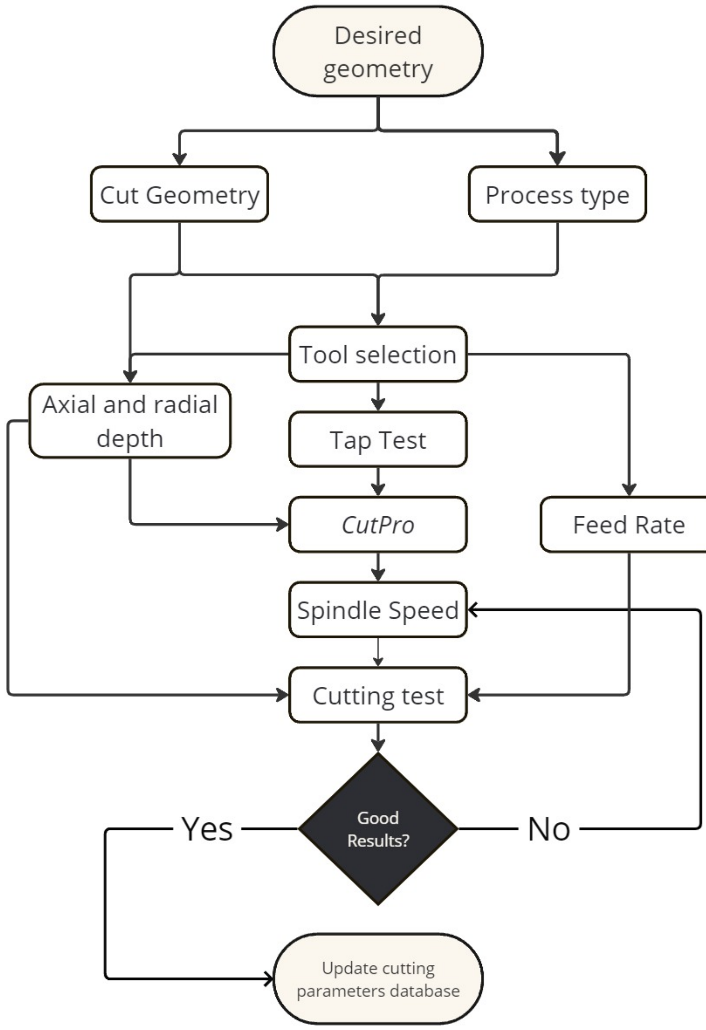

Figure 2.10: Current parameters selection process

2.5.2 Cutting parameters

2.5.2.1 Introduction

Tool wear and vibration pose significant challenges in the milling process of aviation aluminium alloy. The machining accuracy and surface quality of aluminium alloy milling are influenced by various factors, including cutting parameters, material mechanical properties, machine tools, and other relevant parameters [33].

The careful selection of cutting parameters is of paramount importance in any machining process, a crucial task that industries face daily [34]. Traditionally, cutting parameters have been determined using machining data handbooks, operator experience, or cutting tests. However, with the advancement of technology, alternative methods for obtaining cutting parameters have been explored [35].

Cutting parameters, consisting of spindle speed, feed rate, cutting depth, and cutting width, play a critical role in determining machining productivity, cost, and quality [36].

An optimized set of cutting parameters can minimize tool wear, reduce vibration, and achieve high-quality machining outcomes. However, selecting the appropriate parameters can be challenging due to the complex interplay between material properties, machine capabilities, and machining conditions.

2.5.2.2 Cutting speed selection

Aernnova employs a technique called "Tap test" to determine the optimal spindle speed and therefore the cutting speed for machining thin-walled components. This method, also known as impact testing, assesses the structural dynamics of a machine tool assembly by exciting it with a hammer and measuring its response.

The tip of the milling tool is struck with a hammer to induce vibrations, and the resulting acceleration data is collected using an accelerometer (figure 2.11). The relationship between the applied force (input) and the measured acceleration (output) represents the structure's transfer function, also known as the (Frequency Response Function (FRF)) [37].

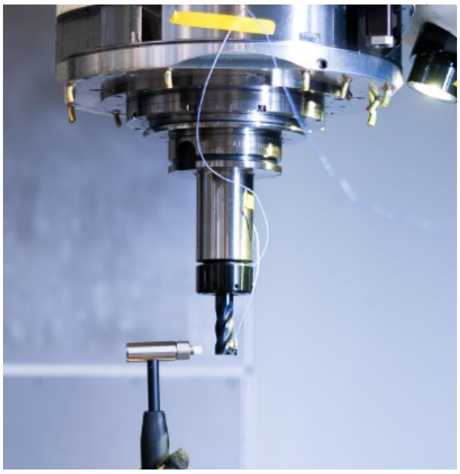

Figure 2.11: Tap test illustration

A software called CUTPRO [38] utilizes the FRF as input and calculates the optimal spindle speed. By considering the FRF and the system's natural frequencies, CUTPRO can optimize the cutting speed (RPM) to avoid resonance. It calculates the optimal spindle speed that moves the cutting conditions away from the resonance zone, thereby reducing the likelihood of unwanted vibrations or chatter.

This tap testing technique provides a precise and data-driven approach for selecting the optimal spindle speed for thin-walled components, leading to improved machining quality and enhanced productivity in the aerospace industry.

2.5.2.3 Feed rate selection

The feed rate, f [mm/rev], is the distance travelled by the cutting tool per revolution. In cutting tools with multiple cutting edges, the feed per tooth, f_z [mm/tooth], is the distance travelled by each cutting edge per revolution [39].

In high speed milling, the tool manufacturer usually defines an optimal feed per tooth, commonly between 0.2 and 0.25 [mm/tooth]. The feed rate is then calculated with Equation 2.1, as a function of feed per tooth and the number of cutting edges, Z.

$$f = f_z \cdot Z \tag{2.1}$$

2.5.2.4 Axial and radial depth of cut

The axial depth of cut, a_p [mm], denotes the length of the cutting edge that directly participates in the machining process, measured perpendicular to the workpiece plane (Figure 2.12) as defined in ISO 3002-1. Throughout this work, the axial depth of cut is simply referred to as the depth of cut. The radial depth of cut, a_e [mm], refers to the dimension of the machined area measured in the workpiece plane, normal to the feed direction (Figure 2.12) (ISO 3002-1).

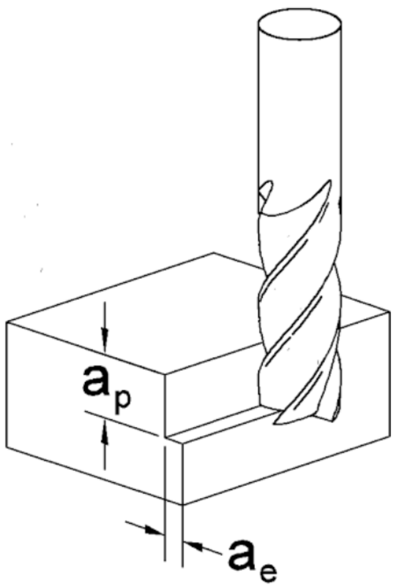

Figure 2.12: Axial depth (a_p) and radial depth (a_e)

2.6 Machining database

As said in section 2.1, Makino A12-MAG Series machines are capable of measuring data while the parts are being machined. The data recorded with an acquisition rate of 3Hz and is then saved into two Comma-separated Values (CSV) files (FOCAS and AST) that are read with the Makino software, as shown in figure 2.13.

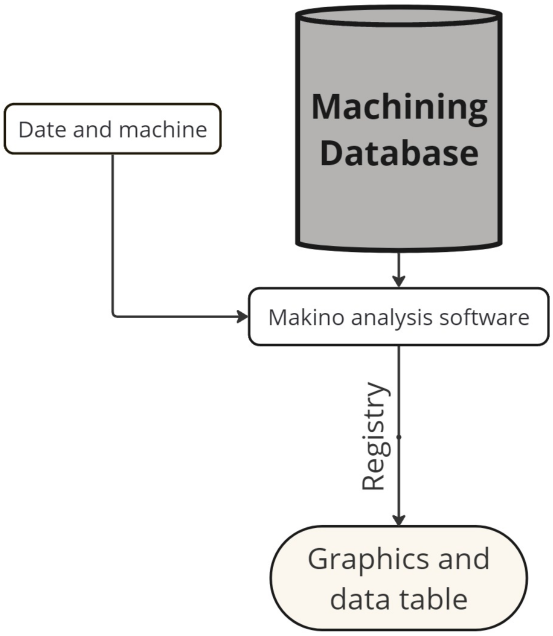

Figure 2.13: Current data treatment process used at Aernnova

Makino software analyses the available data and creates a number of graphics (Figure 2.14), and a table with relevant data (Table 2.2). Table 2.3 presents observations related to the data acquired from the machines. These will be relevant and used to "gain insights into current processes and identify opportunities for improvement"(Section 1.4).

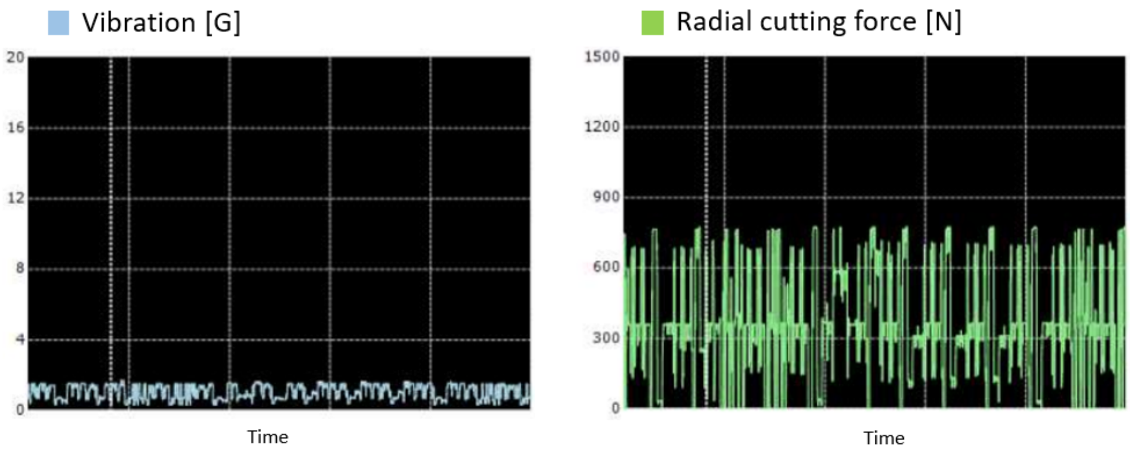

Figure 2.14: Example of graphics - Vibration and radial cutting force

Table 2.2: Machining data example

CSV Type	Data Name	Value	Unit
FOCAS	Date	28/06/2023 07:18:28.0	
	Motor Coil	61	[ºC]
	Front Out (exterior)	30.3	[ºC]
	Rear Out (exterior)	27.2	[ºC]
	Spindle Command Speed	33000	[RPM]
	Spindle Actual Speed	32992	[RPM]
	Spindle Direction	CW	
	Command Feed Speed	20250	[mm/min.]
	Actual Feed Speed	17649	[mm/min.]
	Feed Override	90	[%]
	Jog Override	20	[%]
	Rapid Override	100	[%]
	Spindle Pot	2	
	Spindle PTN	1	
	PN	XXXXXXXXX	
	Execution Block	N69934 X-1349.4239 Y626.2282 F20250.	
	Vibration	0.7	[G]
	Spindle Load	69.42	[%]
AST	Radial Force	648	[N]
	Axial Force	131	[N]
	Spindle Power	83.3	[kW]
	Spindle Torque	24.1	[N m]

Table 2.3: Data observations

Data	Observations - This information will be used at "Methodology definition" and "Database interpretation and discovery of correlations"
Motor Coil Front Out (exterior) Rear Out (exterior)	Allows to evaluate the severity of the process on the machine itself.
Spindle Actual Speed	Provides real-time correct information.
Radial Force Axial Force	Forces are not measured, they are calculated by the machine.
Vibration	Allows evaluating working tool conditions.
Spindle Load Spindle Power Spindle Torque	Allows to evaluate the machine capacity that is being used.

2.7 Used milling cutter

2.7.1 Tool characteristics

The 50 mm Walter M2131 Ramping milling cutter (designated T1 by Aernnova) is the most used tool at the factory, since it is necessary in the production of every single part. The milling cutter is paired with Walter (DGT150408R-K85 WNN15) inserts [40], specially designed with a positive rhombic shape optimized for pocket milling. The insert's geometry is shown in figure 2.15 as well as the specifications (Table 2.4). The assembly of the tool is shown in Figure 2.16 and the current cutting parameters used for this tool are presented in Table 2.5. v_c and RPM are 2 parameters that are related to each other. v_c is the most commonly referred when talking about cutting parameters, Aernnova uses RPM since it is the value that machine tools use for input.

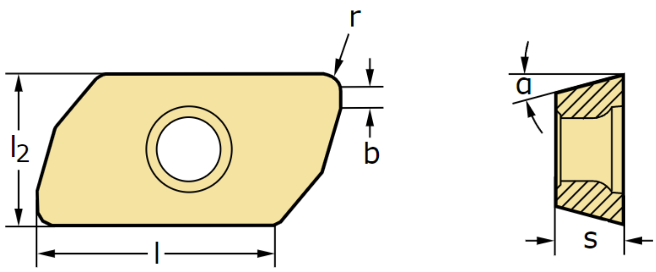

Figure 2.15: Walter ZDGT150408R-K85 WNN15 insert geometry

Table 2.4: Walter ZDGT150408R-K85 WNN15 insert specifications [40]

Description	Symbol	Value
Indexable insert tolerance class		G
Number of cutting edges		2
Indexable insert width	l_2	10.5 mm
Cutting edge length	l	16.2 mm
Insert thickness		4.76 mm
Clearance angle major	α	15°
Corner radius	r	3.0 mm
Wiper cutting edge length	b	1.2 mm
Tool diameter	ø	50 mm

2.7.2 Current problems

The 50 mm Walter M2131 Ramping milling cutter is used for rough milling and has an extremely high material removal rate. TWP require loads of material removal, making this tool exceptional for this purpose.

Discussion with the company helped identify the tool's current problems:

- TL of 350 min, mainly due to tool wear (tool life stands for the time the tool is being used; cutting time + air time);

Figure 2.16: Walter M2131 ramping milling cutter with inserts

Table 2.5: Current parameters used for T1 tool

Parameter	Value	Unit
Spindle Speed	33000	[RPM]
Feed Speed	24000	[mm/min]
a_p	7.6	[mm]
a_e	40.0	[mm]
f_z	0.18	[mm/tooth]
Material Removal Rate	6566	[cm^3/min]
	18.06	[kg/min]
v_c	5181	[m/min]

- Since it is used in all parts, it comprises high consumption that leads to high costs;
- Inserts failure:

  In high speed machining the spindle usually rotates at 30000 RPM. Pieces that break off of the inserts can provoke irreparable damage to the working piece, damage the machine itself, or even break the door's glass.

The potential costs associated with these events include scrapped components, downtime costs, and repair expenses, which can significantly impact the overall cost of the projects.

2.8 Cutting tool wear mechanisms

Cutting tool edge wear and failure can be identified in different categories. Sandvik has a list of the most common types of tool wear mechanisms:

1. **Flank wear:**

   Among tool wear types, flank wear takes the top spot. It's favoured because it allows for consistent and dependable tool lifespan. This wear happens due to abrasion caused by hard elements within the material being machined [41].

An example of Flank wear is shown in figure 2.17.

Figure 2.17: Flank wear - Example [41]

2. **Crater wear:**

   Crater wear eats away at the top surface (rake face) of the cutting tool insert, as seen in figure 2.18. This wear stems from a chemical reaction between the tool and the workpiece material, and it gets worse as cutting speed increases.

   If left unchecked, crater wear can significantly weaken the cutting edge, even leading to breakage [41].

Figure 2.18: Crater wear - Example [41]

3. **Built-up edge:**

   This wear happens when tiny chips of material weld themselves onto the cutting tool insert, as presented in figure 2.19

   It's a common problem when machining materials that tend to stick, like low-carbon steel, stainless steel, and aluminium. Using a slower cutting speed can also make built-up edge more likely [41].

Figure 2.19: Built-up edge - Example [41]

4. **Notch wear:**

   This type of insert wear shows up as deep gouges on both the top (rake face) and the side (flank) of the insert, right where the cut is made, figure 2.20. It's caused by chips sticking to the insert under high pressure and heat, making the insert surface harder and more prone to wear.

   This wear is common when machining materials like stainless steel and high-strength steels (HRSA) [41].

Figure 2.20: Notch wear - Example [41]

5. **Thermal cracks:**

   Sharp temperature swings from hot to cold at the cutting edge can cause cracks to develop. These cracks typically run straight down (perpendicular) from the cutting edge,as shown in figure 2.21.

   This type of wear, called thermal cracking, is more likely to happen during milling because of the interrupted cutting action [41].

Figure 2.21: Thermal cracks - Example [41]

6. **Edge chipping/breakage:**

   Chipping or a complete tool break (figure 2.22) happens when the cutting tool gets overloaded.

   This overload can be caused by several things, like the chips hitting the tool repeatedly (chip hammering), taking cuts or feeds that are too aggressive, hidden hard materials in the workpiece, a build-up of machined material on the tool (built-up edge), shaky machining conditions (vibrations), or a tool insert that's already badly worn [41].

Figure 2.22: Edge chipping - Example [41]

3

Tool consumption registry analysis

3.1 Introduction

In 2021, an Excel file was implemented to record all tool changes performed. In this file it is registered the tool involved, the reason for its change/failure, the machine it was being used on, the TL until the occurrence, and the PN that was being machined.

The flowchart presented in figure 3.1 describes the process tool change and consumption registry. The process is started by the activation of the machine tool alarm for tool TL, and the operator checks if there is visible damage to the tool. In case of no damage, operator increases tool life alarm value and the machine can continue top use the tool. If there is visual damage, the operator removes the tool from the machine and takes it to the presetter room.

If it is not an insert tool, the operator changes the tool and continues the process. If it is an insert tool, the operator checks if the inserts have already been rotated and if not, he proceeds to rotate them (used inserts have 2 sets of cutting edges so they are used twice, in two different orientations).

If they have already been rotated, operator changes to a new set of inserts and torque bolts. He then proceeds to make the registry of different information in the Excel file. Finally, operator resets tool TL to 0 and measures and sets new tool offsets.

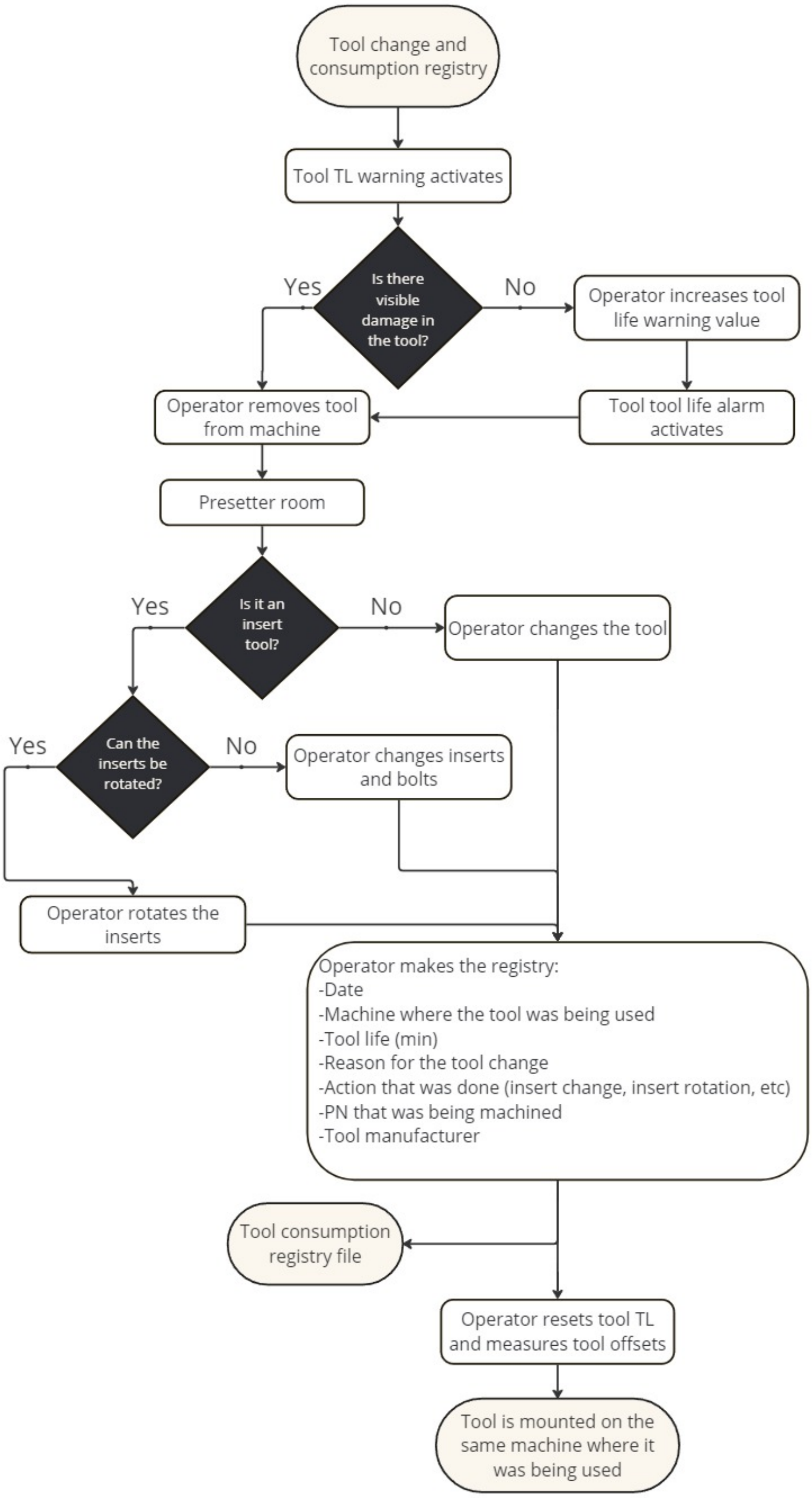

Figure 3.1: Flowchart of tool change and consumption registry process

Analysing this file can help find correlations between the parameters mentioned above.

A resume of all tool changes was carried out and the top 5 most frequent are shown in the graph 3.2.

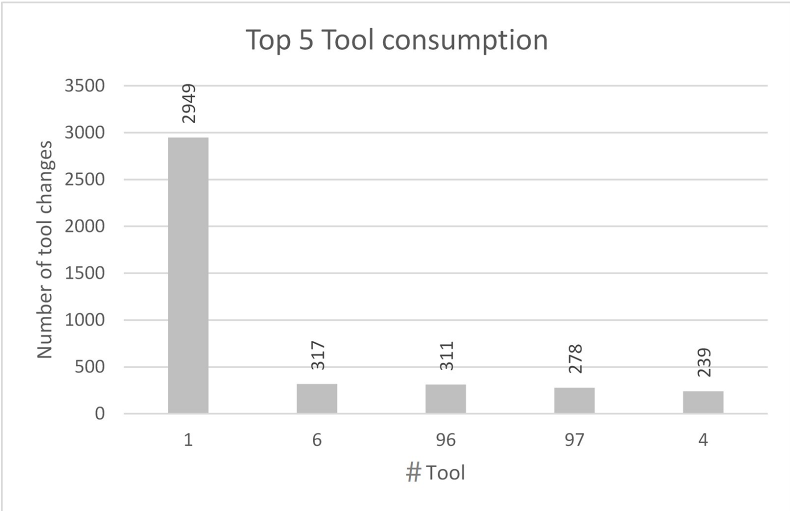

Figure 3.2: Top 5 tool consumption

It can be observed that the consumption of tool T1 is about 10 times higher than any other used in the factory. This is the main reason why this will be focused on the T1.

3.2 T1 Tool life

The table 3.1 presents all the registered data related to the lifetime of the inserts. These data were gathered from 2021-02-25 to 2024-04-03, making a total of 2949 entries. Some conclusions can be taken from this table:

- 39.6 % of the inserts reached TL goal (>350 minutes) and then were changed;
- 37.2 % of the inserts lasted between 200 and 350 minutes;
- 10.6 % of the inserts broke;
- About 23% of the inserts end up having a lifetime much lower than what is expected (less than 200 minutes);
- There are some registry errors (registered as "TL exceeded" but the change occurred before the TL was achieved) and some information was not registered.

Table 3.1: T1 change reason vs tool life

Reason	Tool life (min)			
	Total	t <200	200<= t <350	350<= t
TL exceeded	1930	107*	761	1052
Insert wear	315	156	127	29
Insert breakage	314	181	103	26
Tool holder damaged	98	62	22	13
Spindle Load alarm	85	29	52	3
Measuring error	20	15	1	0
Balluf loss	18	2	4	11
Welded aluminium	15	9	5	1
Insert and tool holder damaged	1	1	0	0
No information	153	112	23	5
Total	2949	674	1098	1140

*Data should be ignored due to registry error It was then possible to analyse the lifetime of this tool on different machines, as shown in graph 3.3. Aernnova has defined a theoretical TL for this tool that depends on the machine it is being used on. These are empirical values since that have never been confirmed by testing. It can be observed that the average TL of the tool is lower than what was determined. When the term "tool life" is used, Aernnova is referring to the time that the tool is being used, the sum of cutting time and air time.

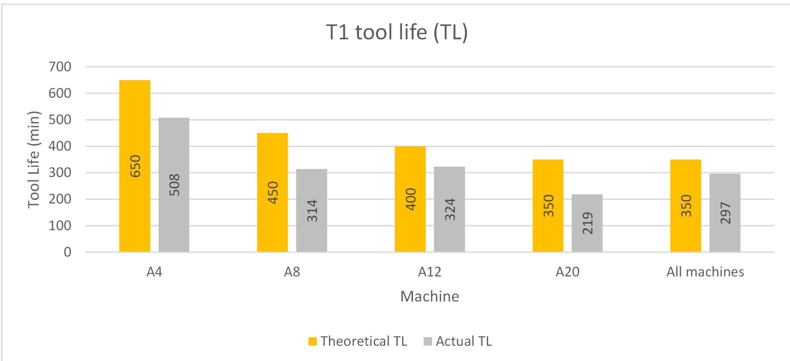

Figure 3.3: T1 tool life by machine

The longer the machine, the shorter the TL. This may be related to the length of the parts being machined on each machine. For example, on the machine tools A20, the tool can make continuous cuts of 17/18 meters, while on an A4, much of the TL is spent in air time.

Graph 3.4 shows the dispersion of the tool life since 2021. The R^2 is about 0.15, which demonstrates the difficulty in finding relationships, the variation of the data relative to the regression line is quite pronounced, showing that TL is almost aleatory. The T1 tool is utilized to produce an extremely high variety of parts, also explaining the variability of the data.

The reasons for tool changes were then analysed, which can be seen in graph 3.5.

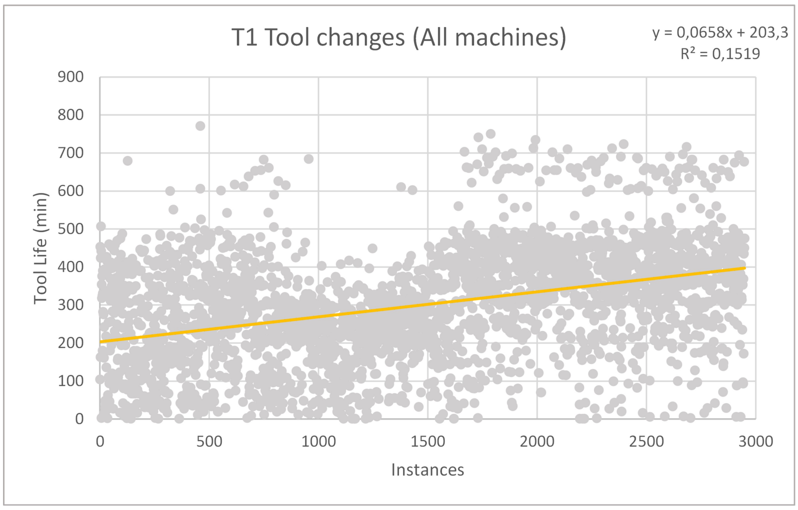

Figure 3.4: T1 tool changes (all machines)

Values are previously shown in table 3.1.

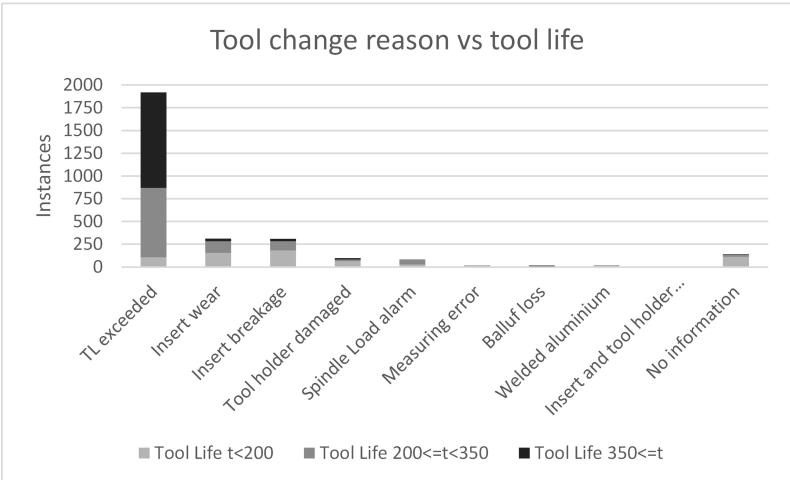

Figure 3.5: T1 change reason vs tool life - graph

3.3 Insert breakage analysis

The tool consumption is marked by the TL being exceeded, but about 10% of tool consumption is due to insert breakage. As mentioned earlier, this can translate into high costs to the company.

Another analysis was also carried out which concluded that insert breakage on the A20 machine tools is twice as high as on the other machines, as can be seen in graph 3.6.

Mitigating insert breakage can be quite advantageous, as it can lead to reductions in tool consumption costs, but also avoid costs related to scrapping parts.

Graph 3.7 shows the dispersion of the TL when the inserts break. In graphs 3.8, 3.9, 3.10 and 3.11, the same analysis is done, but individually, for each type of machine.

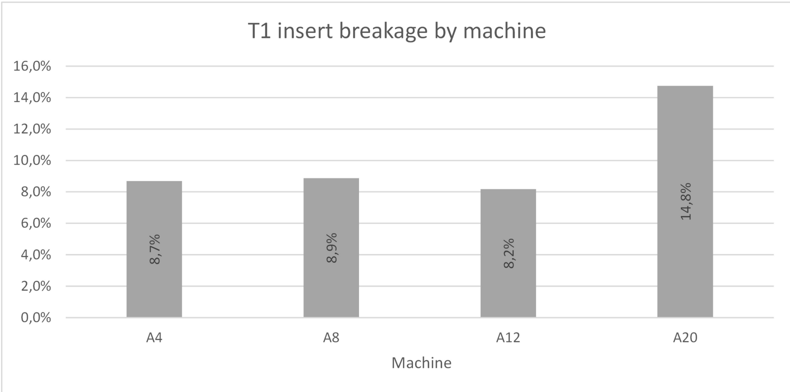

Figure 3.6: Percentage of insert breakage by machine

Once again, the R^2 of all graphs is quite low, which shows the high unpredictability of insert failure.

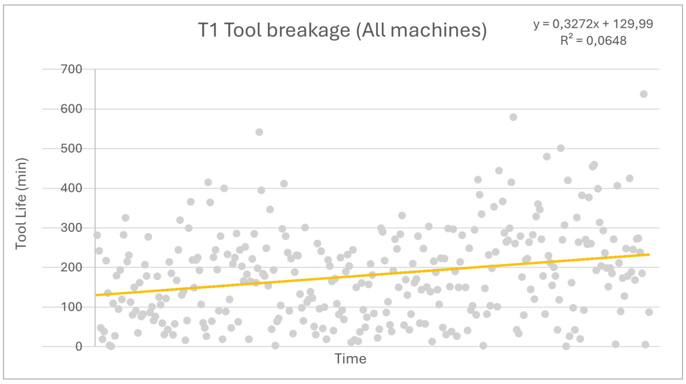

Figure 3.7: T1 tool breakage dispersion

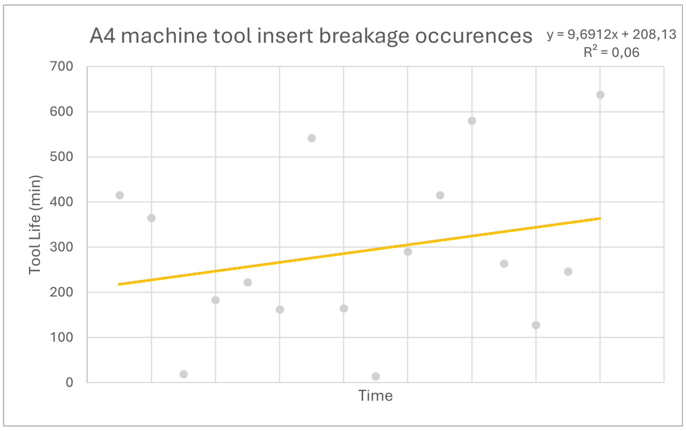

Figure 3.8: T1 tool breakage - A4

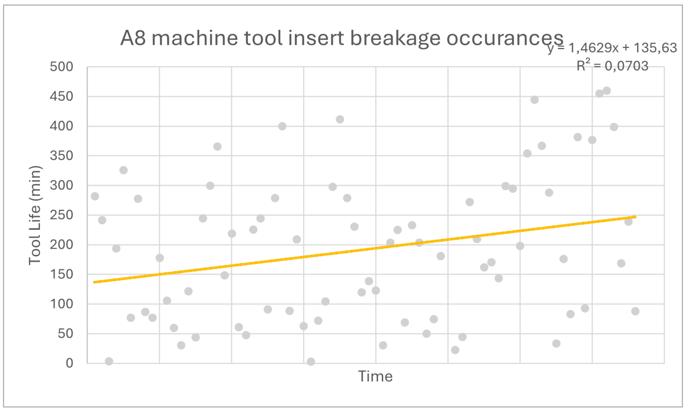

Figure 3.9: T1 tool breakage - A8

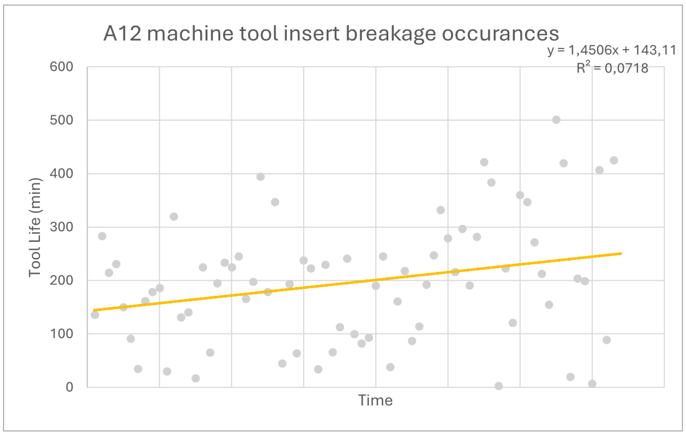

Figure 3.10: T1 tool breakage - A12

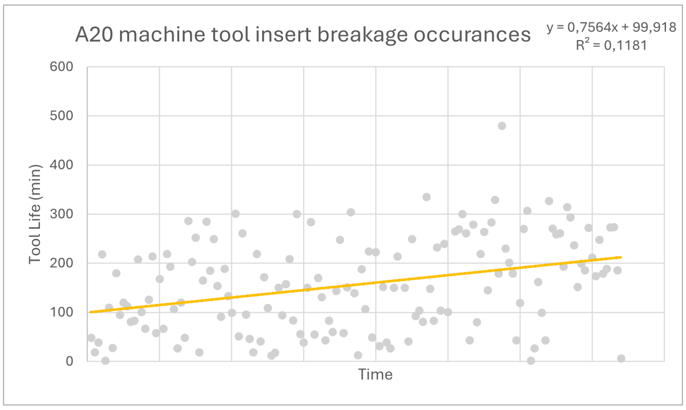

Figure 3.11: T1 tool breakage - A20

3.4 Relation between PN and T1 tool breakage

With the analysis of this file, it was also found that some PNs are more susceptible to insertion failures. Table 3.2 lists the top 5 PNs with the most insert breakages. This analysis specifically examined inserts that failed before reaching a 150-minute time limit during the almost 3-year time period. Due to Aernnova policy, part numbers cannot be revealed so they are referred to as "Part A", for example.

Table 3.2: Insert breakages while machining certain PNs

Part Number	Number of insert breaks
Part A	16
Part B	9
Part C	7
Part D	6
Part E	4

3.5 Implemented changes to the process

Information obtained from the file wasn't sufficient to assess tool damage effectively.

To address this gap, a new process was implemented where inserts are collected, numbered, and stored. This allows for individual insert analysis and comparison to determine if replacements were made when inserts were at the limit. Figure 3.12 illustrates this revised process.

At this time, tools aren't usually balanced at Aernnova. This can lead to more tool wear due to vibrations.

Figure 3.12 also shows a change in the process where the tool balancing is systematically done. This change and its impact can be analysed and quantified in future work.

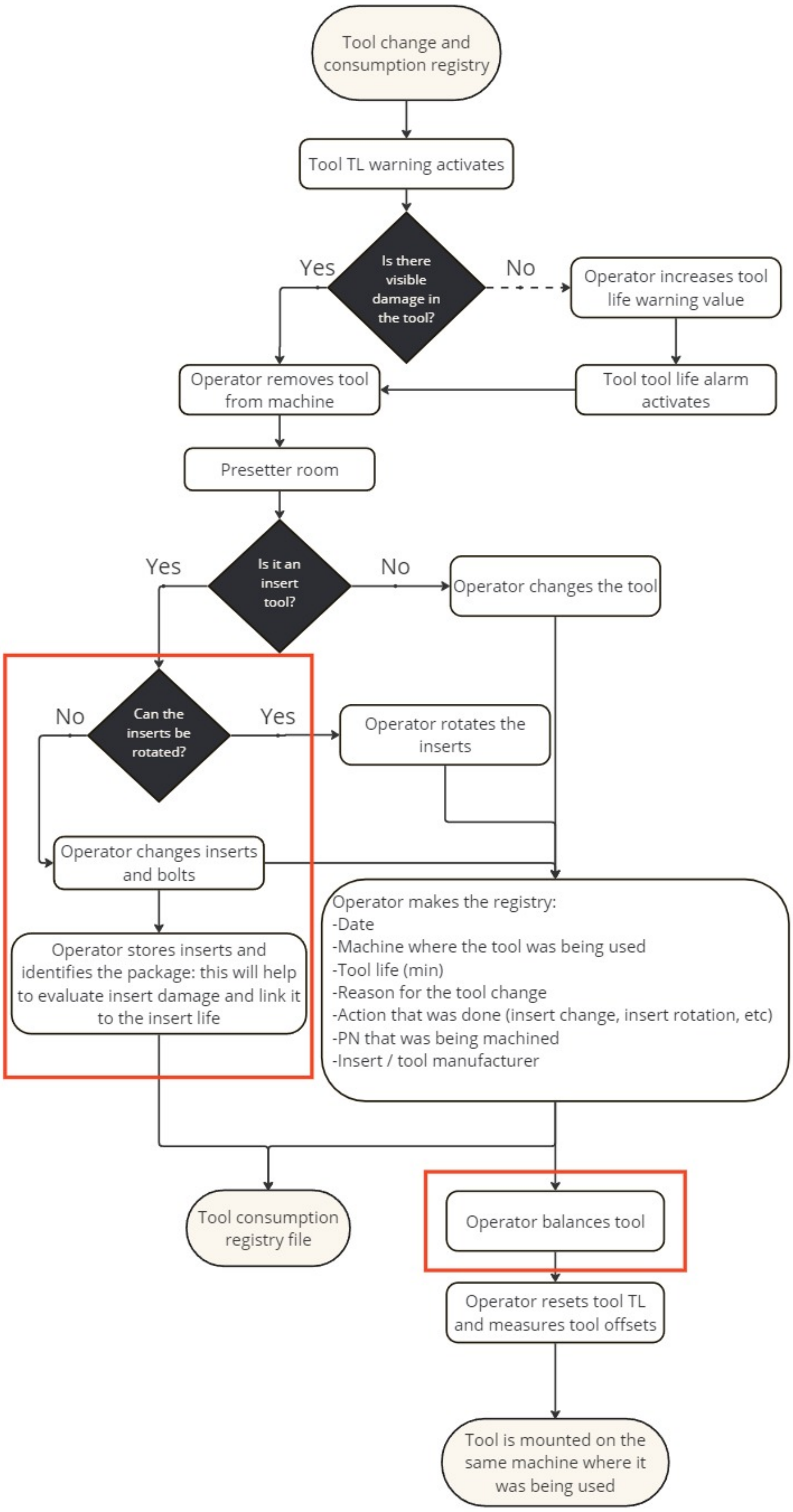

Figure 3.12: Flowchart of tool change and consumption registry process (updated)

3.6 Insert analysis and wear mechanism identification

Inserts from the A8 machines started being collected, identified and stored in 03/04/2024 by Aernnova operators. In this procedure, 9 samples were analysed to better understand if insert changes were being executed at the right time.

Inserts can now be analysed and catalogued by wear mechanism according to the categories presented in section 2.8. Since this is the first iteration of the work, the analysis of insert's damaged was based only on visual aspects.

The figures below show the comparison between collected inserts and standard wear mechanism, namely:

- Figure 3.13 shows inserts with flank wear that can be compared with the example shown in figure 2.17;
- Figure 3.14 shows inserts with little to no flank wear. These inserts could have been used for a longer period of time;
- Figure 3.15 shows inserts with edge chipping that can be compared with the example shown in figure 2.22;
- Figure 3.16 shows inserts with a built-up edge that can be compared with the example shown in figure 2.19.

Figure 3.13: Inserts with flank wear

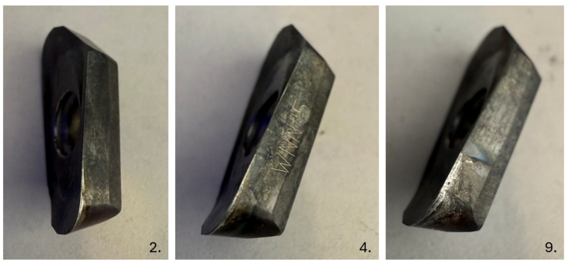

Figure 3.14: Inserts with no flank wear

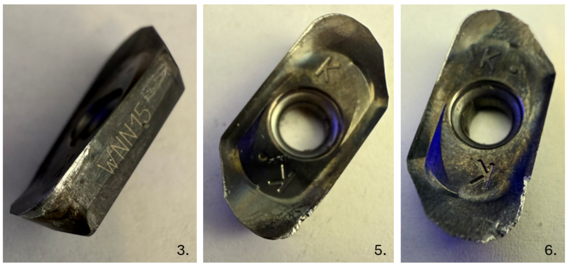

Figure 3.15: Inserts with edge chipping

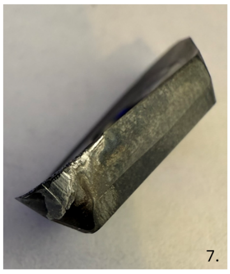

Figure 3.16: Inserts with build-up edge

The conclusions of the visual inspection are presented in table 3.3.

In the future, if this work shows some kind of improvement in inserts tool life definition, a more complex, based on ISO 3685:1993 standard analysis of insert wear should be defined and executed.

Table 3.3: Insert damage characterisation

Insert pack number	TL (min)	Type of wear mechanism	Still good to be used?
1	479	Flank Wear	No
2	444	No edge wear	Yes
3	473	Edge chipping	No
4	459	No edge wear	Yes
5	275	Edge chipping	No
6	423	Edge chipping	No
7	448	Built-up Edge	No
8	521	Flank Wear	No
9	159	No edge wear	Yes

The visual inspection of the insert packs revealed that some were changed in a state of wear that could still be categorised as good to use. Unnecessary insert changes lead to sub-utilization of inserts durability, thus increasing overall machining costs.

3.7 Theoretical analysis of tool life

3.7.1 Introduction

The theoretical analysis of tool life involves developing mathematical models and simulations to predict the lifespan of a cutting tool based on various influencing factors. This analysis aims to quantify the impact of real-world parameters on tool wear.

By understanding the interactions between cutting speed, feed rate, depth of cut, tool material, workpiece material, and other variables, models can be developed to estimate tool life more accurately. These models are crucial for optimizing machining processes, reducing costs, and improving product quality.

3.7.2 Taylor's tool life equation

The Taylor's tool life equation (3.1) is a fundamental equation used in machining to estimate the relationship between cutting speed and tool life. It is a formula that helps predict how long a cutting tool will last (tool life) based on the speed it is being used at (cutting speed).

$$V \cdot T^n = C \tag{3.1}$$

Where,

V = Cutting speed (m/min)
T= Tool life (minutes)
n = Tool life Index, depends on cutting tool material and work type
C = Machining constant (specific to the tool-work material combination)

The utilization of Taylor's tool life equation would be a good way to gain a better understanding of the work, but there are some points that in this case difficult the application of the theory, namely:

- The goal of this work is to utilize data gathered every day at Aernnova. The current data lake is not suitable to the Taylor's tool life equation. Taylor's tool life equation would require the realization of experiments, and that is something we were not looking to do.

- For T1 tool, the manufacturer of the inserts (Walter) does not stipulate an estimated tool life since the inserts can be used in a vast quantity of different materials and applications.

- The results of the tool consumption registry analysis shows that tool life varies in each machine type. Aernnova uses the same cutting parameters across all machines, for the same tool. Since tool, cutting speed and work-piece material are the same on all cases, the application of Taylor's tool life equation would indicate the same tool life for all machines. This contradicts the data that is extracted at Aernnova. The differences in T1 tool life while being utilizes in each machine can be seen in section 3.2, figure 3.3.

3.7.3 Conclusion

The chapter on Taylor's tool life equation provided a comprehensive exploration of one of the most widely recognized models for predicting tool life in machining processes. Taylor's equation, which expresses the relationship between cutting speed and tool life, has been instrumental in the development of machining theory and practice. However, its application within the specific context of Aernnova's operations revealed several limitations that underscore the need for more customized approaches to tool life prediction.

Taylor's Tool Life Equation has proven effective in many industrial applications due to its simplicity and empirical basis. The equation's ability to provide a first-order approximation of the relationship between cutting speed and tool life is invaluable in general machining settings. However, its effectiveness is contingent upon the consistency of operational conditions, such as machine calibration, tool material, and workpiece properties.

The application of Taylor's equation at Aernnova highlighted its limitations when dealing with high variability in operational conditions. Variations in machine performance, material properties and cutting geometries and parameters introduced significant deviations from the predictions made by Taylor's equation. This variability made it challenging to apply a single set of parameters across different machines, even when similar tools and cutting speeds were used.

Given the variability observed, it became clear that Taylor's equation requires adaptation and calibration to reflect the specific conditions present in Aernnova's machining environment. This could involve adjusting the equation's constants or developing a more complex model that incorporates additional variables beyond cutting speed and tool life. The chapter underscored the importance of using empirical data to refine these constants, ensuring that the equation remains relevant and accurate for specific applications.

To address the limitations of Taylor's equation, this research incorporated empirical data collected from actual machining operations. By analysing this data, it was possible to identify patterns and deviations that were not accounted for by the theoretical model.

In conclusion, while Taylor's Tool Life Equation remains a valuable tool in the field of machining, its application is not without challenges, particularly in environments with significant variability in operational conditions. The research conducted in this chapter demonstrated that while Taylor's equation can serve as a useful starting point, it often requires adaptation and supplementation with empirical data to achieve accurate and reliable tool life predictions.

For Aernnova, and similar manufacturing environments, a more integrated approach that combines theoretical models with real-world data will likely yield the best results in optimizing tool life and improving overall process efficiency.

4

Proposed methodology to deduct practical tool life

4.1 Introduction

During the machining process, the tool may encounter periods of air time, where it moves without actually cutting the material.

While the machine tracks overall tool operating time, air time does not reflect the actual cutting time, potentially introducing inaccuracies into tool life measurements.

By analysing air time across different machines, we can gain valuable insights into the variations observed in tool life, hence the necessity to create a methodology that will help to reach real air time values. By correctly measuring the amount of time that the tool spends in non-cutting conditions, we can more precisely reach a true tool life value that will help define tool wear alarms and warnings.

4.2 Methodology to correctly deduct tool life by machine

The methodology to correctly deduct tool life by machine is shown in figure 4.1. The flowchart represents the process that will be followed to reach a tool life value that will be used to define tool wear warning and alarm. Correct definition of alarms mitigates the catastrophic failure of tools thus reducing costs with part scrapping and machine tool damage and also helps to use full tool durability.

The process initiates by selecting the tool that we want to analyse, as well as the machine where we want to optimize the process. The next steps are described in sections 4.3 and 4.4.

After concluding the 2 methodologies, the outputs from both processes are used to calculate the final tool life value that will be used to define tool wear warning and alarm.

This value can be reached with the application of the equations shown below:

$$a = b * cc \tag{4.1}$$

Where,

a = Corrected average machine air time value [%]
b = Average machine air time value [%]
cc = Correction coefficient

$$d = e \div (\frac{100 - a}{100}) \tag{4.2}$$

Where,

a = Corrected average machine air time value [%]
d = Tool life value used to define warning and alarm [min]
e = Experimentally deducted tool life while cutting [min]

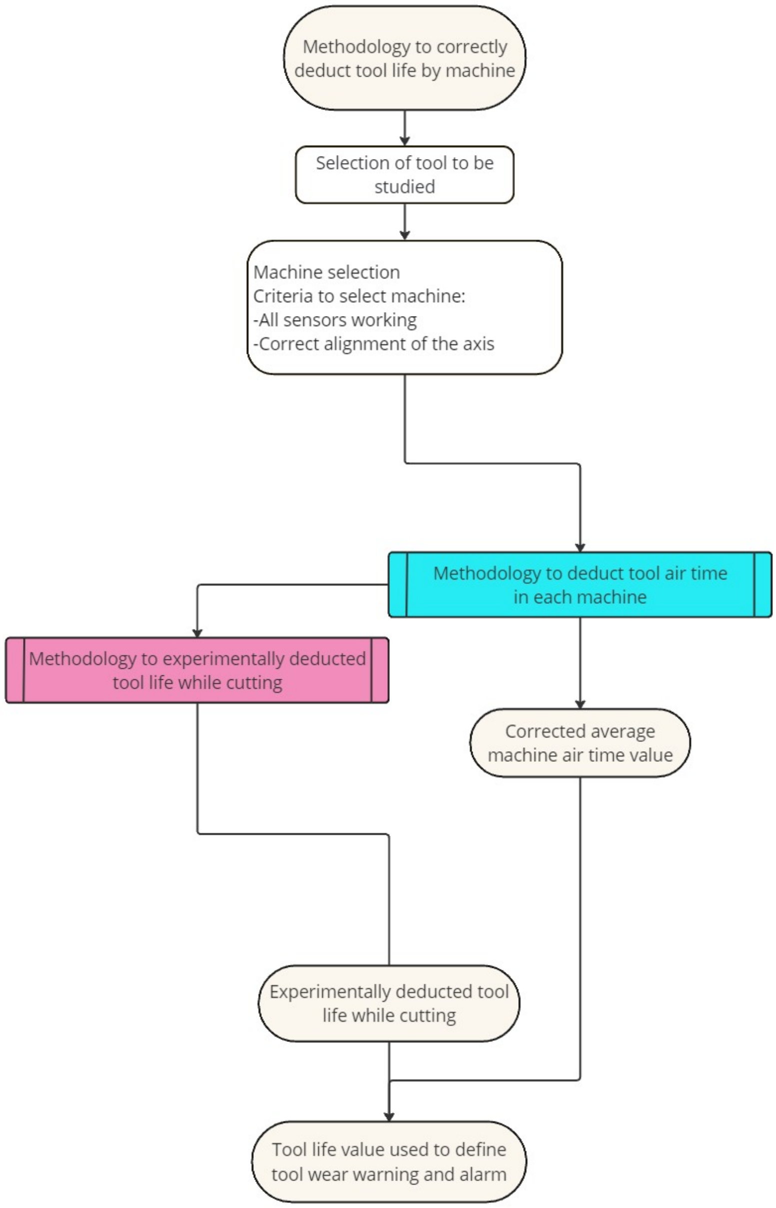

Figure 4.1: Flowchart of the methodology to correctly deduct tool life by machine

4.3 Methodology to experimentally deducted tool life while cutting

Methodology to experimentally deducted tool life while cutting is presented by figure 4.2. The first step is to choose a PN that will be used to stress test the tool. If possible, this PN should be one with a high production rate since it would produce more data to analyse.

Sometimes machine tools have more than one of the same type of tool, so it is important to choose the one that will be used for testing. The objective is to use the full durability of the tool, so inspection between machining phases and part change is mandatory to prevent part scrapping due to tool breakage.

The test ends when the operator concludes that the tool is no longer safe to work through visual inspection of the tool. In the future, a methodology to decide whether the tool wear state would affect its cutting capabilities or not.

After this, the tool life value counted by the machine tool is registered and crossed with PN air time value calculated with the developed PowerBI script. With both values we can use them to estimate the experimental tool life while cutting.

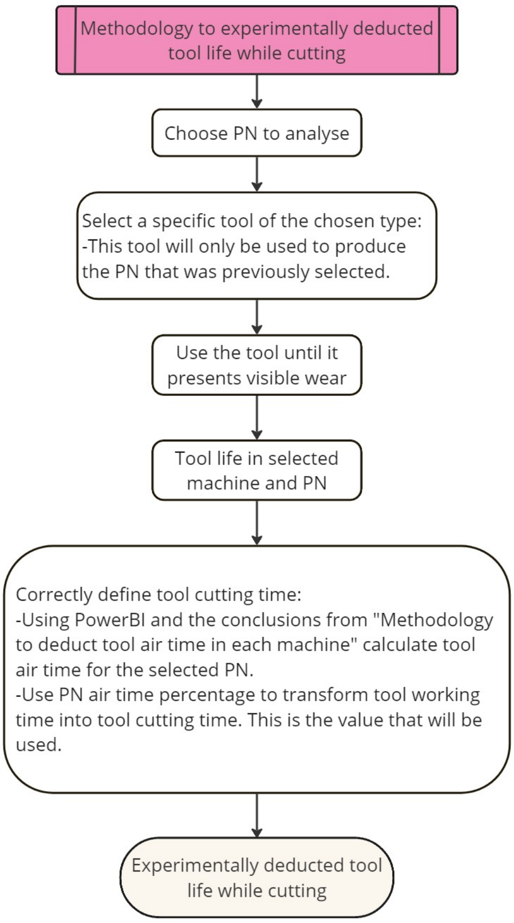

Figure 4.2: Flowchart of the methodology to experimentally deducted tool life while cutting

4.4 Methodology to deduct tool air time in each machine

The methodology to deduct tool air time in each machine is represented by a flowchart shown in figure 4.3. This methodology presents the steps to maintain consistency of the results as well as keeping them closest to reality.

The next steps, methodology to define machine analysis type and correction coefficient, is described in section 4.5. After defining the best analysis type and correction coefficient, an automated power BI data treatment is run using the selected analysis. This analysis estimates the average air time value for the chosen tool and machine that is then corrected with the correction coefficient.

After this step, the corrected average machine air time value is deducted, for the chosen tool.

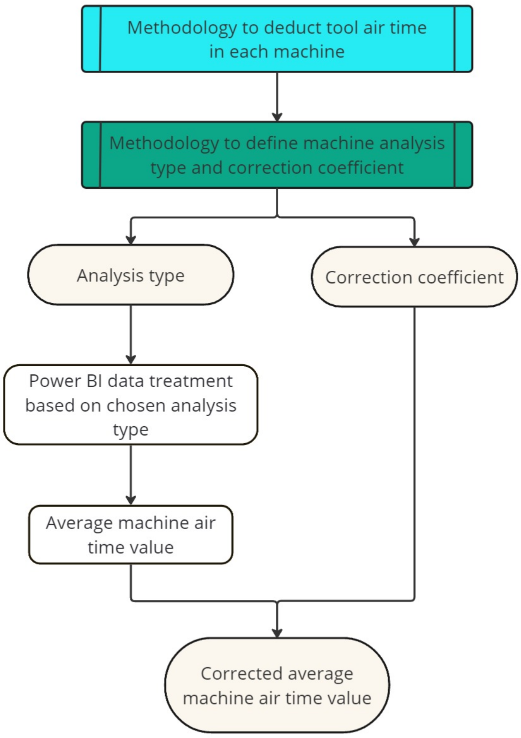

Figure 4.3: Flowchart of the methodology to deduct tool air time in each machine

4.5 Methodology to define machine analysis type and correction coefficient

The methodology to define machine analysis type and correction coefficient is represented by a flowchart shown in figure 4.4.

The first step is to decide the quantity of PN's to study. Then a PN is selected and the methodology for PN Air time definition, described in section 4.6, is used. The process is repeated until the number of analysed PN's is equal to the decided quantity.

With the different PN air times defined, a correction coefficient can be calculated by minimizing the error between force and chosen analysis air time values. If the coefficient is not stabilized, there is a need to increase the quantity of studied PN's and repeat the process.

After the coefficient is stabilized, the best analysis type and the correction coefficient is defined for the selected tool and machine.

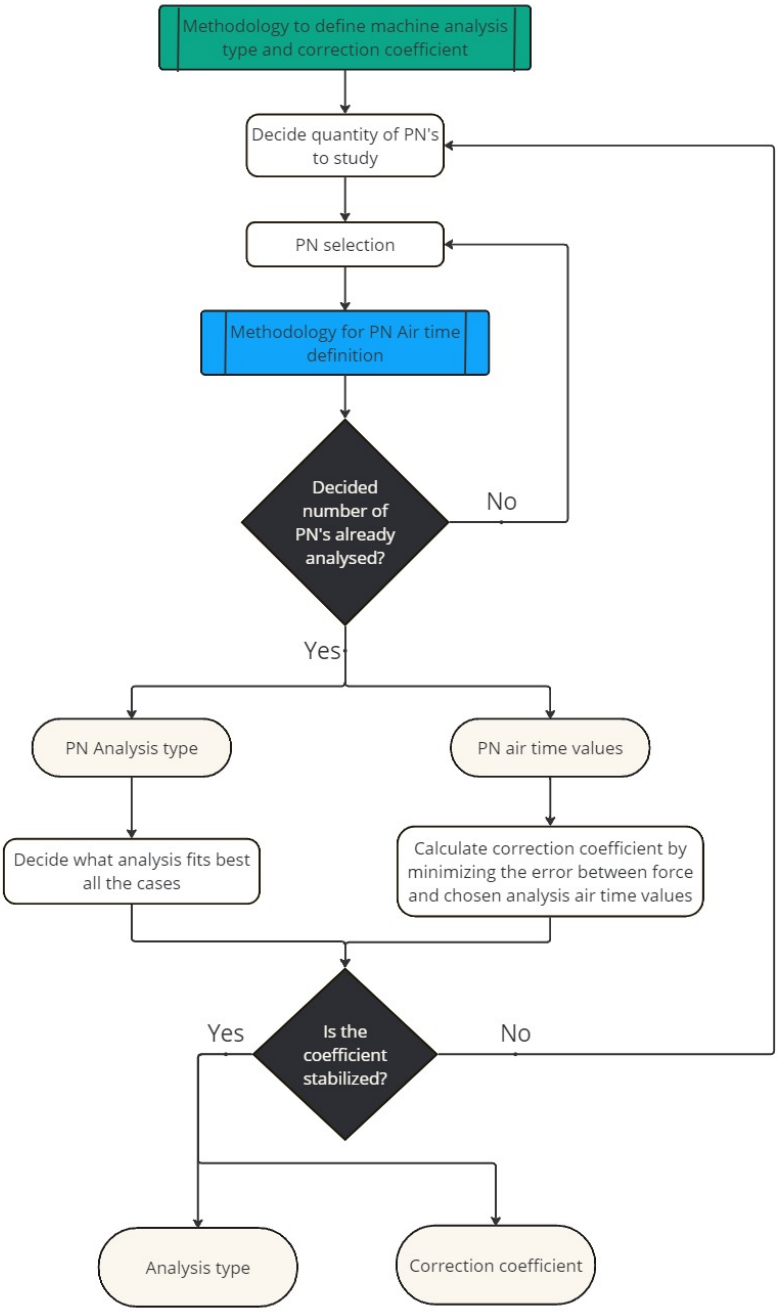

Figure 4.4: Flowchart of the methodology to define machine analysis type and correction coefficient

4.6 Methodology for PN air time definition

The methodology for PN air time definition is represented by a flowchart shown in figure 4.5.

Since the objective is to correctly deduct air time, there was a need to define different types of analysis. This enables us to compare different values and choose what makes the most sense.

We reached 4 different criteria based on 3 data sets, these being Vericut, FOCAS and AST, presented in subsections 4.7.1, 4.7.2 and 4.7.3, correspondingly.

With four air time values deducted, the next step is to compare them and choose the one that is closest to the AST value. The reason for this comparison will be explained in subsection 4.7.3.

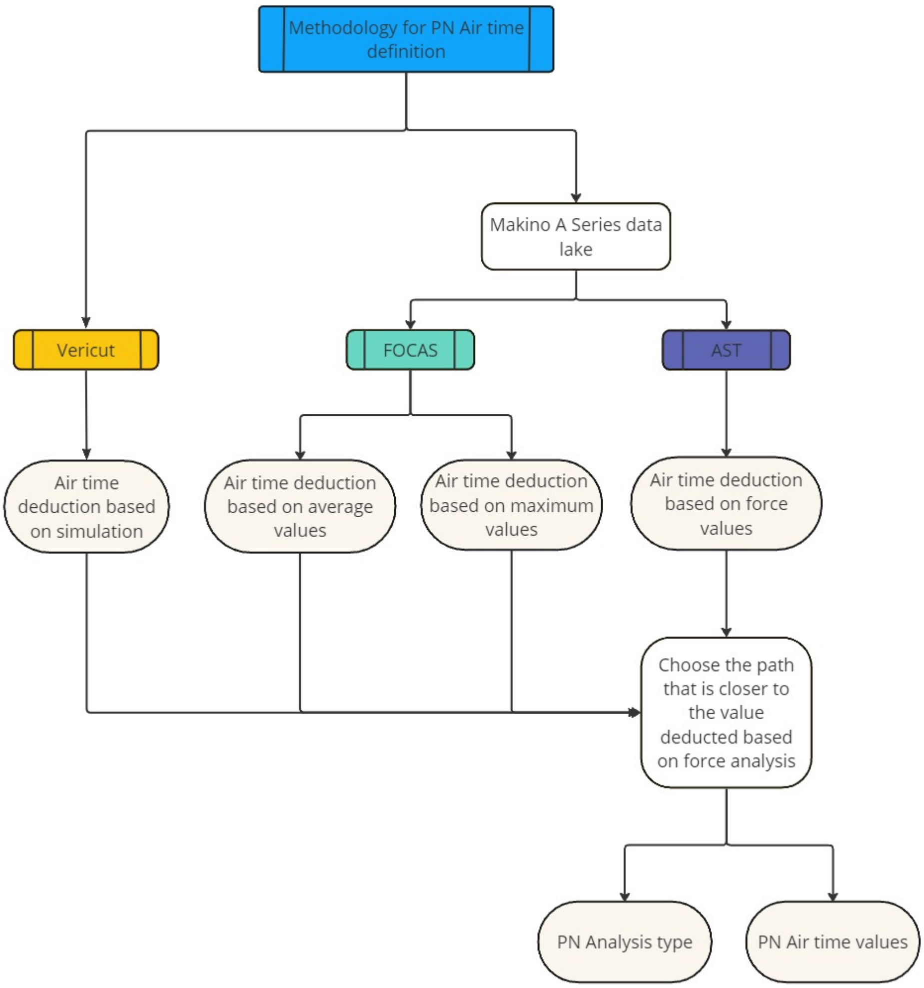

Figure 4.5: Flowchart of the methodology to deduct PN air time

4.7 Analysis types

4.7.1 Vericut

When a new machining program is made, there is a need to simulate the machining process in Vericut since it detects collisions between spindle, tool, and material. After simulating, a report is generated and the expected air time by tool is given.

By following the process in the flowchart shown in figure 4.6 we can estimate a certain PN air time.

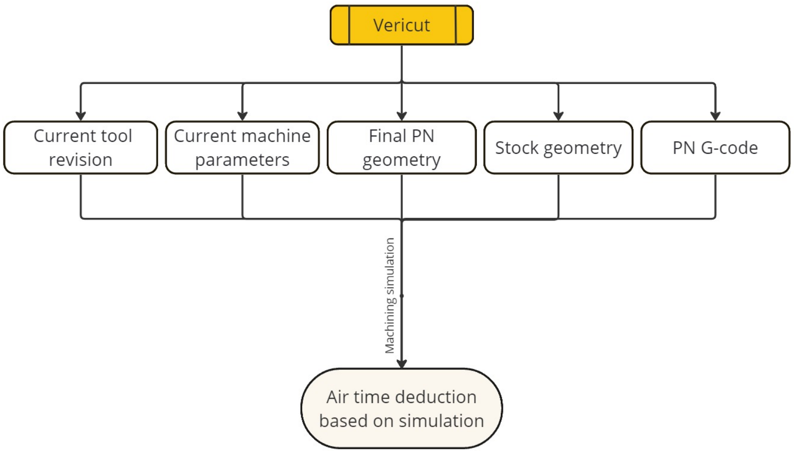

Figure 4.6: Flowchart of the Vericut process

4.7.2 FOCAS

4.7.2.1 Spindle load

To effectively identify air time, we established criteria based on the machine's operating conditions. Spindle Load (SL), the percentage of total power utilised by the motor (measured in real-time by the machine), serves as a crucial indicator.

A low SL value suggests that the tool is not under load (cutting) and is likely experiencing air time.

Through data analysis, we are able to deduct a SL the average and maximum values while in air time.

Despite spindles and tools being similar, variations in SL values exist across different machines. These variations could potentially be attributed to differences in spindle wear and internal component friction.

4.7.2.2 Vibration

During cutting, vibrations can be caused by a combination of factors - the interaction of the cutting tool with the workpiece material, imperfections in the workpiece itself, and even vibrations transmitted from the machine base. However, these factors are absent during air time, when the tool isn't engaged.

Similar to SL, a low vibration value can also indicate that the tool is moving without cutting the material. The analysis of the data revealed average and maximum values of the measured vibrations in air time.

The difference in values across all machines is also related to distinct spindle wear, and can also be affected by the lack of tool balancing.

4.7.2.3 FOCAS data treatment

The flowchart shown in figure 4.7 presents 2 distinct forms of treating FOCAS data. Air time can be deducted by using average or maximum SL and vibration values. SL and vibration values can be calculated with the definition of some criteria in Power BI data treatment. The power BI application is programmed to automatically calculate air time based on the previous values.

This process was developed with the objective of being automated and can be applied to all tools and machines.

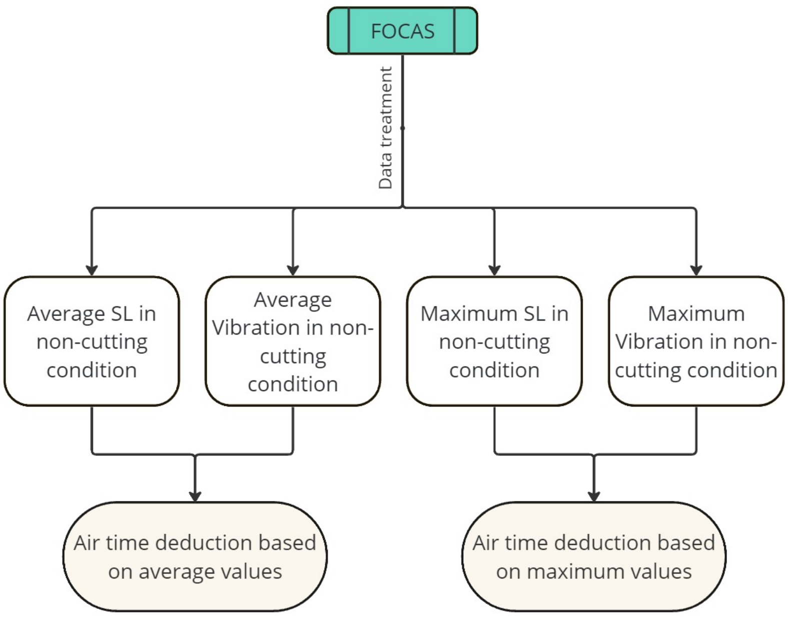

Figure 4.7: Flowchart of the FOCAS data treatment

4.7.3 AST

Radial force refers to the outward force exerted by the cutting tool on the workpiece during the machining process. It's a key factor in chip formation, surface finish, and overall cutting efficiency. Makino machine tools are able to calculate radial forces by analysing a set of measured parameters.

The recorded force value being higher than 0 than means that the tool is under cutting condition. Contrarily, if force values are 0, then the tool is in a non-cutting condition. It is known that this is the most precise form of deducting tool air time.

Force values are saved in the AST file that only contains time stamps and force values. Because of this, we can not relate force to PN and tools, the analysis needs to be done manually for each PN and for each tool. This is the reason for comparing the results with the AST analysis. This way, after defining what analysis is closest to AST, air time values can be obtained in an automated form and also corrected with the correction coefficient. The process of AST data treatment is shown in the flowchart presented in figure 4.8.

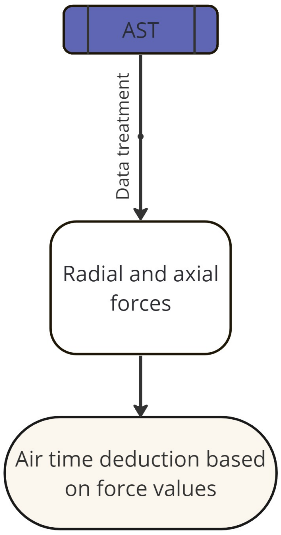

Figure 4.8: Flowchart of the AST data treatment

4.7.4 Value comparison

The values obtained from the AST file are known to be the most precise, but the analysis is complex and time-consuming. To automate the process, all the values from the different types of analysis are compared to the AST value. The value closest to the AST is selected to proceed with the methodology, along with the type of analysis from which this value was derived.

The definition of the correction coefficient ensures that the results are as accurate as possible.

5

Case study

5.1 Air time in A12.1 machine

The methodology that was developed was applied to a specific case inside the factory.

In conversation with Aernnova engineering staff it was decided to study the T1 tool while being used in the A12.1 machine. Figure 5.1 shows the followed path to reach the corrected average machine air time and the estimated tool life values.

The corrected average machine air time and the experimentally deducted tool life while cutting values can now be used to calculate tool life. Tool life value will then be used to define the new TL alarm for the A12.1 machine.

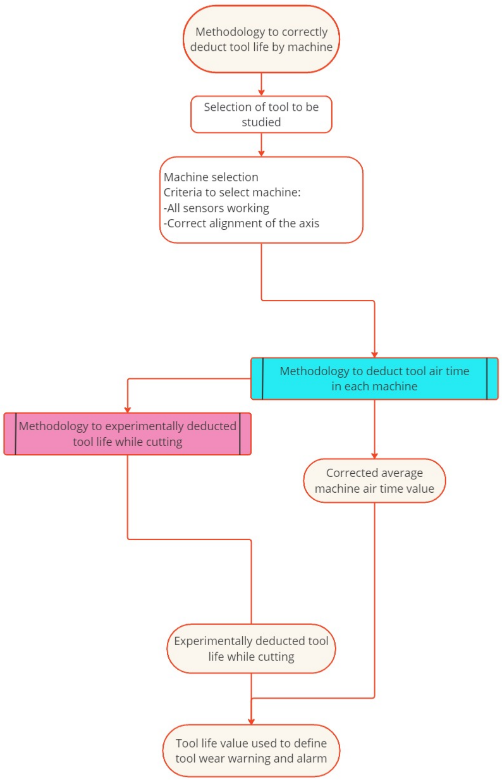

Figure 5.1: Followed path in flowchart of the methodology to deduct tool life in each machine

5.2 Experimentally deducted tool life while cutting

During the development of this work the focus was to completely define the methodology, making sure that it could easily be applied at Aernnova.

In conversation with Aernnova engineering personal, it was decided to not do this part of the methodology since it would require an intense following of the tool wear and cutting capacity throughout the whole process.

Having this in account, it was decided to use an estimate value (340 min) for the "experimentally deducted tool life while cutting". This step can be developed in future work in order to reach usable values.

5.3 Tool air time in A12.1 machine

The application of the "methodology to deduct tool air time in each machine" allows determining the corrected average machine air time value.

The "methodology to define machine analysis type and correction coefficient" gives the necessary information and values to continue the process. The analysis type is used as an input in the Power BI script and the average machine air time value is calculated based on the data lake gathered by Aernnova.

This value is then corrected by the correction coefficient. The followed path is presented in figure 5.2.

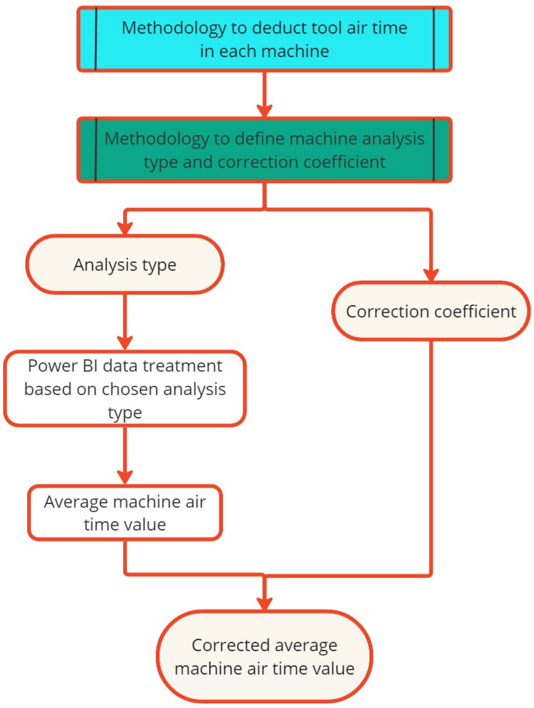

Figure 5.2: Followed path in flowchart of the methodology to deduct tool air time in each machine

5.4 Machine analysis type and correction coefficient

The "methodology to define machine analysis type and correction coefficient" starts by deciding the quantity of PN's that will be studied. Firstly, it was chosen 5 different PN's. After this, the methodology for PN air time definition needs to be applied to all chosen PN's, as shown in figure 5.3.

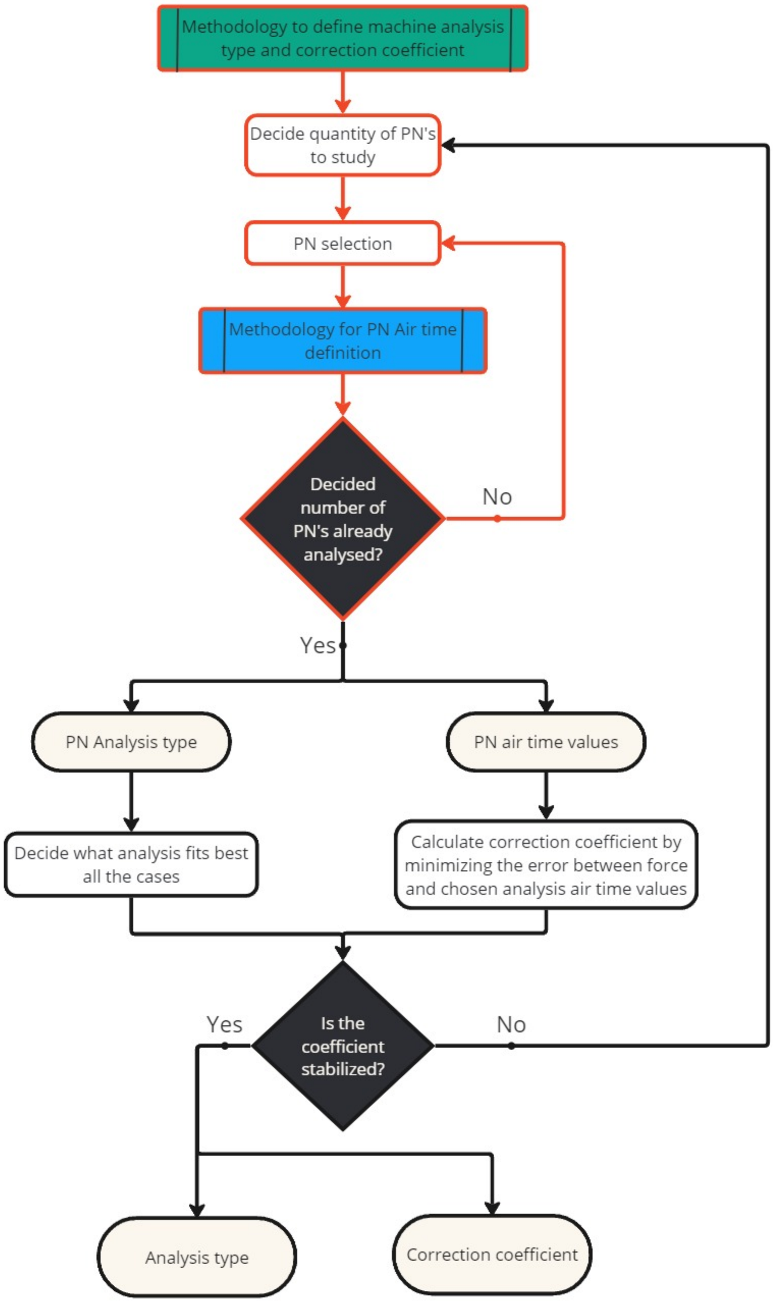

Figure 5.3: Followed path in flowchart of the methodology to deduct tool air time in each machine - 1º path

After all 5 PN's are analysed, we can continue to follow the methodology. The study of the 5 PN's was not enough to reach a stabilized correction coefficient value, as seen in figure 5.4.

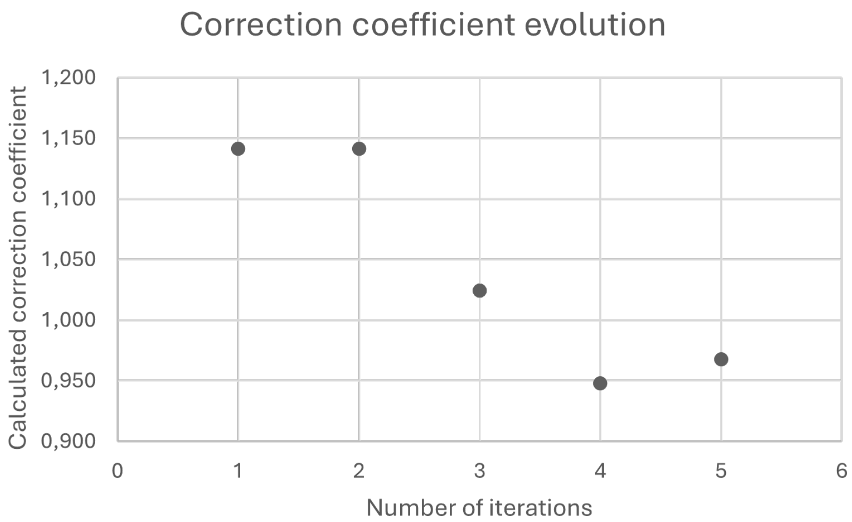

Figure 5.4: Evolution of the correction coefficient with the number of analysed PN's - 5 iterations

The path shown in figure 5.5 was followed and the number of PN's was increased to 8. As seen in figure 5.6, in this case, the value is stabilized with 8 iterations.

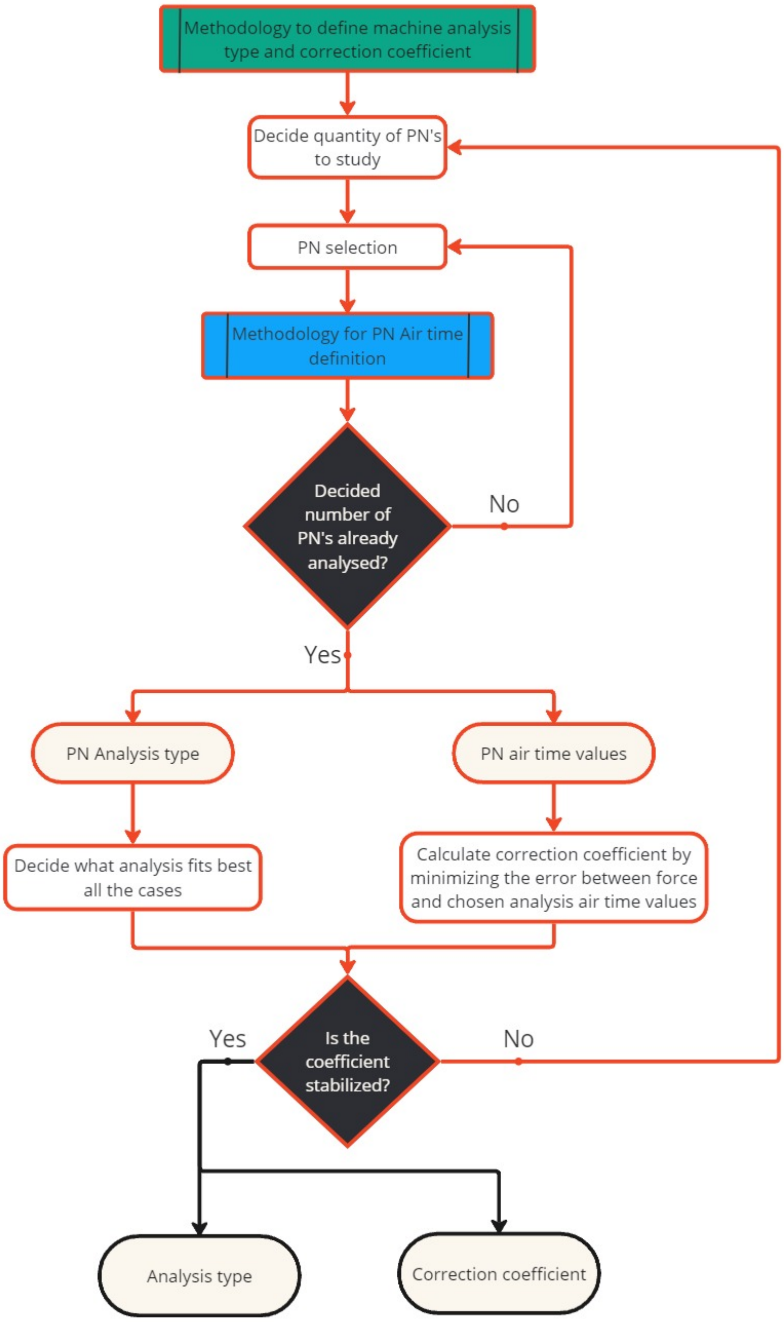

Figure 5.5: Followed path in flowchart of the methodology to deduct tool air time in each machine - 2º path

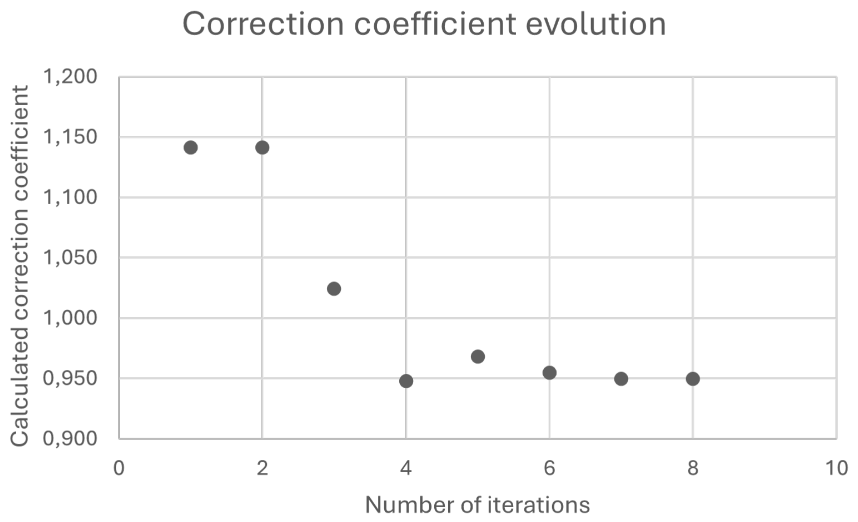

Figure 5.6: Evolution of the correction coefficient with the number of analysed PN's - 8 iterations

Table 5.1 presents the results obtained for each PN. For each PN, 2 operations were analysed and Vericut, average values analysis, maximum values analysis and force analysis air time values were obtained. By comparing the values, we can conclude that air time definition through maximum values of SL and vibration is the closest to the values obtained through force analysis (AST). The values in green will be used to proceed with the application of the methodology.

The chosen analysis type to continue the methodology is based on the maximum SL and vibration values. The followed path to end this part of the methodology is shown in figure 5.7.

Table 5.1: PN's air time results

		Air time [%]			
PN	**OP**	**Vericut**	**Average values**	**Maximum values**	**Force analysis**
550-01201-013	50	17	0.0	19.8	22.6
	60	20	0.1	11.8	13.6
550-01202-019	40	66	0.4	5.2	9.2
	50	44	1.2	9.0	7.9
550-01222-015	40	50	1.4	18.4	18.9
	50	58	0.5	27.3	24.5
550-01513-003	50	21	0.4	10.9	10.4
	60	16	0.9	11.6	10.8
555-01220-003	30	44	2.6	17.7	19.9
	40	41	0.9	14.4	13.9
555-01220-004	30	44	2.5	17.2	15.5
	40	41	1.0	16.0	15.3
555-01221-003	30	37	3.3	22.1	15.6
	40	28	1.9	15.6	14.8
555-01221-004	30	37	1.8	19.6	16.5
	40	28	1.4	15.3	15.4

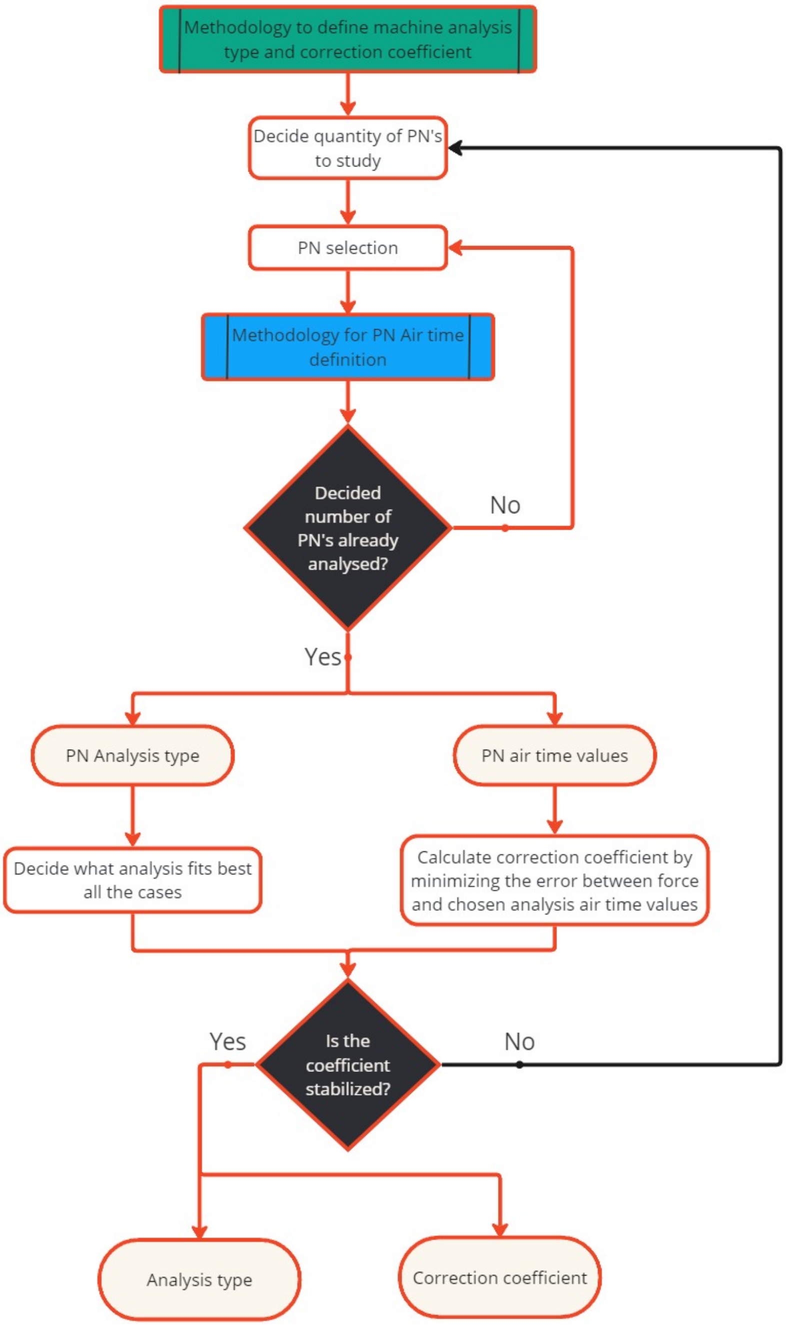

Figure 5.7: Followed path in flowchart of the methodology to deduct tool air time in each machine - 3º path

5.5 PN air time

The methodology for PN air time definition is the core of this work. AST is the most precise path that can be followed, since it detects if axial or radial forces are applied on the cutting tool. If the machine records force values we can conclude that the cutting tool is in contact with the material.

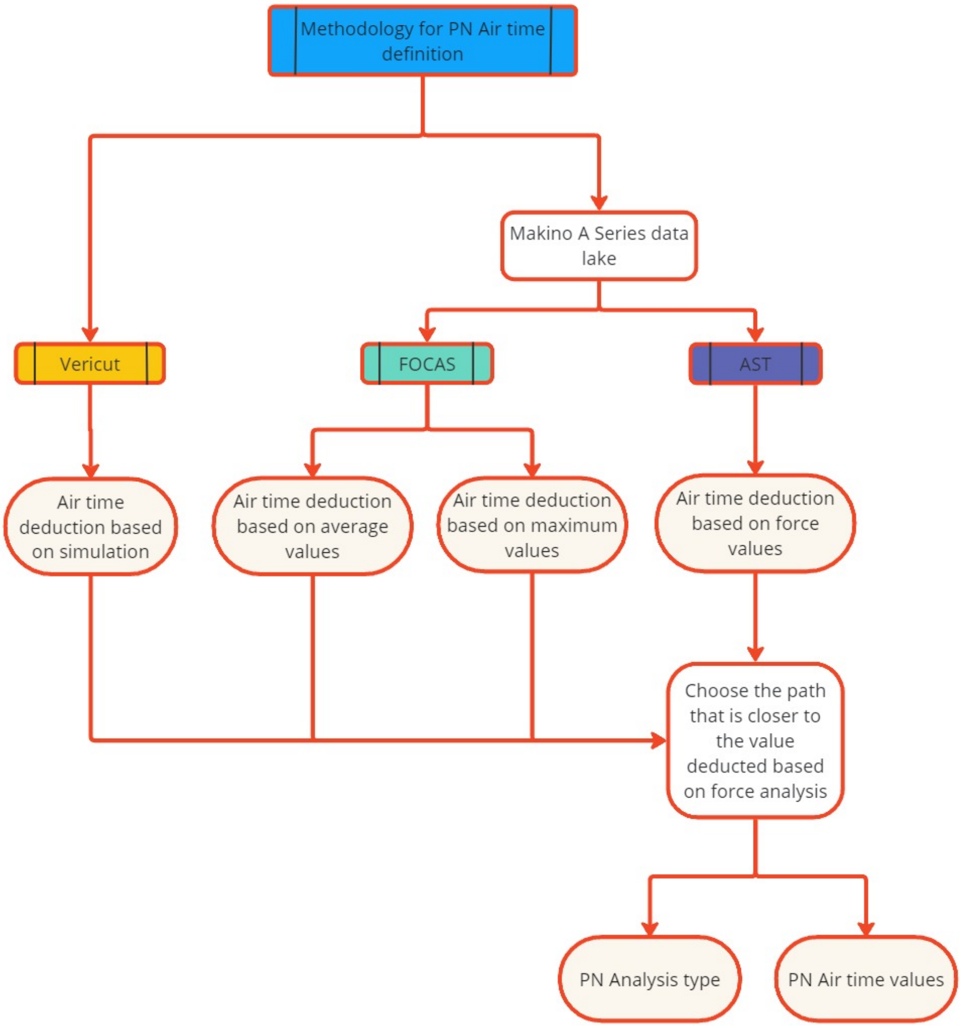

Figure 5.8: Flowchart describing the methodology to deduct PN air time

Using the script that was developed trough PowerBI it was possible to calculate the average and maximum values for spindle load and vibration in non-cutting conditions. The results are shown in table 5.2.

Table 5.2: Spindle load and vibration values in A12.1 machine tool while in air time

Machine		Average values		Maximum values	
		SL [%]	Vibration [G]	SL [%]	Vibration [G]
A12	#1	2.64	0.4	4.98	1.7

5.6 Methodology results

The different results and conclusions obtained trough out the application of the methodology are shown in table 5.3. The necessary calculations to reach some of these results are explained by equations 5.1 and 5.2.

Table 5.3: Methodology results

Designation	Value	Used at:
Tool	T1	Section 5.1
Machine	A12.1	Section 5.1
Analysis Type	FOCAS (Air time deduction based on maximum SL and vibration values)	Section 5.3
Correction coefficient	0.95	Section 5.3
Average machine air time value [%]	27.00	Section 5.3
Corrected average machine air time value [%]	25.65	Section 5.1
Experimentally deducted tool life while cutting [min]	340.00	Section 5.1
Tool life value used to define warning and alarm [min]	457.29	-

$$\begin{aligned} a &= b * cc \\ &= 27 * 0.95 = 25.65 \end{aligned} \tag{5.1}$$

Where,

a = Corrected average machine air time value [%]
b = Average machine air time value [%]
cc = Correction coefficient

$$\begin{aligned} d &= e \div (\frac{100 - a}{100}) \\ &= 340 \div (\frac{100 - 25.65}{100}) = 457.29 \end{aligned} \tag{5.2}$$

Where,

a = Corrected average machine air time value [%]
d = Tool life value used to define warning and alarm [min]
e = Experimentally deducted tool life while cutting [min]

5.7 Case study conclusion

The case study presented in this chapter provided a detailed examination of the practical application of the developed tool life prediction methodology.

By focusing on real-world data and operational conditions, the study offered insights into the challenges and opportunities associated with implementing theoretical models and empirical approaches in a complex manufacturing environment.

The case study also highlighted the need for continuous improvement in tool life prediction methodologies. As operational conditions evolve, so too must the models and strategies used to predict and manage tool life.

This iterative process of refinement, supported by ongoing data collection and analysis, is vital for sustaining the benefits achieved during the case study and for addressing new challenges as they arise.

6

Conclusion

This dissertation has explored the complexities and challenges associated with predicting and managing tool life in machining processes, with a particular focus on operations at Aernnova, an aero structures manufacturing company.

The goal of this research was to enhance the understanding of tool wear occurrences and develop a more reliable method for estimating tool life, thereby improving process efficiency and reducing operational costs.

The study began with a review of the theoretical models commonly used in tool life prediction, notably Taylor's Tool Life Equation. This equation, which establishes a relationship between cutting speed and tool life, is widely recognized and used in machining industries. However, its application proved limited in the specific context of Aernnova's operations.

The primary limitation arose from the variability in tool life data across different machines, even when identical tools and cutting parameters were used. This highlighted the need for a more tailored approach to tool life prediction in environments with high variability.

Given the limitations of theoretical models, an empirical approach was adopted to compute tool life more accurately. The methodology involved collecting and analysing data from actual machining operations at Aernnova. One key aspect of this analysis was the development of the process that allowed to determine the correction coefficient for tool air time through the analysis of the available machining data. This correction was crucial for adjusting the data analysis predictions to better fit the observed realities of the production environment.

The computed tool life values were based on a detailed analysis that incorporated both the corrected machine air time and the specific operational conditions at Aernnova. The result was a more accurate and reliable prediction of tool life, which could then be used to set warning and alarm thresholds for tool replacement. This method helps mitigating the risk of unexpected tool failures, which can lead to costly downtimes and quality issues in the manufacturing process.

Throughout the study, several challenges were identified, including the difficulty in standardizing tool life predictions across different machines and operations. To address these challenges, it is recommended that Aernnova continues to refine its data collection processes, ensuring that all relevant variables are consistently monitored and recorded.

Additionally, further research could explore the integration of machine learning algorithms to analyse the complex relationships between these variables and predict tool life more dynamically.

The practical application of this research at Aernnova has the potential to significantly enhance the efficiency of their machining processes. By improving the accuracy of tool life predictions, the company can optimize tool usage, reduce waste, and minimize downtime. The development of more accurate warning and alarm thresholds for tool replacement is expected to result in better quality control and lower operational costs.

This thesis has contributed valuable insights into the challenges of tool life prediction in a high-precision manufacturing environment. While the limitations of traditional theoretical models were clearly demonstrated, the success of the empirical approach underscores the importance of tailoring solutions to specific operational contexts.

In conclusion, the research has demonstrated that an analysis of empirical data such as power usage, time in air of the tool and tool usage time in combination with a theoretical understanding can lead to significant improvements in tool life management. Continued efforts in this direction, particularly with the adoption of advanced data analytics and machine learning, will likely yield even greater efficiencies and cost savings in the future.

The proposed methodology will allow Aernnova to continuously improve tool life values prediction with the evolution of the data that is collected daily at the shop floor. The update of the database allows to refine tool life values, since small changes can be done daily with the help of the automated PowerBI script. This will provide a continuos improvement for Aernnova operations as well as cost reductions.

7 Future work

The research presented in this dissertation has laid a strong foundation for improving tool life prediction in machining processes, specifically within the context of Aernnova's operations.

However, there remain several avenues for further investigation and development that could enhance the robustness and applicability of the findings. This chapter outlines key areas where future work could be directed to build upon the insights gained from this study.

Throughout this document some points for future work were referenced:

1. **Tool balancing:** In section 3.5 some changes to the current tool consumption registry and change process were proposed but tool balancing was not implemented. Tool balancing could contribute to lower tool wear due to the reduction in spindle vibrations.

2. **ISO 3685:1993 standard analysis of insert wear:** In subsection 3.6 inserts damage characterization was only based on visual inspection. In order to obtain precise results that can be quantified, a methodology based on the ISO 3685:1993 standard should be developed.

   This would ensure that the classification would not only be based on the operator opinion.

3. **Theoretical analysis of tool life:** In chapter 3.7 a small reference to the theoretical analysis of tool life is done. A theoretical study could bring valuable insights and give support to the methodology developed in this work.

   Also, experimental tests can be done in order to calibrate and adapt Taylor's tool life equation to Aernnova work conditions.

4. **Experimental deduction of tool life while cutting value:** In section 5.2 an estimated value was used to continue the methodology application. This means that the methodology end results can not be used to define tool alarms.

The realization of the experimental tests by Aernnova would provide results and information to correctly define and optimize tool wear.

Besides the suggestions made throughout the document, there are some more topics that could be approached:

- **Integration of advanced machine learning techniques:**

  One of the primary limitations encountered during this research was the variability in tool life data across different machines, even under similar operating conditions. To address this, future work could explore the use of advanced machine learning algorithms to model these complex and non-linear relationships more effectively.

  By leveraging large datasets collected from machining operations, machine learning models could be trained to predict tool life with higher accuracy, considering a wider range of influencing factors such as material properties, environmental conditions, and real-time machine performance metrics.

  This could be achieved through the implementation of predictive maintenance systems that utilize machine learning to continuously monitor tool wear and predict tool life in real-time. This would allow for more dynamic and adaptive tool management strategies.

- **Development of a comprehensive tool wear database:**

  The empirical analysis conducted in this study relied heavily on data collected from Aernnova's existing operations. However, the quality and consistency of this data were sometimes limited.

  Future research should focus on developing a comprehensive and standardized database of tool wear information, encompassing a broader range of machining conditions, tool materials, and workpiece characteristics.

  By establishing a centralized tool wear database within Aernnova that is continuously updated with new data from ongoing operations. This database could serve as a valuable resource for future research and operational decision-making.

The findings of this dissertation have opened up several pathways for future research and development in tool life prediction and management. By integrating advanced technologies such as machine learning, real-time monitoring, and new material science innovations, it is possible to further enhance the efficiency and reliability of machining processes.

These future efforts will not only benefit Aernnova but also contribute to the broader field of manufacturing engineering, driving continuous improvement and innovation in tool life management.

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